Power quality requirements and responsibilities at the point of connection

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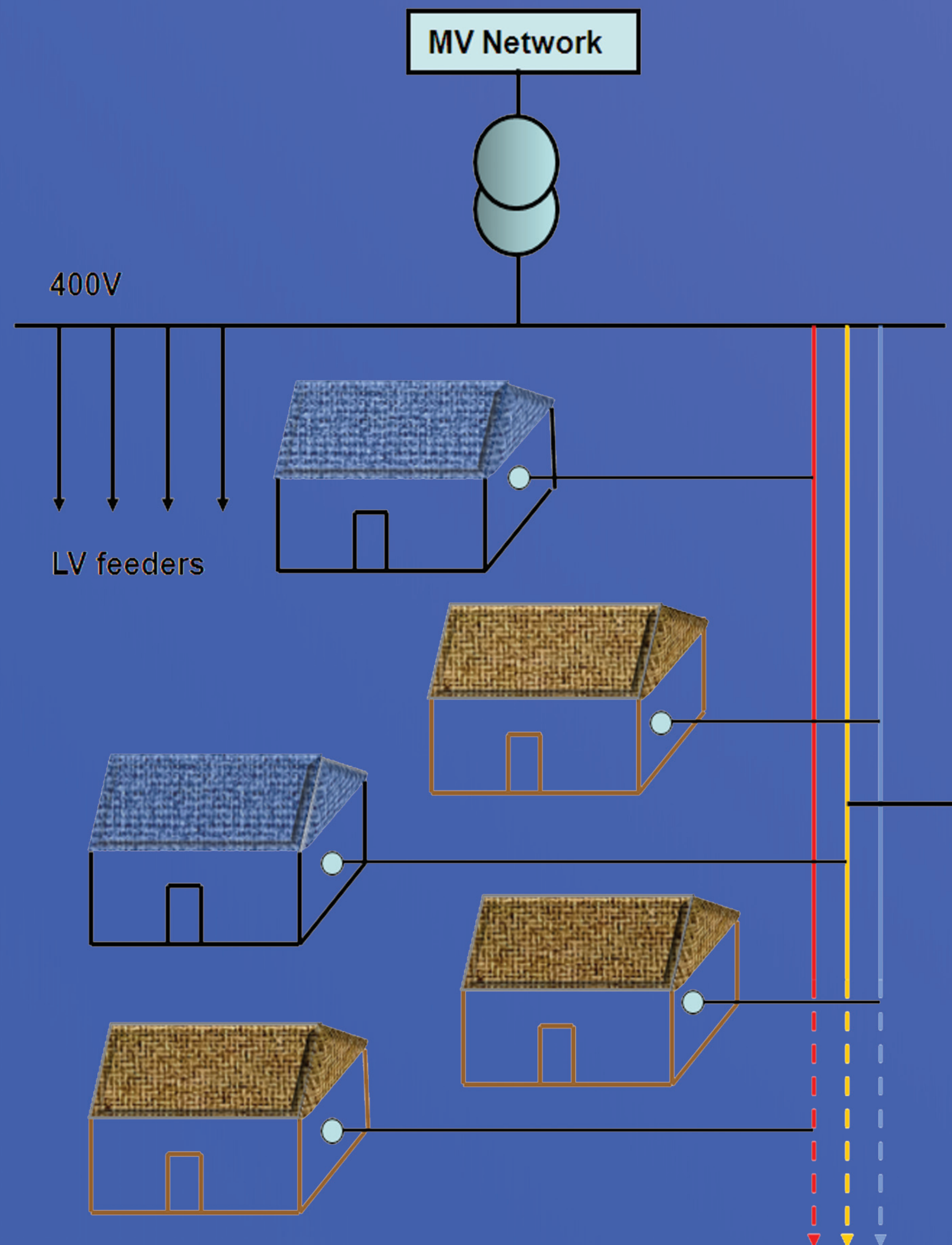

Power Quality Requirements and Responsibilities at the Point of Connection   Sharmistha Bhattacharyya

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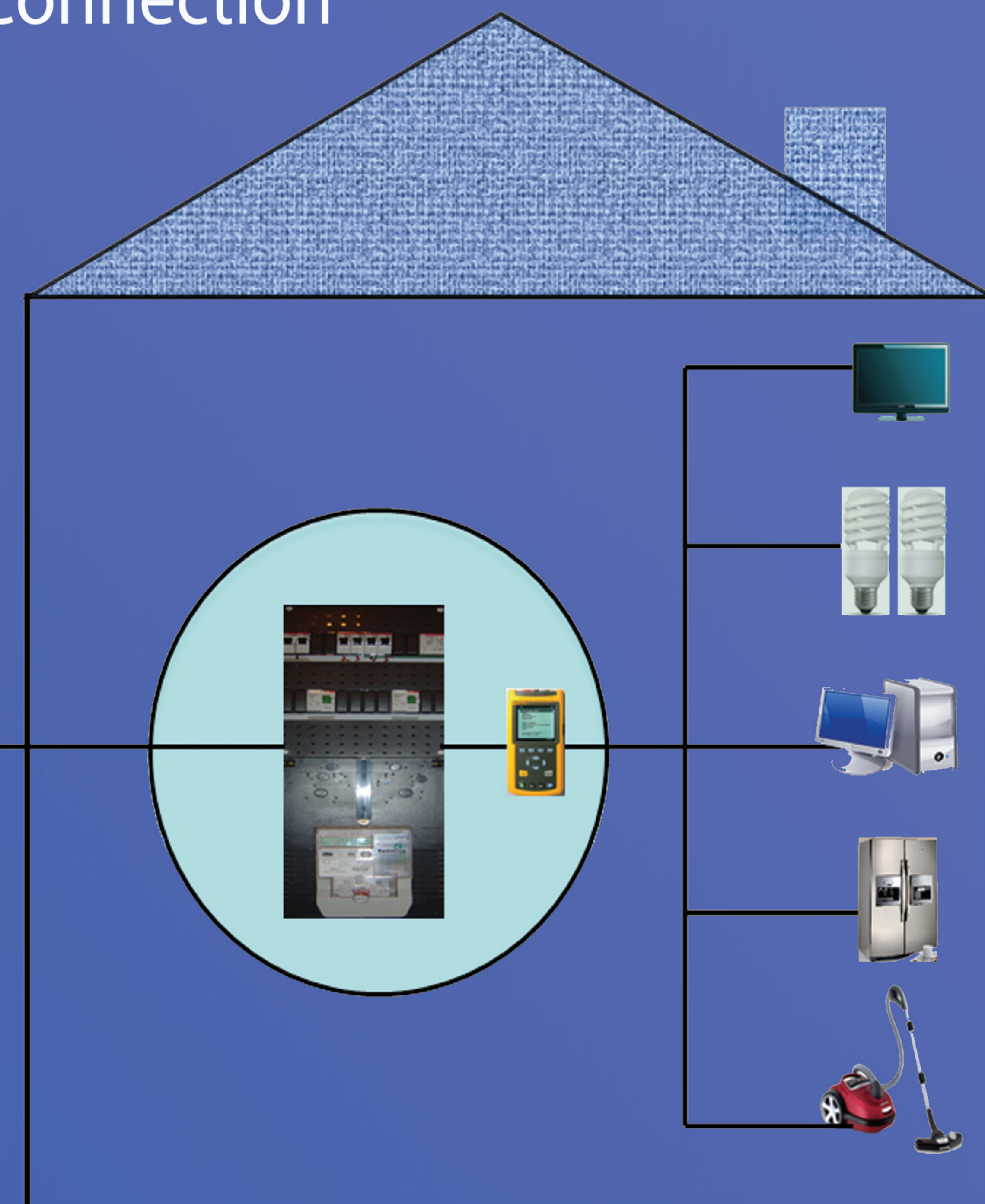

Sharmistha Bhattacharyya

Invitation

You are kindly invited
to attend the public
defense of my thesis

Power Quality Requirements and Responsibilities at the Point of Connection

The defense will
take place on
Monday
June 27
2011
at 16:00
in the Collegezaal 4
Eindhoven University
of Technology

You are also invited
to join the reception
after the defense

Sharmistha Bhattacharyya

Power Quality Requirements and Responsibilities at the Point of Connection

PROEFSCHRIFT

ter verkrijging van de graad van doctor aan de
Technische Universiteit Eindhoven, op gezag van de
rector magnificus, prof.dr.ir. C.J. van Duijn, voor een
commissie aangewezen door het College voor
Promoties in het openbaar te verdedigen
op maandag 27 juni 2011 om 16.00 uur

door

Sharmistha Bhattacharyya

geboren te Calcutta, India

Dit proefschrift is goedgekeurd door de promotor:

prof.ir. W.L. Kling

Copromotor:
dr.ir. J.F.G. Cobben

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"Karmanye Vadhikaraste Ma Phaleshu Kadachana,
Ma Karma Phala Hetur Bhurmatey Sangostva Akarmani"

Sri Bhagavad Gita, chapter II, 47

"Your right is for action alone, never for the results. Do not become the agent of the results of action. May you not have any inclination for inaction."

Translated by Swami Gambhirananda

To my parents and to my husband

Promotor:
prof. ir. W.L. Kling, Technische Universiteit Eindhoven

Copromotor:
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Power Quality Requirements and Responsibilities at the Point of Connection

Summary

In the present power delivery environment, the quality of electricity as a product has become more important than before. Modern electrical devices are complex in terms of their functionalities and are more sensitive to the quality of the supplied electricity. A disturbance in supply voltage can cause significant financial losses for an industrial customer. Moreover, there are increasing number of disputes in different countries around the world among the network operators, the customers and the device manufacturers regarding their individual responsibility concerning 'Power Quality' (PQ) problems and solutions. In addition, the existing standards on PQ give very limited information about responsibility sharing among the involved parties.

PQ disturbances can be originated in the network as well as at the customer's installation and can propagate to other parts of the network. The PQ level in the network is also highly influenced by PQ emission behaviors of connected devices and the network characteristics. During the last decades, PQ related complaints have increased largely. Inadequate PQ can lead to various technical and financial inconveniences to the customers and the network operators. This research aims to find out a socio-economically optimum solution to PQ problems. The main objectives of this thesis are defined as:

"Analyze main PQ problems and their consequences to various involved parties. Next, define optimal PQ criteria at the customer's point of connection (POC) and finally specify responsibilities of the involved parties".

The thesis is based on practical field measurements of PQ parameters in the network, on analyzing the developed network models by using computer simulations and laboratory experiments. The most important part of the work is the verification of simulation results with the practical measurements. Further, the obtained results are compared with the values given in the available standards. Lastly optimal PQ parameters and requirements at a POC are defined for flicker, harmonics and voltage dips. The results of the research work reported in this thesis can be summarized as follows:

- Obtained a deeper insight in PQ problems around the world.
- Developed typical network models for computer simulations on different PQ phenomena (such as flicker, harmonics and voltage dips) and verified the results with field measured data.
- Gathered practical information on various technical and financial consequences of inadequate PQ for different parties namely: the network operators, the customers and the equipment manufacturers.
- Made an inventory on various existing (and developing) standards and technical documents on PQ around the world. Then, compared the limits given on various PQ parameters in those standards/documents and analyzed their relevance and applicability in the future.
- A proposal is given about optimal PQ limits (for flicker and harmonics) at the low voltage (LV) customer's POC. Also, the average and maximum values of voltage dips in the networks are estimated.
- Suitable planning level limit values for flicker, harmonics and voltage dips are described.
- PQ related responsibilities of the customers, network operators and device manufacturer at the customer's POC are defined.

The main conclusions and contributions of this thesis are:

- It is found that a harmonization among the presently available PQ standards is required and a dedicated set of global standards is needed to get optimal PQ at the customer's POC. Various limiting values on different PQ parameters (e.g. flicker emission and harmonic current emission limits for a customer) at a POC are proposed in this thesis. Also, the average and maximum numbers of voltage dips in the Dutch high voltage (HV) and medium voltage (MV) networks are estimated.
- A new set of planning level values for flicker index P_{lt} at different voltage levels of a network is proposed. For harmonics, a proposal is given to change the planning level values for 'triple n' harmonic voltages and new values are suggested for the MV and LV networks. Moreover, it was proposed that the 3rd harmonic summation coefficient value of the standard can be modified to a higher value as sufficient diversity is found in the system. Regarding voltage dips, the number of voltage dips for planning and compatibility levels are proposed for a customer connected to the MV network in the Netherlands.

In this thesis, PQ responsibility sharing procedures are described for a network operator, customer and a device manufacturer. Network impedance is identified as an important parameter in deciding flicker and harmonics at a POC. The network operator should provide information on the approximate number of occurrence of voltage dips in a year at a customer's POC. To maintain sufficient PQ level in the network, all the involved parties should follow certain rules and duties. PQ regulation can be successfully implemented when all the involved parties are aware of their responsibilities in the system.

Power Quality eisen en verantwoordelijkheden op het aansluitpunt

Samenvatting

In de huidige energiemarkt, de kwaliteit van elektriciteit als product is belangrijker geworden dan voorheen. Moderne elektrische toestellen zijn complex ten aanzien van functionaliteit en zijn gevoeliger voor de kwaliteit van de geleverde elektriciteit. Een verstoring in de voedende spanning kan significante financiële kosten veroorzaken voor een industriële klant. Verder zijn er een toenemend aantal discussies in verschillende landen op de wereld tussen netbeheerders, klanten en producenten van toestellen over hun individuele verantwoordelijkheid ten aanzien van "Power Quality" (PQ) problemen en oplossingen. Bovendien, de bestaande normen over PQ geven maar beperkte informatie over de verdeling van de verantwoordelijkheden tussen de verschillende partijen.

PQ verstoringen kunnen hun oorsprong hebben in het net maar ook in de installatie van de klant en kunnen zich voortzetten naar andere delen van het elektriciteitsnet. Het PQ niveau in het net wordt grotendeels beïnvloed door PQ emissies van de aangesloten toestellen en de eigenschappen van het net. Gedurende de afgelopen decennia zijn PQ gerelateerde problemen sterk gestegen. Onvoldoende PQ kan leiden tot diverse technische en financiële ongemakken voor de klanten en de netbeheerders. Dit onderzoek beoogt een sociaaleconomische optimale oplossing te vinden voor PQ problemen. De belangrijkste doelstellingen van dit proefschrift zijn gedefinieerd als:

"Analyseer de belangrijkste PQ problemen en hun gevolgen voor verschillende betrokken partijen. Vervolgens, definieer optimum PQ-criteria op het aansluitpunt van de klant en tenslotte specificeer de verantwoordelijkheden van de verschillende partijen".

Dit proefschrift is gebaseerd op praktische metingen van PQ parameters in het net, het analyseren van de ontwikkelde net modellen door gebruik te maken van computer simulaties en experimenten in het lab. Het meest belangrijke deel van het onderzoek is de verificatie van de simulatieresultaten met praktijkmetingen. Verder

zijn de verkregen resultaten vergeleken met de waarden gegeven in de beschikbare normen. Tenslotte zijn optimale PQ parameters en eisen op het aansluitpunt gedefinieerd voor flikker, harmonischen en spanningsdips. De resultaten van het onderzoek, beschreven in dit proefschrift kunnen als volgt wordt samengevat:

- Een beter inzicht in PQ problemen over de wereld is verkregen
- Typische net modellen voor computer simulaties ten aanzien van verschillende PQ fenomenen (zoals flikker, harmonische en spanningsdips) zijn ontwikkeld en de resultaten zijn geverifieerd met meetdata vanuit de praktijk.
- Praktische informatie met betrekking tot diverse technische en financiële gevolgen van onvoldoende PQ voor de verschillende partijen, namelijk de netbeheerders, de klanten en de producenten van toestellen, zijn verzameld.
- Een inventarisatie is gemaakt van verschillende bestaande (en in ontwikkeling) zijnde normen/standaarden en technische documenten in de wereld. Daarna zijn de limieten ten aanzien van diverse PQ parameters, opgenomen in deze normen, vergeleken en is hun relevantie en toepasbaarheid van de toekomst geanalyseerd.
- Een voorstel is gemaakt voor optimum PQ limieten (voor flikker en harmonischen) op het aansluitpunt van (LS) klanten. Ook een schatting gemaakt van het gemiddelde en maximale aantal spanningsdips in het net.
- Bruikbare limieten voor planningniveaus voor flikker, harmonischen en spanningsdips zijn beschreven.
- PQ gerelateerde verantwoordelijkheden voor de klanten, netbeheerders en producenten van toestellen zijn gedefinieerd.

De belangrijkste conclusies en bijdragen van dit proefschrift zijn:

- Harmonisatie van de huidige beschikbare PQ normen is noodzakelijk en een toepasselijke set van globale normen is nodig om optimale PQ op het aansluitpunt van de klant te krijgen. Diverse limieten ten aanzien van diverse PQ parameters (bijvoorbeeld limieten voor flikker emissie and emissie van harmonische stromen voor een klant) op het aansluitpunt zijn voorgesteld in dit proefschrift Ook het gemiddelde en het maximale aantal spanningsdips in de Nederlandse hoogspanning (HS) en middenspanning (MS) netten zijn geschat.

- Een nieuwe set van planningniveaus voor de flikker index P_{lt} voor verschillende spanningsniveaus van een net, is voorgesteld. Ten aanzien van harmonischen een voorstel gedaan om het planningniveaus van "veelvouden van drie" harmonische spanningen te veranderen en suggesties voor nieuwe waarden zijn gedaan voor MS en LS netten. Verder is er voorgesteld om de waarde van de 3^{e} harmonische sommatie coëfficiënt in de norm te veranderen naar een hogere waarde als voldoende diversiteit in het systeem is waargenomen. Ten aanzien van spanningsdips is het aantal spanningsdips voor het planning- en comptabiliteitsniveau voor een klant aangesloten op het MS net in Nederland, voorgesteld.

In dit proefschrift zijn procedures voor de toewijzing van PQ verantwoordelijkheden beschreven voor de netbeheerder, de klant en de producent van toestellen. De netimpedantie is geïdentificeerd als een belangrijke parameter in beslissingen rondom flikker en harmonischen op een aansluitpunt. De netbeheerder moet informatie verschaffen over het aantal spanningsdips dat bij benadering per jaar optreedt op het aansluitpunt van een klant. Om voldoende PQ in de netten te behouden moeten alle betrokken partijen zich houden aan bepaalde regels en verplichtingen. Regulering van PQ kan succesvol worden geïmplementeerd als alle betrokken partijen zich bewust zijn van hun verantwoordelijkheden in het systeem.

Contents

Chapter 1

Introduction

1.1 Background

‘Efficiency’ and ‘sustainability’ are some of the most important issues of the present power system infrastructure and the electricity supply. The increasing rate of replenishment of scarce natural resources, global warming and the growth of energy demand are also the strong challenges for the modern civilization. All these issues force Governments and regulatory bodies of all over the world to take steps forward in promoting the use of more ‘sustainable’ resources for energy production and encourage the users to consume energy more efficiently. In the next decades, many decentralized generators (DG) using various sustainable energy resources are expected to be integrated in the electricity network. The DG is connected to the distribution network through various converters with power electronics interfaces. Moreover, the use of power electronics based appliances has increased significantly in our daily life. The electricity consumers are more and more concerned about the electricity supply as they often use sensitive devices at their installations that require high quality voltage. In addition, the electrical devices have become more complex in terms of their functionalities and the way they interact with other devices connected to the electricity network. A small disturbance in the supply voltage might cause significant inconveniences and large amount of financial losses for the (industrial) customer. Therefore, the customers expect to receive a voltage at their point of connections that should fulfil the quality requirements as specified in the national grid code and other applicable standards. Complaints on inadequate Power Quality (PQ) that cause technical and financial inconveniences are increasing every year among different types of customers. From surveys, it is found that PQ disturbances can be originated in the network as well as at a customer's premise and can propagate to other parts of the network. In the last decades, there are many disputes and discussions among the network operator, the customers and the device manufacturers regarding their individual responsibility concerning power quality aspects. Figure 1.1 depicts the relationship of the different parties in order to maintain a stable operation of the electricity business.

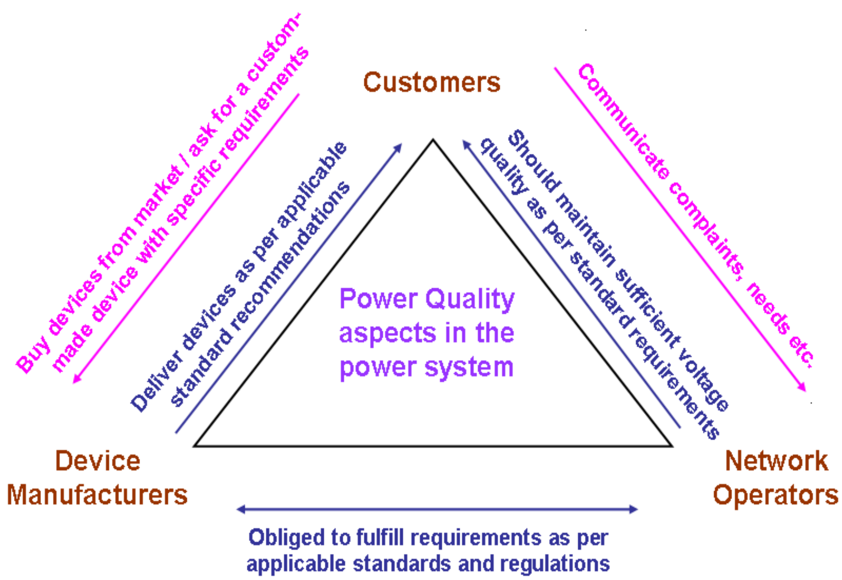


Figure 1.1. Mutual relationships among the parties concerning power quality

In the present electricity environment, discussions are going on to incorporate more intelligence in the system by implementing smart grids and smart meters. Also, integration of large number of decentralized generations has modified the electricity infrastructure significantly. Moreover, the role of the customers is changing too as they do not only consume the electricity but also produce it. Therefore, the network in the future will be more complex in terms of its functionality and management aspects. Hence, regulation is needed that will define clearly the responsibilities of the involved parties to minimize disputes in the network.

1.2 Definition of power quality

Many definitions of power quality are found in different standards and books. The International Electrotechnical Commission (IEC) has defined PQ in the IEC 61000-4-30 standard [Iec08] as: "the characteristics of the electricity at a given point on an electrical system, evaluated against a set of reference technical parameters". In the IEC standards, the term 'Electromagnetic Compatibility' is used that is very much related to power quality. Electromagnetic Compatibility (EMC) is the ability of an equipment or system to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances to anything in that environment. The IEC has published many standards and technical reports on EMC that are part of the IEC 61000 series. Most of the international standards on PQ are based on this series. The Institute of Electrical and Electronics Engineers (IEEE) defines PQ in the IEEE 100 standard [Iee04] as: "the concept of powering and grounding sensitive equipment in a manner that is suitable to the operation of that equipment". The limitation of the latter definition is that it considers PQ as a concern only when the involved devices and their performances are affected. On the other hand, PQ is defined in the report of IEEE P1433 power engineering society (PES) working group [Iee09] as: "any power problem manifested in voltage, current and frequency deviation that results in the failure or mal-operation of a customer's equipment". Reference [Bol01] defines PQ as a combination of voltage and current qualities. Voltage quality is concerned with deviations of the actual voltage from the ideal waveform and current quality is the equivalent definition for the current. Any deviation of voltage and current from the ideal may cause a power quality disturbance. Voltage disturbances generally originate in the network and potentially affect the customers. On the other hand, current disturbances originate at a customer's installation and possibly affect the network components and other installations. Therefore, the voltage quality is considered to be a responsibility of the network operator, while the customer is responsible for current quality in the network. Another definition of PQ, as given by the Council of European Energy Regulators (CEER), is discussed in the next section of this thesis. Various PQ disturbances are described in detail in chapter 2.

1.3 PQ issues perceived by different parties

During the last two decades, PQ related problems have increased in almost every country. Modern society is highly dependent on digital technology and (power) electronics devices. The use of electronics appliances, computers, data processing devices, variable speed drives, electronic ballasts, power electronics interfaces, etc., has increased enormously. These devices are quite vulnerable to supply voltage deviations and distortions. In contrast, they produce current emissions in the network because of their non-linear operating characteristics and in this way influence the quality of the network voltage. A customer generally complains to the network operator when the operation of his (sensitive) device is affected leading to data loss, corruption of data, physical damage, flickering of computer screens or complete loss of connection of certain devices. It is also noticed that different customers have different sensitivities (and associated techno-economic inconveniences) to various PQ related disturbances. In the recent years, Governments of different countries of the world have encouraged customers to use more energy efficient devices to reduce electricity consumption. However, it is noticed that those devices often distort the network's waveforms with current harmonics. The harmonics cause extra energy losses in the system and an increment of apparent power demand in the network. Therefore, PQ has implications and interactions with the environmental concerns too and has much wider consequences in the modern society than just an economic indicator [Bol01]. The perception of PQ is quite different among various involved parties and is further discussed in the following sections.

1.3.1 PQ from regulator’s view point

Regulators are interested in all qualitative aspects of the power system that have an impact on a customer’s device or the installation from the view point of power quality and supply reliability. Due to the liberalization and deregulation in the electricity business, the customers have become more aware of the Quality of Service (QoS) aspect of the electricity supply that is provided by a network operator at the Point of Connection (POC). The CEER defines the QoS as a combination of reliability and voltage quality of the electricity supply, and the mutual business relational aspects between the network operator and customers regarding the service delivered (also called commercial quality) [Cee01] as illustrated in Figure 1.2.

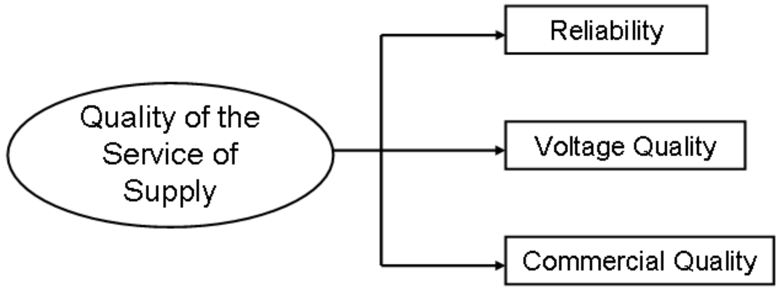


Figure 1.2. Quality of service for the electric supply as defined by CEER

1.3.2 PQ in the customer's view point

Customers need an electricity supply at their installations that is reliable and of adequate quality so that they do not suffer any inconvenience and discomfort. They use many power electronic devices that are often sensitive to various PQ aspects. It is noticed from various surveys that the industrial and commercial customers can be seriously affected when a voltage dip or an interruption occurs at their installations. These types of disturbances can cause large financial losses, depending on the type of customers and their electricity usages. Some other PQ issues for example the variations in voltage level, transient over-voltages, and harmonics can also have high impacts on the operation of the customers' devices. In contrast, light flicker is a PQ phenomenon that generally does not have major financial impact for customers. However, it may cause irritation and psychological inconveniences to the customers when they use incandescent lamps. Alternatively, the prohibition of incandescent lamps will reduce the incidence of light flicker. Also, the use of energy efficient devices and lamps can reduce electricity consumption ('kWh' units of energy) of a customer. However, he may probably not be aware of the fact that some energy efficient devices produce large emissions in the network that can decrease the PQ level of the network [Did01], [Kor01]. Thus, PQ problems can become a barrier to large scale implementation of energy efficient devices in the network.

In the present electricity business, 'customer's satisfaction' is considered as one of the most important factors. When a customer experiences a problem related to the voltage quality, he complains to the network operator and expects it to be solved within a reasonable time. A customer also expects to have a good communication with the network operator regarding any other matter related to the service of supply. Poor co-operation from the network operators can cause customer's dissatisfaction.

1.3.3 PQ in the network operator's view point

In Europe, the network operators are responsible to provide a voltage at the customer's POC that must fulfil the requirements of the standard EN50160 [Std01]. The network operators generally have control on the normal voltage level and the planned interruptions in a network. They can put limits on the PQ disturbances customers introduce, which is mostly described in grid codes. In addition, the physical characteristics of a network such as feeder types, feeder lengths, etc., determine grid impedances and influence the PQ level in the network. These are the network's design features for a network operator.

Supply interruptions and voltage dips are mainly originated from the network side. These generally cause inconveniences to the customer's devices. However, the network components such as cables and transformers are quite rugged and are less vulnerable to such voltage related PQ issues. Hence, in most of the cases, the network operator is not directly affected by a PQ problem unless he receives a complaint from a customer. It is noticed that most PQ complaints in different countries of the world are related to fast voltage variations (flicker) and voltage dips. In the near future, harmonics can become an even greater concern as many non-linear devices are expected to be integrated in the network [Dug01].

1.3.4 Influence of device manufacturer on network's PQ

When a device manufacturer introduces a device in the market, he guarantees that it will satisfy all PQ requirements (such as harmonic current emission) as specified by the applicable standards. Also, the device should be sufficiently immune to all electromagnetic phenomena that may exist in its operating environment. In a real situation, the network voltage is often already distorted because of harmonic current emissions from various disturbing loads in the network. Hence, a customer's device, when connected to a network, mostly receives a non-sinusoidal voltage and does not perform in the similar way as it did at the manufacturer's testing-site. Furthermore, when a customer connects a single device at his installation, the PQ emission produced by it should comply with the standard limit. With the addition of similar kind of multiple devices in the same installation or in the neighbourhood, emissions produced by all devices together can exceed the standard emission limits [Ben01]. Under certain situations, emissions produced by devices can exceed the 'compatibility level' of the system. Thus, the equipment manufacturers also have a vital role as they manufacture and sell their products in the market that should follow the regulatory requirements. In the future, they may be asked to provide further information on their devices under various distorted voltage supply conditions. The relations among disturbance (emission) level, planning level, equipment's immunity and compatibility level in a system are illustrated in Figure 1.3. An individual site generally produces lower disturbance level in comparison to the whole system.

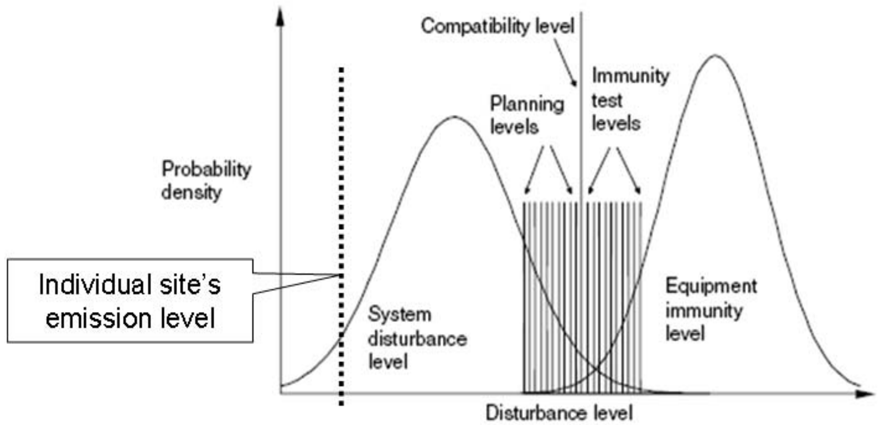


Figure 1.3. Relation between a system's disturbance and compatibility levels

1.3.5 Overall impacts of PQ issues

PQ issues can cause technical and financial inconveniences to various customers in varying degree depending on the nature, frequency and duration of a PQ disturbance. The financial impact of them can be found directly after the event occurs (for example: damage cost assessment due to a voltage dip event at a customer's installation). Costs of other PQ phenomenon such as harmonics are difficult to estimate because of their complexity and hidden effects. To overcome such inconveniences of PQ problems, suitable mitigation method can be adopted either at the network side or at the customer's installation. However, most of the PQ mitigation methods are quite costly. An optimum decision making towards a PQ solution is a complicated issue and requires detailed investigation on costs, as illustrated in Figure 1.4.

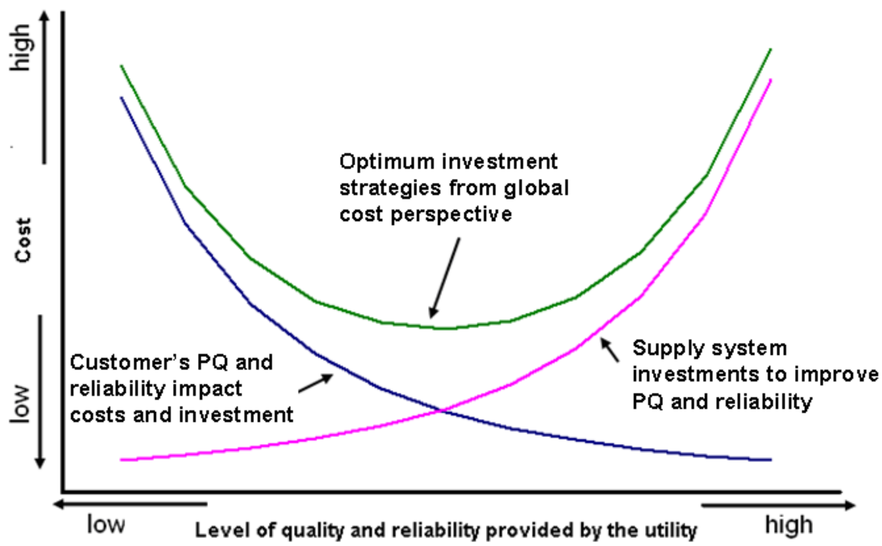


Figure 1.4. Optimum decision making on a PQ solution [Fra01]

1.4 Standards and regulations on PQ

At present a number of standards are available for defining limits to various PQ parameters. The international communities such as IEEE and IEC have created a group of standards for defining different PQ parameters. The standard EN50160 describes the voltage characteristics of the electricity supplied by a network operator (in Europe) at a customer's installation. It applies also for connections of electricity producers in the network. In the Netherlands, the 'Grid Code' [Dte01] is used and it gives some additional requirements on voltage quality in addition to the requirements of the EN50160 standard. However, the existing PQ standards give very limited information regarding the responsibilities of the involved parties in the network. Furthermore, the CEER was not satisfied with the EN50160 standard for regulation purposes. They wanted to improve this standard in a way that it can be applied by the national regulators for fulfilling the voltage quality needs and comparing the voltage quality performances of the networks in different countries. In 2007, the CEER along with the European regulators group for Electricity and Gas (ERGEG) published a conclusion paper [Cee02] after public consultation that suggests a 'roadmap' for the revision of the EN50160 standard. They suggested this standard to be harmonized with the IEC standards for definition, monitoring and measurement purposes. In 2009, the final draft of the EN50160 standard was approved by the regulatory members of the European countries. Another recommendation of the CEER was to define the ‘responsibility sharing curves’ between the network operators and the customers on various PQ aspects. Every customer should be considered with equal importance to involve them strongly in the process. In 2010 (July), the latest version of the EN50160 standard is published [Std04].

The IEC 61000-2-x and 61000-3-x series standards specify compatibility and planning level limits for various PQ parameters in different voltage levels. The planning level is an internal quality objective and could be used by the network operators for designing the networks. It is adopted as a reference value in setting the emission limits for various installations connected to different voltage levels. The compatibility levels, on the other hand, are the reference values for coordinating emission and immunity of devices to ensure electromagnetic compatibility of the connected installation as well as the network (see Figure 1.3). Some standards also give limits for voltage and current at an installation's terminal. For example the IEEE 519 [Iee01] standard indicates voltage and current limits at the customer's point of common coupling (PCC) for different voltage levels. The recent developed standards from IEC 61000 series specify limits for global emissions in different voltage levels. Those standards also indicate individual emission limits for a customer. Therefore, at present, a large variety of PQ limit value is mentioned in different standards. However, no global standard is yet established that can indicate PQ (emission) limits for a customer and his responsibilities at the customer’s connection point

In the deregulated electricity business, it is possible that different customers demand for different levels of PQ for their individual needs and the network operator should be able to meet individual customer’s wish. For this, PQ incentive schemes and specific regulations are needed. Figure 1.5 shows the directions of PQ regulation in the network [Fra01]. First step towards PQ regulation is an indirect method of quality control by continuous monitoring the PQ aspects in the network. This will give an insight to the network’s existing performance level in comparison to limits of the applicable PQ standards. Further, the customers can be informed about the performance and quality that they are receiving from the network operators. The second step is to develop a minimum standard for the network’s voltage supply. It can be achieved by comparing various national and international standards and define clearly the limiting values for each PQ parameter. Finally, the third step is to introduce incentive schemes (as penalty or a reward) for the customers as well as the network operators. Besides that, the customers should be educated more about the efficient usage of electricity. All these would encourage them to take active initiative and help the network operators and the regulators to adopt with the changing situation of the electricity business more efficiently.

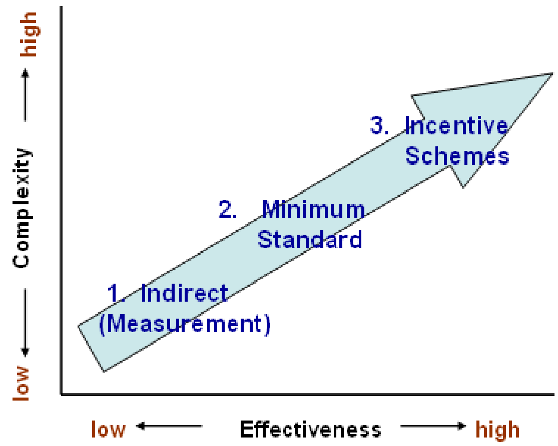


Figure 1.5. Steps towards PQ regulation

1.5 Future electricity trends and PQ

Presently, many people involved in the electricity business are quite optimistic about the success of smart grids and smart meters in the future networks. It means that more information technology (IT) based intelligence will be implemented in the electricity infrastructure. It is expected that a smart grid will be superior to a normal grid as the supervision, control and management of a network will be more efficient and might be able to solve PQ problems adequately. Furthermore, governments in different countries of the world also encourage implementing more sustainable resource based decentralized generations (DG) in the electricity production. However, those DGs generally produce time varying electricity and can increase PQ problems (such as over-voltage, harmonics, etc.) and instability in the network. Additionally, the widespread use of electric vehicles can overload the electricity network and increase complexity of load management in the grid. Governments also promote using more energy efficient devices to reduce overall electricity consumption in the society. All these cause an increased use of non-linear (power electronic) devices and raise PQ related problems and disputes in the present electricity environment. In addition to that, many discrepancies are found in various available standards regarding the definitions of various PQ parameters, their measurement methods, and the limit values for their representative indices.

Discussion is going on among the national and international regulators to develop a global standard that will indicate various limits for different PQ parameters and also specify the rights and duties of the involved parties. The regulators are also considering introducing PQ regulation schemes in the electricity business. An individual (PQ) contract can be signed between the network operator and a customer about specific quality requirements of the electricity to optimize the societal benefit. Alternatively, an incentive-penalty scheme on PQ can be introduced in the electricity business to involve all the parties actively in this changing supply situation.

1.6 KTI research project

The Ministry of Economical Affairs of the Netherlands has developed a long term energy research program called ‘EOS-LT’ ('Energie Onderzoek Subsidie – Lange Termijn' in Dutch) for promoting the knowledge on energy efficiency and sustainable developments in the Netherlands. Under the EOS-LT program, one of the research projects is called ‘Voltage quality of the future infrastructures’ (‘Kwaliteit van de spanning in Toekomstige Infrastructuren (KTI)’ in Dutch). This project consists of three major themes as described in Figure 1.6. This thesis covers research results of the first theme (‘Theme-1’) of the KTI project [Kti01].

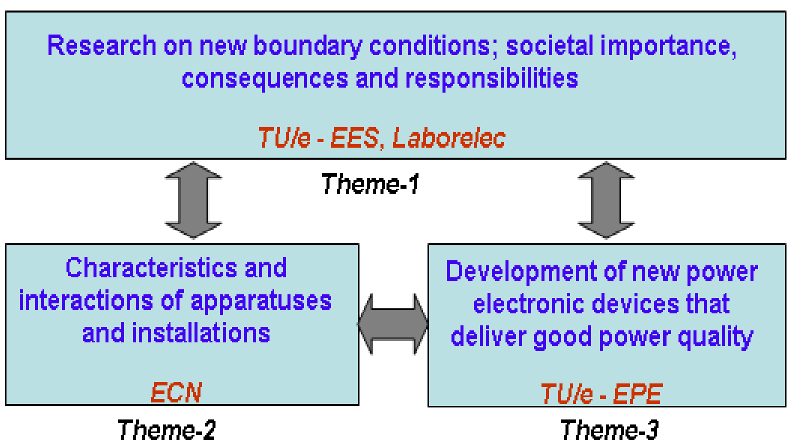


Figure 1.6. Research themes under the KTI project

In this theme PQ Measurements (PQM) were carried out continuously throughout the year at twenty selected locations in the medium and low voltage network of the Netherlands. This measurement activity was mainly conducted by Laborelec, an energy consultancy company in the Netherlands and Belgium, in collaboration with the TU/Eindhoven. Additionally, under the national PQ monitoring program, PQ measurements are done on different types of networks in the Netherlands. The PQM data obtained from the national PQ measurements and the KTI project are analyzed to get an indication of present PQ performance level of the Dutch network. In this research a model network is developed in the analysis tool 'Power Factory' for simulation purposes. Further, the simulation results are compared with the standard limits and the PQM data obtained from the field measurements for similar type of network. Finally, suitable planning level values are suggested that can be helpful for the network operators to design their future networks. The main objective of 'Theme-1' is to give guidelines on PQ responsibilities of different parties at the customer's Point of Connection (POC) in the network.

The research on 'Theme-2' [Hes02] of the KTI project is done by ECN, an energy research company in the Netherlands. In this theme, harmonics interaction behaviours of various power electronic devices with the network are investigated. It also developed harmonics mitigation strategies in the network. The 'Theme-3' [Wan02] of the KTI project (carried out by EPE group of TU/Eindhoven) analyzes new developments of power electronic devices for delivering good power quality supply in the network. This theme also proposed a PQ mitigation control strategy. The findings of both these two themes are utilized in 'Theme-1' as guidance on new developments in the PQ mitigation technologies and are briefly summarised in chapter 3.

1.7 Research goals and approach

Due to the integration of new decentralized generations and operations of many non-linear electronics devices in the network, the waveforms of the supply voltages and currents have been affected. As a result, PQ problems are increasing in the electricity network. In some situations, these can have significant technical and financial impacts to the customers as well as the network operators. Present standards and regulations on PQ do not sufficiently define the responsibilities of the different involved parties, taking into account the changing situation. The primary motivations of this research are as follows:

- The changing needs of the electricity customers (mainly industrial customers) because of increasing use of sensitive (process control) devices and integration of distributed generators in the network.
- The increasing number of power electronic devices connected to the network which produces current distortions, leading to voltage distortions too.
- The higher sensitivity of industrial customers to the loss of production time (due to PQ problems). This is due to the fact that they have to become more and more efficient and competitive in the market place.
- The increasing economic pressure on the network operators due to liberalization, strong regulations by the regulators and the attention to the quality of electricity supply.
- The increasing number of disputes among the network operators, the equipment manufacturers and the customers regarding their respective responsibility on various PQ issues in the network.

1.7.1 Definition of POC and PCC

In this research, the main goal is to define PQ requirements at a customer's Point of Connection (POC). Therefore, it is very important to specify the POC clearly. A POC is the physical point in the network where a customer's installation is connected to the utility grid. Another term often used is the 'Point of Common Coupling' (PCC). A PCC is defined as the nearest electrical point at which more than one customer are commonly connected to the network. A PCC may or may not be the same physical point as a POC, depending on the network configuration [Bol02]. In Figure 1.7, examples of PCC and POC are shown.

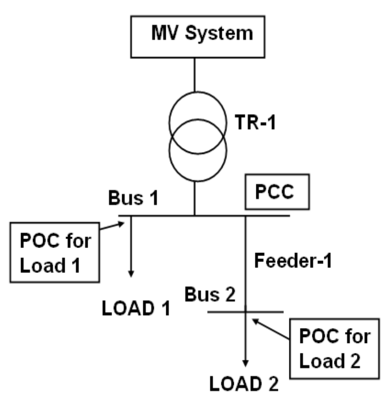


Figure 1.7. Definition of PCC and POC in a network

Figure 1.7 shows two loads connected at two different busbars. For ‘Load 2’, the POC is at ‘Bus 2’, while both the load points ‘Load 1’ and ‘Load 2’ have a common PCC at ‘Bus 1’. On the other hand, ‘Bus 1’is also a POC for ‘Load 1’. Thus, depending on the location in the network, the designation of a PCC can be different.

1.7.2 Research questions

The research goal is based on the KTI project objectives and interests, and the knowledge that is obtained from the findings of literature surveys. It is found that voltage dips, harmonics and flicker are the main PQ issues that have large influences to the customers. In this research, attention is given to these three types of PQ aspects. PQ mitigation is also considered to solve the problems. However, it is difficult to select one best solution as it often requires large investments. Therefore, the main goal of this thesis is as follows:

“Analyze the consequences of main PQ problems and define optimal PQ criteria and responsibilities at the customer’s point of connection”

This research aims to find out the socio-economically optimum solution to PQ problems. The following approaches are possible to meet the above objective:

- Network oriented approach
- Apparatus based solution
- Solution for a single customer or a group of customers
- Combination of the above

Three main questions are raised and answered in different chapters of this thesis to meet the research objectives.

- What are the technical and financial consequences of inadequate PQ for the connected parties?

Inadequate PQ can have (large) financial impacts to both the customers and the network operators. Regular complaints from the customers about poor supply voltage quality can degrade the ‘public image’ of the network operator. Similarly, an equipment manufacturer loses reputation when devices under his ‘brand name’ fail frequently before their expected life time at the customer’s installations. The damage costs because of PQ problems depend on several factors such as type of

PQ disturbance, sensitivity of customer's devices, production loss and business conditions.

A PQ disturbance may affect a single piece of equipment but the consequences may be wider affecting other devices or other customers too. As the cost evaluation is a complicated issue, the 'CIGRE Joint Working Group - JWG C4.107' has suggested two methods [Tar01]:

- Direct method: it is an analytical approach to consider the probabilities and impacts of the events.
- Indirect method: it considers historical data for analysis and the customer's willingness to pay to solve the problem.

Based on the above, an approach can be taken to determine qualitatively the cost of PQ for each party. Also, various PQ mitigation methods that are presently available in the market are summarised. The financial benefits of those mitigation methods are evaluated by estimating the relative improvements of performance of the network and the resulting cost reductions. In order to take an optimum decision, it is required to evaluate the techno-economic impacts of inadequate PQ and compare them with the investments necessary for various alternative mitigation measures.

- What are the optimal PQ requirements at a customer's POC?

When a customer is connected to the network (in Europe), he expects to receive a voltage supply at his installation that meets the requirements of the EN50160 standard (and the national grid code) under normal operating conditions. On the other hand, the devices connected at a customer's installation should meet PQ requirements as given in the applicable IEC 61000 series standards (and the relevant product standards). At present, a device is tested for normal test conditions considering that the supply voltage is sinusoidal. However, the presence of background PQ disturbances in the network distorts the supply voltage waveform. This, in turn, can change (harmonic) current emission behaviour of a customer's device significantly. The available standards give limited information about the PQ requirements at a customer's POC. Therefore, those standards should be improved and indicate clearly the PQ emission limits (regarding harmonic current, flicker, etc.) at the POC of a customer's installation. Moreover, the customer should also get information from the network operator about the (approximate) number of voltage dips in a year at his POC. This will help the customer to operate his installation more in an efficient way. Simulations are done on a real model network considering PQ pollution contributions from various customers' devices in the network. Further, the simulation results are compared with the field measurement data. From the analysis, the optimum PQ criteria at a customer's installation are defined.

- What are the responsibilities of each involved party at the POC?

The answers to the first two research questions can be used as guidelines to define PQ responsibilities of different parties involved. When a PQ problem occurs in the network and the customer complains, first the problem source is to be investigated. Further, detailed technical analyses are required to define (technical) responsibility of the involved parties. It can happen that neither the customer nor the network operator is directly responsible for the supplied voltage's quality distortion; rather it is caused by the interaction of a specific type of device. Hence, in certain cases the equipment manufacturer can also be responsible for a PQ problem in the network. Next, it is needed to check for PQ related damage costs and various possible mitigation options. In every possible alternative, a financial analysis is to be done to obtain socio-economically optimum solutions. The investments related to PQ mitigations and the cost sharing among the involved parties can be done based on defined responsibilities.

1.7.3 Approach

Figure 1.8 describes a step-by-step method that is followed for answering the research questions. The first step is to identify the type of PQ problem occurring in the network. Next step is to characterize it and analyze the problem critically. Therefore, PQ measurements have to be done at many locations in the network. Further, the measured data is to be verified with the limiting values specified in the existing standards and the national grid codes. Next simulate the problem in the network analysis tool and identify the source of PQ problem. From this analysis, it will be possible to find out the parties who are technically responsible for that specific problem in the network. Furthermore, various PQ mitigation measures are to be investigated that can solve and improve PQ performance of the network. Next step is to evaluate the costs of PQ problems for different connected parties in the network and the investments required for various PQ mitigation measures to solve the PQ problem. Finally, the optimum PQ solution can be selected after performing detailed cost-benefit analysis. The cost sharing among various involved parties can be decided based on their mutual agreements or previously defined responsibilities (as decided after the technical analysis). However, no detailed financial analysis is done in this research to find out actual costs of PQ disturbances and the investments required for various mitigation measures. The main purpose of this thesis is limited to define PQ related responsibilities of the involved parties at a POC.

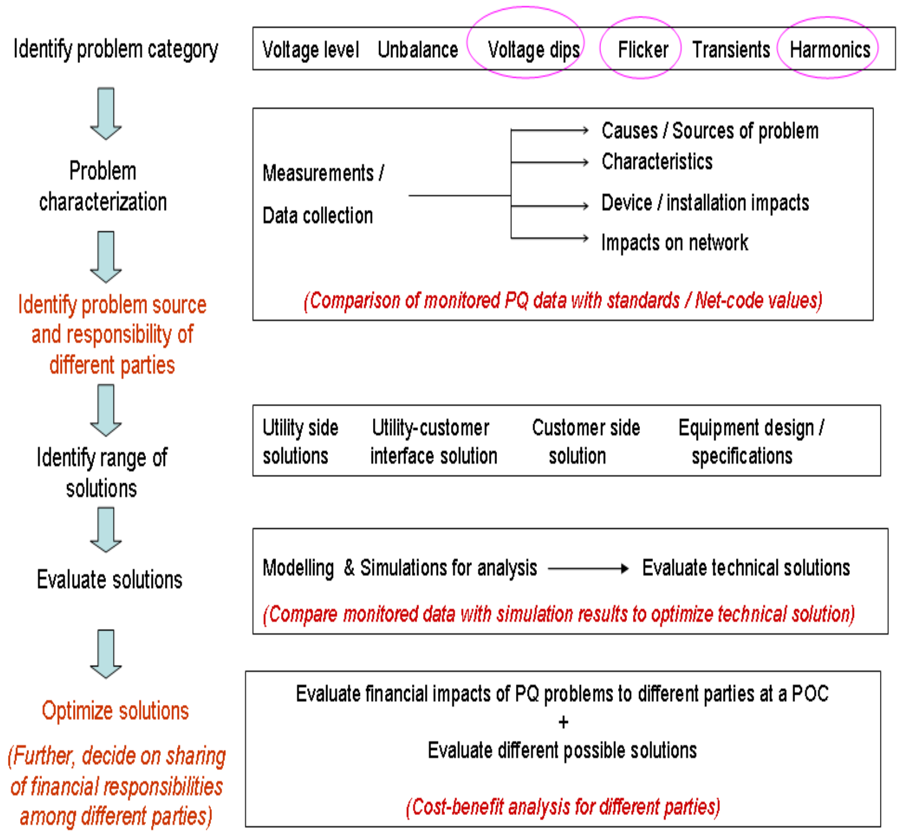


Figure 1.8. Research steps of 'Theme-1' of the KTI project

1.8 Thesis outline

This section presents the outline of the thesis.

Chapter 1: An introduction on power quality in the present electricity environment as perceived by the regulators, the network operators, the customers and the equipment manufacturers is given. Furthermore, the research project objectives, research questions and the approach are discussed.

Chapter 2: Firstly, in this chapter, the definitions and measurement indices of various PQ parameters (such as flicker, harmonics and voltage dip) are described. Next, the present status of PQ in different countries and the PQ trends in the Netherlands are briefly discussed. Also, a medium and low voltage network model is described that represents a typical modern network of the Netherlands. Furthermore, various influencing factors that affect PQ attenuation and propagation in the network are discussed in this chapter.

Chapter 3: This chapter summarises various techno-economic consequences of PQ problems in the network that are gathered from literature surveys. Further, various mitigation methods available in the market and the PQ solutions that are developed under the KTI project are summarized.

Chapter 4: The model network (described in chapter 2) is simulated to evaluate PQ performance level (e.g. flicker, harmonics and voltage dip) at different customers' POCs in the network. Also, some relevant field measurements are compared with the simulation results to validate the analysis.

Chapter 5: Various standards and regulations related to PQ are discussed in this chapter. Further, the PQ field measurements of the Dutch networks and the simulation results obtained from chapter 4 are compared with the limits given in different standards. This chapter proposes new limits for various PQ aspects (such as flicker, harmonics) at the customer's POC. Also, the number of voltage dip events in the Dutch HV and MV networks is estimated.

Chapter 6: This chapter proposes methodologies to define PQ responsibilities at the customer's POC for the various involved parties in the network. Additionally, some examples of practical case studies on flicker, harmonics and voltage dips conducted at the customers' sites are discussed. Based on the findings, responsibility of the customers, network operators and equipment manufacturers are defined for flicker, harmonics and voltage dips at a POC.

Chapter 7: The findings and main contributions of this research are summarized in this chapter. Further, recommendations for follow-up research works are given.

Chapter 2

Power quality – definitions, present status and influencing factors

2.1 Introduction

In chapter 1, a general definition of Power Quality (PQ) is given. In this chapter three PQ phenomena namely flicker, harmonics and voltage dips are discussed. Further, the status of PQ problems in the Netherlands and other countries are reviewed. The PQ trends of the Dutch networks are described by analyzing the power quality measurements (PQM) data of the national monitoring program. Also, the main findings of the PQM done under the KTI project are summarized. The network of the Netherlands is taken as reference for the analysis of PQ problems in this thesis. Therefore, a typical Dutch network is modelled for simulation purposes. It is found that a PQ problem can originate locally, but can propagate to different parts of the network. The PQ propagation mainly depends on the network structure, network impedance and the characteristics of connected customer's devices (such as the inrush current demand during motor starting, harmonic current emissions of the connected devices, equipment's voltage-time immunity response, etc.). Moreover, mutual interactions between the network voltage and the flowing currents also can have significant influence on the PQ level of the network. In the last part of this chapter flicker, harmonics and voltage dip propagation behaviours in the network are discussed.

2.2 Power quality disturbances

As discussed in chapter 1, PQ is a combination of voltage and current qualities. In an ideal situation, both the network's voltage and current should be of sinusoidal waveform. However, the presence of non-linear devices in the network distorts their original waveforms. The network operator is generally responsible for the voltage quality in the network while the customer’s load influences the current quality in the network. Due to the interactions of these two quantities, the supply voltage becomes distorted that eventually leads to PQ disturbances in the network. PQ disturbances can be classified in two main categories:

- ‘Continuous’ or ‘variation type’
- ‘Discrete’ or ‘event type’

Continuous type disturbances include voltage variations, unbalance, flicker and harmonics. Discrete type disturbances appear as independent events and mainly include voltage dips, voltage swells and oscillatory or impulsive transients. The level and frequency of PQ disturbances at a customer’s point of connection (POC) depend on many factors, such as:

- Type of customer and the equipment involved
- Topology of the electrical network
- Length and type of feeders that determines the network impedance at a customer’s terminal
- Short-circuit power at the considered point

In the thesis, main focus is given to the following three PQ aspects that cause inconveniences to the customers:

- Flicker
- Harmonics
- Voltage dips

2.2.1 Flicker

Flicker often leads to light flicker (depending on the lamp types [Cai01]) that causes annoyance to the customers. In extreme cases, it can cause health problems like headaches, vision-related illnesses, and reduced concentration level. In the last couple of years, it is noticed that the Low Voltage (LV) customers of different countries in the world for instance Norway, Sweden, Slovenia, Argentina, and the Netherlands have often complained to their network operators regarding flicker-related problems [Hal01], [Iss01], [Lab01]. In the recent years, governments of many countries in the world banned the use of incandescent lamps which are very sensitive to voltage variations. With the advancement of modern lighting technologies, the lamps such as compact fluorescent lamps (CFL) and light emitting diode lamps (LED) have become less sensitive to voltage variations. This may reduce the light flicker problems in the network significantly.

2.2.1.1 Origin of flicker problem

The flicker problem is perceived when a customer observes an unsteadiness of visual sensation induced by a light stimulus that fluctuates with time. The reasons of increased number of flicker problems in the network are as follows:

- Many devices might be running with the same repetitive cycle of operation
- Increase of high-power devices and installations that are connected to the network without proper mitigation techniques
- In the LV network, flicker is generated by the operation of elevators, air conditioners or other motor start-ups, drilling and welding device, copy machine etc.
- Large industrial motors with irregular loads, welding machines or arc furnaces are the main sources of flicker in the MV and HV networks.

The severity of flicker at a POC depends highly on the short-circuit power (network impedance) of that point. When the load demand in the network suddenly changes, the current changes and rapid voltage variations (fluctuations) occur in the network. This may lead to observable light flicker, depending on the current of the source, the network impedance, the frequency of the fluctuations and the lamp types.

2.2.1.2 Flicker severity indicators

Flicker severity is measured in units of perceptibility. Two important parameters are used to indicate the severity of a flicker problem: i) a short-term flicker indicator (P_{st}) that is measured for a ten-minute period and ii) a long-term flicker indicator (P_{lt}) that is estimated over a two-hour period.

A P_{st} value can be calculated by equation (2.1) in which $P_{st(i)}$ represents the flicker emission levels from various sources in the network that are influencing the P_{st} level at the point in the network under consideration. The symbol 'α_f' represents a coefficient that depends on the type of flicker source and is commonly taken as 3. Various values of 'α_f' are shown in Table 2.1 for different load types.

$$P_{st} = \sqrt[\alpha_f]{\sum_{i=1}^{n} P_{st(i)}^{\alpha_f}} \tag{2.1}$$

Table 2.1. Coefficient ‘α_f’ for different load types [Uie01]

Value of coefficient ‘α_f’	Load characteristic
$\alpha_f = 1$	High probability of simultaneous voltage variations by disturbing loads
$\alpha_f = 2$	When chance of presences of simultaneous random disturbances
$\alpha_f = 3$	When the risk of simultaneous voltage variations is minimum
$\alpha_f = 4$	To account voltage fluctuations produced by arc furnaces, operated in a manner to avoid simultaneous operation

P_{st} value can also be calculated by using the empirical equations (2.2) and (2.3) as given in the standard IEC 61000-3-3 [Iec01].

$$t_f = 2.3 \cdot (F \cdot d_{max})^{3.2} \tag{2.2}$$

In equation (2.2), a flicker impression time (t_f) in seconds is estimated for the evaluation period by measuring each maximum relative voltage change (d_{max}), expressed as a percentage of the nominal voltage as shown in Figure 2.1. ‘F’ is called shape factor which is associated with the shape of voltage change waveform. The maximum value of F is 1.0 and is considered in the analysis of this thesis.

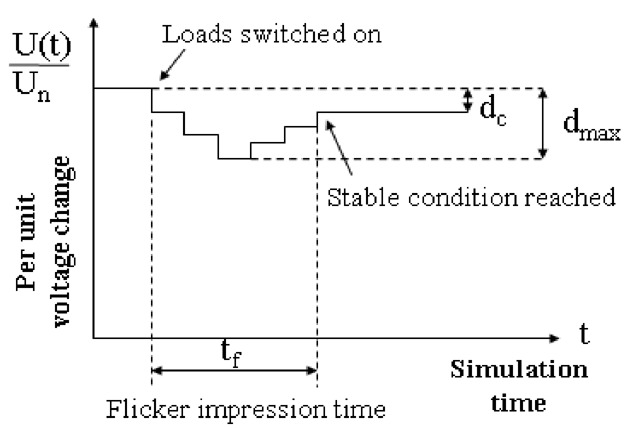


Figure 2.1. Relative voltage changes during load change in the network

Equation (2.3) calculates a P_{st} value by summing up all flicker impression times (t_f) during the evaluation period (T_p) at a point in the network. This analytical method of calculating P_{st} is expected to produce a result within ±10% accuracy when a direct measurement is done at the same load terminal. In contrast, this method is not recommended if the time duration between the end of one voltage change and the start of the next is less than 1s, as per IEC 61000-3-3 [Iec03].

$$P_{st} = \left(\frac{\sum t_f}{T_p} \right)^{\frac{1}{3.2}} \tag{2.3}$$

Also, the relation between P_{st} and P_{lt} is shown in equation (2.4).

$$P_{lt} = \sqrt[\alpha_f]{\frac{\sum_{i=1}^{12} P_{st(i)}^{\alpha_f}}{12}} \tag{2.4}$$

In the IEC 61000-3-3 standard, some devices are mentioned (such as vacuum cleaner, refrigerator, food mixer, lighting devices, etc.) for which no P_{st} and/or P_{lt} requirement is specified. Hence, the above formula is not applicable for those devices.

2.2.2 Harmonics

Voltage and current harmonics can be defined as sinusoidal components of periodic waveforms having frequencies that are integer multiples of the fundamental frequency (50Hz) component. It is important to determine harmonics in the network to avoid dangerous (resonant) conditions. When harmonic currents propagate along the networks, they can result in increased losses and possible ageing of network components. Also, they can interfere with control, communication and protective devices in the network. Harmonic currents cause heating of end-use equipment and overheating of neutral wires of the low voltage feeders at which many single-phase polluting loads are connected.

2.2.2.1 Main sources of harmonics

Various harmonics producing sources are as follows:

- Magnetic core reactors, transformers and induction motors produce non-linear currents due to the saturation behaviour of their magnetic cores [Tsa01].

- DC links and power electronics based power flow controllers also cause current waveform distortions (because of the presence of AC-DC-AC converters) in the network.
- Non-linear loads containing power electronics converters (with six pulse and twelve pulse rectifiers) can cause harmonic pollutions in the network. These devices are generally used in the generation, transmission and distribution networks and generate harmonics during their switching processes [Tsa01].
- Electronics equipment such as personal computer, television, battery chargers consist of a single-phase diode rectifier and a large capacitor that produces a constant DC voltage. They produce odd harmonic currents, with the third harmonic dominating [Bol01].
- Use of large numbers of similar type compact fluorescent lamps (CFL) with electronic ballasts can increase harmonic current pollutions in the network [Rad01].
- Single-phase non-linear loads produce harmonic currents.

2.2.2.2 Harmonics measurement indices

The periodically distorted voltage and current waveforms can be analyzed using 'Fourier analysis' to examine their harmonic components. Each order of harmonic component can be measured with respect to the fundamental component and is called 'Harmonic Distortion' (HD) for each harmonic number. The most commonly used indicator for the deviation of a measured waveform from a pure sine wave is expressed by the 'Total Harmonic Distortion' (THD) which can be obtained by summing up the HD's of all harmonic orders. The IEEE standard 519 [Iee02] defines THD as the ratio between the rms values of all harmonics (n) up to 40^{th} order and the rms value of the fundamental component (F_1), as shown in equation (2.5).

$$THD_1 = \frac{\sqrt{\sum_{n>1}^{\infty} (F_n)^2}}{F_1} \tag{2.5}$$

where,

- F_n: n^{th} harmonic component of the waveform.

However, some old standards use the ratio between the rms of all harmonics and the total rms value of a complete waveform and then THD is defined by equation (2.6).

$$THD_{rms} = \frac{\sqrt{\sum_{n>1}^{\infty} (F_n)^2}}{F_{rms}} \tag{2.6}$$

The presence of harmonics causes an additional power flow in the network. The standard IEEE 1459 [Iee03] describes various terms related to harmonic power consumption in the network and are described briefly in Appendix A-1. Harmonics change the power factor (PF) of the network to a lower value and increase the demand of total active power (P) and apparent power (S) in the network. Equation (2.7) shows the definition of PF when the network contains harmonics.

$$PF = \frac{P}{S} = \frac{P_1 + P_H}{\sqrt{S_1^2 + S_N^2}} = \frac{\left[1 + \frac{P_H}{P_1}\right] \cdot PF_1}{\sqrt{1 + THD_I^2 + THD_V^2 + (THD_I \cdot THD_V)^2}} \tag{2.7}$$

where,

- P_H: active part of the harmonic power
- P_1: active power at the fundamental frequency
- S_1: apparent power at the fundamental frequency
- PF_1: displacement power factor (at fundamental frequency)
- S_N: apparent power at non-fundamental frequencies
- THD_I : total harmonic current distortion
- THD_V: total harmonic voltage distortion

When no harmonic is present in the network, PF_1 and PF will be same. Equation (2.8) represents the PF at a point in the network for the conditions when THD_V is less than 5%, THD_I is more than 40% and the harmonic power losses in the network are small compared to the fundamental component of active power [Moh01], [Iee03].

$$PF = \frac{PF_1}{\sqrt{1 + THD_I^2}} \tag{2.8}$$

It is noticed by the network operators that when the THD_V at a POC is more than 10%, the customers always complain about the voltage supply. In contrast, when THD_V is less than 5%, the customer generally does not have any noticeable effect. A harmonic distortion of $5\% < THD_V \leq 10\%$ can cause long-term effects on the customer's devices [Pqt01]. Harmonics are time varying in nature and have impacts in the power system. Therefore, the IEC 61000-3-6 [Iec11] standard introduce short time limit value (3 seconds or less) for THD_V and also specify planning level (and compatibility level) limit value for each harmonic voltage up to 50^{th} order in different voltage levels (refer chapter 5).

2.2.3 Voltage dip

Voltage dip is one of the most important PQ issues and has often direct financial impact to the customers. It is because many of the customer's loads are incorporated with electronics devices that are highly vulnerable to voltage dips. A voltage dip is defined as an event where the supply voltage at the POC is between 90% and 1% of the declared (nominal) voltage and continues for several milliseconds up to few seconds (generally between 10ms and 1 minute).

2.2.3.1 Interpretation of voltage dips

Voltage dips are mainly caused by short-circuits in the network (due to a fault or because of a natural event). Sometimes, the source is motor acceleration, transformer saturation or a switching event in the network. A voltage dip event or the number of voltage dips is often difficult to define precisely because of several reasons as follows:

- Voltage dips occurrence data are not fully reliable as the indices are not easily available. Moreover, network reconfigurations may change the indices significantly.
- Sometimes customers misinterpret voltage dip events at their sites and call them as interruptions, for instance dips that are generated locally by heavy loads start up. Thus, those are omitted from the count of voltage dip event.
- Immunity of a device is very important in determining whether the specific device will respond to a particular voltage dip event or not. A specific device may not react to a voltage dip event because of its higher voltage dip immunization characteristic (voltage-time tolerance graph: 'V-T'). Other device, with lesser immunization property, however can fail when the same voltage dip event occurs.

2.2.3.2 Voltage dip indices

A single voltage dip can be characterized by the residual voltage and duration of the event. Alternatively, it can also be represented by the voltage dip aggressiveness index, voltage tolerance curve based indices, the voltage dip energy index or the voltage dip severity index. The standard IEEE P1564 [Iee02] introduces the voltage dip energy index (E_{VS}) and voltage dip severity index (S_e). Those indices can be calculated for different busbars or for a specific customer.

The annual voltage dip profile of a site can be presented in different ways such as: voltage dip-duration table, scatter plot, contour plot etc. All these different methods give information on the frequency of occurrence of voltage dip events for various voltage dip magnitudes and respective durations. In this thesis, the behaviour of a site is characterized by voltage dip-duration table that indicates the number of events occurring for a certain residual voltage and duration, as described in the standards IEC 61000-2-8 [Iec02] and IEC 61000-4-11 [Iec03]. Also, a scatter plot is used to represent the voltage dip profile of a site to compare it with the voltage-time immunity characteristics of a specific customer's installation. The South African standard NRS 048-2-2007 [Nrs01] and the latest version of the EN50160 standard specify different rectangular regions in the voltage dip-duration table. Additionally, the South African standard also gives the characteristic number of dip events for each region of the dip-duration table in different voltage levels (refer chapter 5 of this thesis). In Table 2.2, the dip-duration table as described in the latest version of the EN50160 standard is presented [Std04].

Table 2.2. Classification of dip-duration table as per EN50160:2010

Residual voltage U [%]	Duration t [ms]				
	$20 \le t \le 200$	$200 < t \le 500$	$500 < t \le 1000$	$1000 < t \le 5000$	$5000 < t \le 60000$
90>U≥80	CELL A1	CELL A2	CELL A3	CELL A4	CELL A5
80>U≥70	CELL B1	CELL B2	CELL B3	CELL B4	CELL B5
70>U≥40	CELL C1	CELL C2	CELL C3	CELL C4	CELL C5
40>U≥5	CELL D1	CELL D2	CELL D3	CELL D4	CELL D5
5 >U	CELL X1	CELL X2	CELL X3	CELL X4	CELL X5

2.3 PQ problems in general

Every year the network operators of different countries around the world receive many complaints about PQ problems from different groups of customers. A customer complains when the operation of devices in his installation is interrupted leading to inconveniences. An overview of different PQ problems as noticed by different customers is summarized as follows [Bha01]:

- Residential customers suffer inconveniences because of under-voltage and light flicker. These problems generally do not have major financial impacts.

- Agricultural customers complain about under-voltage problems.
- Voltage dips can create inconveniences to commercial customers because of equipment damage and data loss followed by business down time. Also, they complain about large neutral currents because of harmonics that cause additional heating of their devices. This group of customer is also vulnerable to sudden transient current surges that can cause unwanted tripping of protective devices.
- Large industries (for example the semiconductor industry, paper plants, glass and steel industries, etc.) suffer significant financial losses when voltage dips occur at their sites. The industrial customers also complain about harmonics that cause fast ageing and early failure of various devices.
- Network operator suffers inconveniences because of inaccurate operation of protective devices and failure or decreasing life time of network components such as transformers, cables, etc. These problems are often caused by harmonic currents generated from the customer's installations.

2.3.1 PQ problems in different countries

The amount of complaints about PQ disturbances is growing all over the world. It is observed that almost 70% of the PQ disturbances are originated at the customer's premises while 30% are coming from the network side [Ema01]. The Electric Power Research Institute (EPRI) conducted a five year (1990-1995) monitoring program for distribution power quality (DPQ-I) among 24 utilities throughout the United States of America. Another program DPQ-II was conducted in 2001-2002. Figure 2.2 shows those study results which indicate that voltage sags (dips) and swells, transient over-voltages, harmonics and grounding related problems are the most common PQ complaints among the American customers [Mel01], [Epr01].

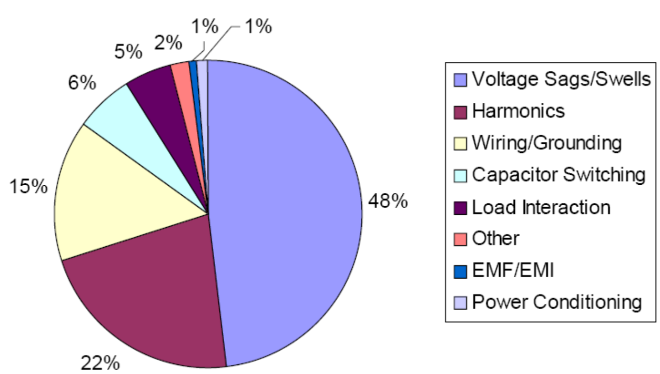


Figure 2.2. PQ problems experienced by American customers

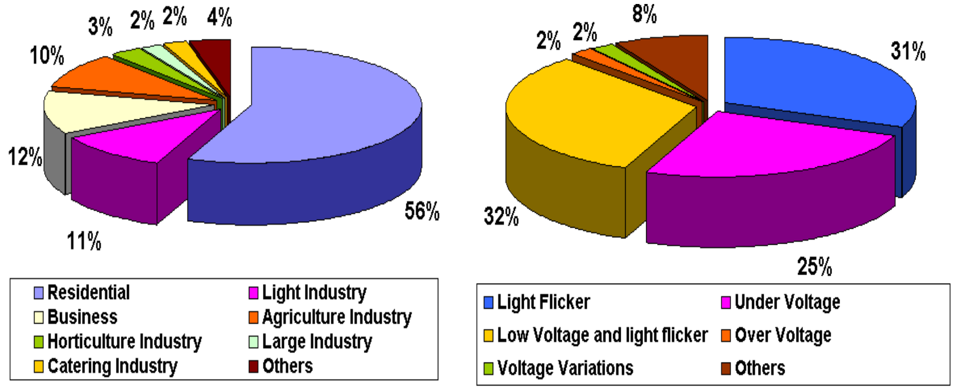
In 2001, the European Copper Institute has done a PQ survey covering 1,400 sites in 8 countries of Europe. It was found that harmonic distortions, power supply reliability, voltage dips and electromagnetic compatibility are the most important issues for the European Union (EU) countries [Lpq01]. Another PQ campaign was conducted by the Leonardo Power Quality Initiative (LPQI) among various customers in the EU-25 countries in 2004. It was concluded that on average the absolute share of impacts of power quality and reliability related problems are due to voltage dips (23.6%), short interruptions (18.8%), long interruptions (12.5%), harmonics (5.4%), transients and surges (29%) and other PQ related problems (10.7%) [Lpq02].

In the United Kingdom [Wha01], the customers mainly complain because of disputed accounts and the issues related to the restoration time after fault interruptions. Some complaints are also about the supply voltage quality issues such as voltage dips, harmonics and flicker. In South Africa [Joh01], voltage dips and transients have been identified as major PQ problems because large part of the electricity infrastructure consists of overhead lines.

2.3.2 PQ status in the Dutch networks

Reference [Cob02] recalls that PQ monitoring of the Dutch networks started in 1989. From this year the network operators of the Netherlands started to monitor the 5th and 11th harmonics in their networks. In 1996, the PQ monitoring (PQM) program has been extended for low, medium and high voltage networks. Various PQ parameters such as slow voltage variations, fast voltage variations, asymmetry and harmonics data were recorded. In 2003, another PQ monitoring program (PQM II) was introduced to register voltage dips and short interruptions for a minimum period of one year in 20 selected locations. In PQM II, the extra high voltage network was also included in this continuous monitoring program. At present, there are 149 measurement locations (that include 60 locations each in the MV and the LV level, 20 locations in the HV, and 9 locations in the extra high voltage level) throughout the country. Each location is measured continuously for one week period in a year. The measurement gives a performance indication of the Dutch networks and checks if the network's voltage quality complies with the requirements of EN50160 standard and the Dutch national 'Grid Code'.

Every year, the Dutch network operators register complaints about various PQ related problems from the customers. When analysing the database with complaints it is hard to see which PQ phenomenon was responsible for a particular complaint. This is because most people do not recognize the type of PQ problem that they are facing. The consequences of inadequate PQ can be obtained by analysing the reported damage. However, it is hard to quantify correctly the damage related to a certain PQ disturbance. Figure 2.3 shows the survey results of PQ problems in the Netherlands, conducted by Kema and Laborelec in 2006 [Lab01].



(a) Complaints from customers (b) Type of complaints

Figure 2.3. PQ problems as reported by the customers in the Netherlands

2.3.2.1 National PQM results at a glance

The national PQ survey results of the MV and LV networks for years 2005-2008 are analysed to find out the voltage variation trend in the Netherlands. The EN50160 standard [Std01] gives limits for voltage variations in the LV and MV networks as ±10% of the nominal voltage (or declared voltage for the MV networks) for 95% of the measured (every 10 minutes rms) data on one week's measurement period. In the same standard, the lower voltage limit for 100% of the time is given as -15% of the nominal voltage. Figure 2.4 shows the voltage variation trend of the LV network. From the analysis of the PQM data (around 40,000 recorded '10 minutes rms' data on week measurements at different LV sites for a year), it was found that in 2006 only four measurements and in 2007 twelve measurements exceeded the standard limit of ±10% (not visible in Figure 2.4), but stayed within -15%. It is less than 0.01% of the measured data.

Figure 2.5 shows the voltage variation trend in the MV networks of the Netherlands. Most of the recorded data remained within the standard limits, with an exception in 2005. In November 2005, extreme weather conditions occurred and many voltage events were recorded. Therefore, that period is not considered in the analysis. Appendix A-2 gives more information on the national PQM results.

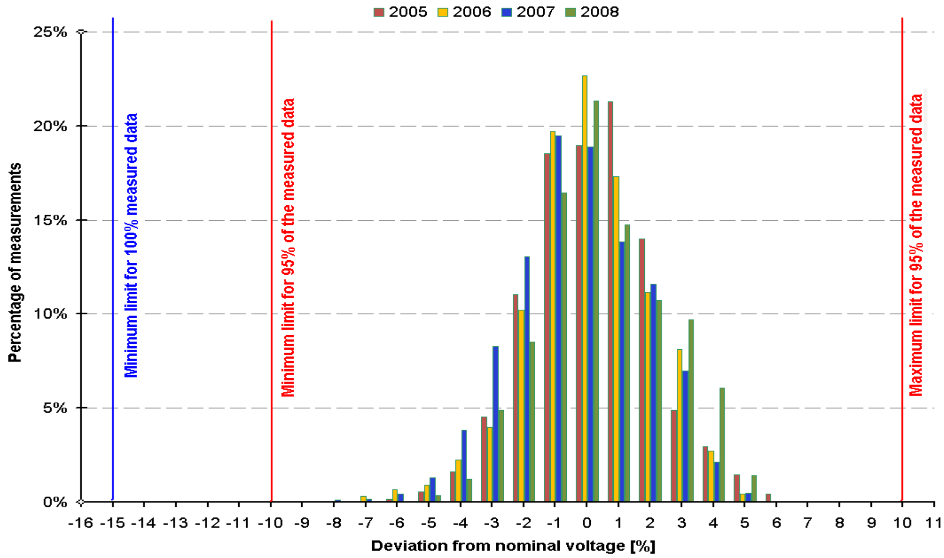


Figure 2.4. Voltage variations in the LV networks in the period of 2005-2008

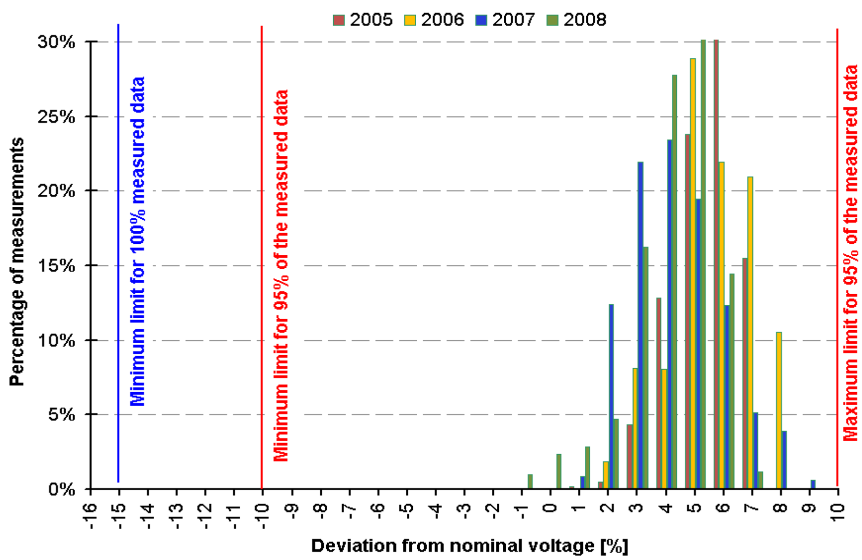


Figure 2.5. Voltage variations in MV networks in the period of 2005-2008

In Figure 2.6, the flicker severity (P_{lt}) trends of the LV and MV networks in the Netherlands are compared. The blocks shown in Figure 2.6 (red for LV network and green for MV network) represent the 95% of the measured data at different measuring points in the network for each of the measurement year. It is found that some P_{lt} values in the Dutch networks exceeded P_{lt} =1, specified in the EN50160 standard. In few cases during year 2005 and 2008, the P_{lt} values in the MV network exceeded the limit of P_{lt} ≤5, as required by the Dutch Grid Code.

After detailed analysis, it is concluded that those occasional high flicker severities (P_{lt}) are probably generated because of some local events such as starting of heavy load leading to voltage drops or other reasons in the neighbourhoods. Further, they did not have any visible impact on the voltage quality at other parts of the network. In the LV network approximately 95% of the measured P_{lt} values are in the range of 0.20–0.50, whereas the 95% of the measured P_{lt} values in the MV network mostly remained within 0.25.

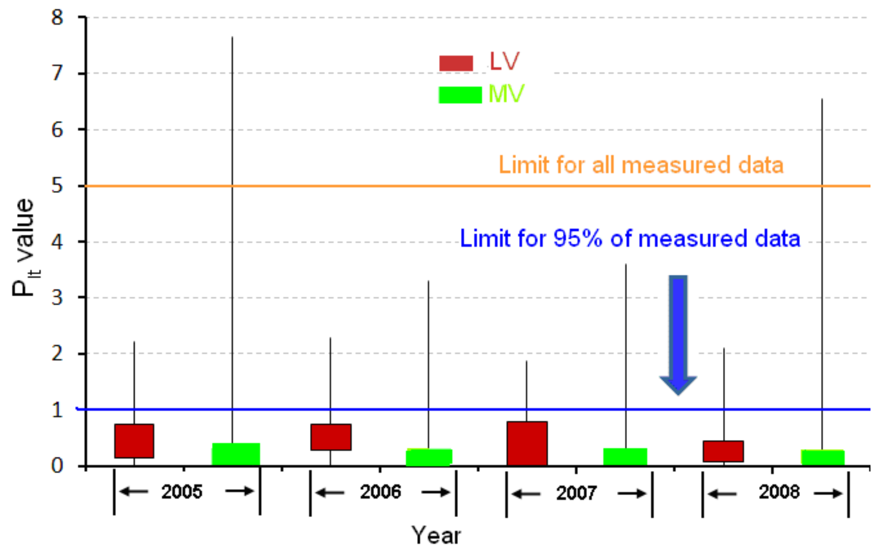


Figure 2.6. Comparison of the P_{lt} trends in the Dutch MV and LV networks

The THD_V trends of the Dutch networks are shown in Figure 2.7 in which the red and green blocks represent 95% of the measured data at different measuring points in the LV and MV networks respectively. It is found that all THD_V values of the measured data remained within the standard limits of the EN50160 standard and the Dutch Grid Code. The 95% probability value of THD_V in the MV network is within the range of 2.7-3.2% and that in the LV network is 3.4-3.9%. All the measurements (100% data) of THD_V values remained within the limit of 8% as specified in the EN50160 standard. Thus, from the analysis of the national PQM data it can be concluded that in general the Dutch network largely meets the EN50160 standard requirements. Few measurements that occasionally exceed the standard limits are mainly due to some PQ disturbances generated locally.

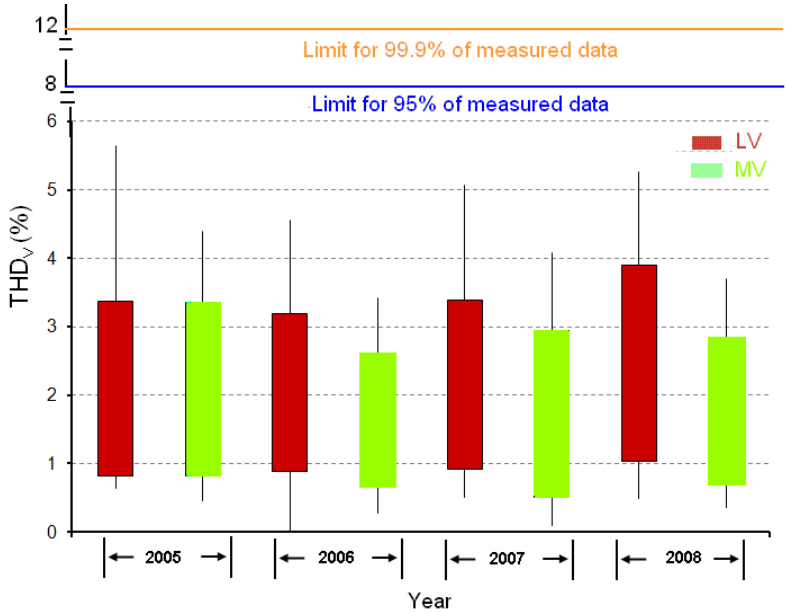


Figure 2.7. Comparison of THD_V trends in the Dutch MV and LV networks

In the Netherlands, voltage dip events are recorded in the high and extra high voltage networks as mentioned before. Table 2.3 shows the average number of voltage dip events recorded at the measuring points in the HV network for various residual voltages and durations for 2008 [Hes01].

Table 2.3. Average numbers of voltage dip events in the Dutch HV network (2008)

Residual voltage (pu)	Duration of dips (s)				
	0.01-0.02	0.02-0.1	0.1-0.5	0.5-2.5	2.5-5
0.8-0.9	0.05	2.05	0.95	0.1	0.1
0.7-0.8	0.05	2.05	0.95		
0.6-0.7	0	0.17	0.07		
0.5-0.6	0	0.17	0.07		
0.4-0.5	0	0.17	0.07		
0.3-0.4	0	0.125	0.08		
0.2-0.3	0	0.125	0.08		
0.1-0.2	0	0.125	0.08		
<0.1	0	0.13	0.09		

Note: The values of the above table are rearranged to match with the description of the EN50160 standard. The original table is shown in Appendix A-2. It was obtained from the voltage-dip statistics recorded under the national PQ monitoring program of 2008 and the results were disseminated by KEMA in the annual report [Hes01].

2.3.2.2 PQ survey results of KTI project

As found from the national PQM results in the Netherlands, in most of the situations, PQ problems are local issues rather than a network-wide global problem. In the KTI project, the main attention is given to individual customer's connection points in the MV and LV networks. Twenty measurement locations were chosen based on the Dutch network operator's experiences. Each location has its own specific characteristic. The chosen installations are mainly of three types:

- Installation with a distributed generation (DG) such as wind generator, solar panels, combined heat power (CHP) plant.
- Customer's household terminal with power electronic devices.
- Medium size industrial plant (iron factory).

Measurements are mostly done in relatively new networks. The MV networks in the Netherlands are mainly fed by cables and have relatively higher short-circuit power as compared to the other European networks. Also, the average length of LV cable is quite small (<500m) which makes the network impedance at different customers terminals low. Therefore, the occurrence of PQ related disturbances is relatively less in the Dutch grid. The local problems are mainly due to the operation of customer's devices. To identify the causes of PQ problems in the network, the selected sites are monitored continuously at least for a year. The voltage and current data are recorded and downloaded on a weekly basis. Later the data are analyzed to determine the PQ performance at the measurement location. A short summary is given in Table 2.4. Reference [Lab02] gives extended information of the measurement results.

The main conclusion of the PQM results of the KTI project is that the voltage quality of the MV and LV Dutch networks is quite good in the present situation and mostly meets the EN50160 standard and the Dutch Grid Code requirements. However, in specific situations some violation of PQ parameter limit is visible locally. In the household installations, average flicker severity (P_{lt}) is found around 0.3 which is sufficiently below than the standard limit of 1 as per EN50160. With the increased use of high demanding load (such as heat pumps, air conditioners, E-mobility) at the household installation, the P_{lt} value at a POC can increase in the future. It was noticed that the installations with many PV panels can cause high 15th harmonic voltages in the network. It was also found in the measurement that the neighbourhood with many wind turbines has increased lower order harmonic voltages in the network. The industries with variable speed drives and converter loads also contribute to lower orders (such as 5th, 7th, 11th and 13th) harmonic voltages in the network.

Table 2.4. Summary of PQM results of the KTI project

PQ parameter under consideration	Measurement locations			
	Installation with wind turbines	*Installation with PV panels*	*Household installations*	*Plastic factory*
Location of the PQ meter and the connected devices at measurement point	PQM at LV terminals of a 600kW wind turbine. All these wind turbines consist of variable speed drives with various power electronics control devices.	Area with lot of PV panels (over 2 MWp) and household devices. PV inverters use relatively old control system. Measurement is done at LV side of a 1000kVA transformer	Measured at LV side of 630kVA transformer. Neighbourhood with small shops and houses with PV panels, heat pumps, lighting and other household loads	Industry with lot of variable speed drives (6-pulse VSD's), lighting, and melting equipment. The measurement is done at a customer's 10kV installation
Voltage variations	Within the limits of EN 50160. No seasonal aspects visible	No problem with voltage variation	No problem with voltage variation for all seasons	Voltage is always within the standard limits
Flicker	Correlation found between P_{lt} and power output fluctuation. Average P_{lt} is between 0.4-0.6, occasionally reaches 1.0	Low P_{lt} values recorded, varies in the range of 0.25 -0.35.	P_{lt} is 0.2-0.3 on average, occasionally it reaches to 0.8-1 because of local disturbances	P_{lt} level low (between 0.2-0.35)
Harmonics	Presence of harmonic voltages (5th, 7th, 11th, 13th) in measurements. The 7th harmonic voltage values sometimes exceed the EN50160 standard limit. THD_V value is around 4%	Average voltage harmonics are below standard limit, however sometimes 15th harmonic is quite high. THD_V is 4%	All harmonic voltages are `below the limits of the EN50160 standard. THD_V is around 2.5%	5th, 7th, 11th, and 13th harmonics are clearly visible in the measurement. THD_V is recorded 2-4%

2.4 Main influencing factors for PQ problems

The origin of a PQ problem can be divided in four main categories:

a) Caused by natural phenomena or human errors (for example: storm, lightning, digging of cable, etc.).
b) Caused by neighbouring customers having variable load demands (starting of large motor loads or the operations of other polluting loads).
c) Caused by customer's own installation with its own disturbing equipment.
d) Caused by the utility grid's switching operations or a lack of stiffness in combination with b) and c).

Figure 2.8 summarizes the LPQI survey results (of 2003-2004) regarding blames on PQ problems as reported by the customers in EU-25 countries [Lpq02]. Many industries complain that the network operators are responsible for most of the PQ problems because of the network structure, switching operations of network components, and natural phenomena. Service sectors admit that the majority of PQ problems in their sites are originated from their own installations and from the neighbours.

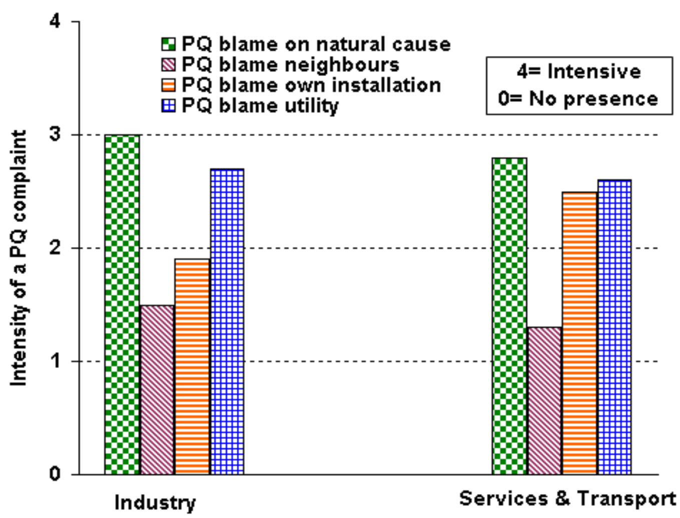


Figure 2.8. Blame on PQ causes by two groups of customers

The criticality of a PQ problem on a device connected to the network depends on many factors such as [Bha01]:

- Type of disturbance happening: the effect of a PQ disturbance on a device depends on the type of disturbance, its magnitude and duration.
- Frequency of occurrence: if an event happens frequently, it can have increased impact on the device as it will be stressed often.
- Sensitivity of the device: if the device is very sensitive, it may fail more easily than a device with less sensitivity (or higher immunity level).
- Location of the device: if the device is located at the beginning of a cable in an installation, it will face lesser problem due to under-voltage and flicker than if it is located at the end of the feeder.
- Age of the device: it might be possible for a device which is relatively new to absorb / ride through a disturbance, than if it is old.
- Short-circuit power at the point under consideration.

Therefore, detailed investigation is required regarding the operational behaviours of the customer's devices, their inrush current features, frequency of starts, harmonic current emission behaviours and immunities against voltage disturbances.

2.4.1 Structure of the networks

The structure of a network plays an important role in determining the performance of the network. In this thesis, the Dutch network is taken as a reference grid for analysis. The national grids of the Netherlands consist of 380kV, 220kV, 150kV and 110kV levels and are mostly of overhead lines. The local grid has voltage levels below 110kV and is mainly fed by cables. In the MV substations, HV/MV transformers are connected and are generally of 'Yyn' type with impedance grounding to restrict fault propagation in the network. The distribution networks consist of voltage levels of 20kV and lower voltage levels. The Dutch MV distribution network largely consists of 10kV cables and mostly has ring or meshed layout with a grid opening. Two types of feeders can be distinguished:

- MV feeders with series reactor (grids with high short-circuit power).
- MV feeders without series reactor (grids with low short-circuit power).

A typical MV substation consists of 15-20 outgoing feeders and each MV feeder is of 12km length on average and loading of 180A (i.e. 3.2MW equivalent). Almost every MV feeder in the Dutch network consists of both primary and secondary protection devices. In the simulation model, an average MV feeder is designed considering the feeder length of 12km and an average current loading of 180A. A description of the typical MV feeder is given in Appendix A-3.

The Dutch LV network mainly consists of cables with radial layouts. Figure 2.9 shows a typical LV feeding structure that is modelled in the analysis tool ‘Power Factory’. This network is used in the thesis for simulating various disturbances in the network.

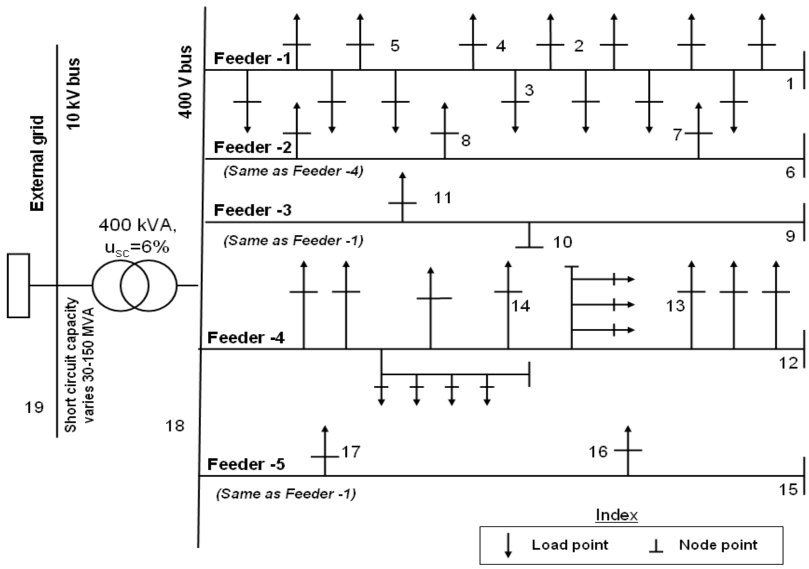


Figure 2.9. LV network with household customers used for simulation

A typical Dutch LV network can serve up to 300 household customers which means that each LV feeder supplies to 50-60 households. The average peak demand of the household customers is taken as 1.2kW. The LV feeders in the Netherlands are mainly of radial configurations either with a single branch or multiple branches. In the LV substation, a 400kVA transformer feeds (on average) five outgoing feeders. Each LV feeder has a 150mm^2 aluminium conductor with XLPE insulation and has an approximate length of 500m. From the field measurements done by the Dutch network operators, the average daily peak loading of a LV feeder is estimated as 70A per phase. Figure 2.9 shows the model LV network with various load points. It is designed in such a way that the maximal loading of each LV feeder is restricted to 70A per phase.

2.4.1.1 Grid impedance and short-circuit power

The grid impedance is an important parameter for determining the PQ performance of a network. At present there are no general standard or requirements with regard to the impedance. A high grid impedance (along with a network current) can contribute to harmonic voltages, high frequency noise, and high flicker severity. On the other hand, a low grid impedance will not be able to limit short-circuit currents and may cause noises as well as mechanical stresses in the conductor [Rus01]. To estimate the emission limit at a specific point in the network, information on the grid impedance is a prerequisite both for the network operator and the customer. For connecting a device in the network, the IEC 61000 series standards can be used based on the device current rating. In the standard IEC 61000-3-3 [Iec01], the reference impedances (also called 'flicker impedance') of a LV network are given as follows:

- Phase impedance = 0.24+j 0.15 Ω (at 50Hz)
- Neutral impedance = 0.16+j 0.10 Ω (at 50 Hz)
- So, phase-neutral impedance = 0.40+j 0.25 Ω = 0.472 Ω

In a typical LV network, a cable has relatively much higher impedance than the impedance of a MV/LV transformer. Thus, the grid impedance at a LV customer's connection point (POC) depends mainly on the distance of that point from the LV transformer substation. Figure 2.10 [Bha02] shows the percentage of customer's installations that share certain range of grid impedances along the length of an average LV network in the Netherlands. The maximum phase impedance at the furthest end of a feeder in the network is found 0.165 **Ω**.

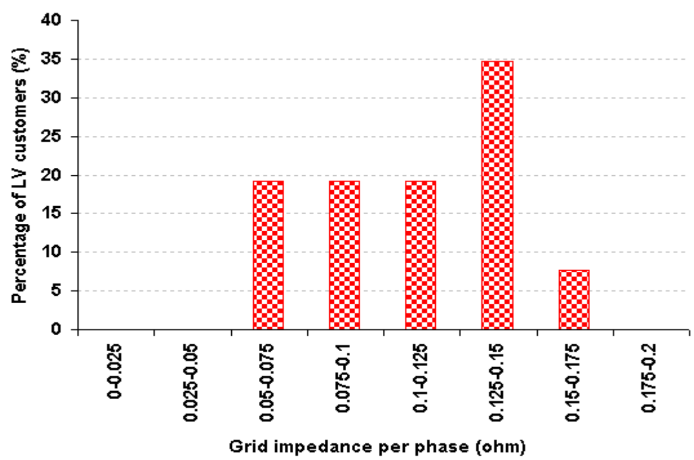


Figure 2.10. Network impedances at different LV customers' installations

The influence of active and reactive power on voltage drop (or rise) depends on the ratio of reactance to resistance (X/R ratio) in the network. The X/R ratio depends on the impedances of various network components (such as transformers, lines, cables, etc.) and can differ largely at different voltage levels. Generally, the HV network has high X/R (>>1) ratio and voltage drop is predominantly determined by the reactive power transport in the network. The MV network with cable has X/R ratio less than 1 and both the active and reactive power have influence on the voltage drop in the network. Thus, the MV network exhibits a mixed behaviour on voltage level control. In contrast, the LV network has mainly resistive characteristic with X/R≤1. For the Dutch MV network, the X/R ratio is around 0.5 [Pro01] and is used henceforth in this thesis for various network simulations. As the LV Dutch network is predominantly resistive and has large cross-section cables, the total voltage drop in the LV feeder is generally quite low even with additional harmonic currents flowing in the network. Reference [Des02] describes an experimental result which showed that with the increase in LV cable cross-sectional areas (from 50mm^2 to 240 mm^2), the impacts on voltage drops due to the equivalent linear and non-linear loads are more prominently visible; but the total voltage drops are much lower in the larger cross-section cables. The short-circuit power (S_{sc}) is a complementary parameter to the grid impedance. In some countries, the network operator specifies the short-circuit power at a customer's terminal. Figure 2.11 [Bha02] shows a typical distribution of short-circuit power at MV side of the MV/LV transformers in the Netherlands.

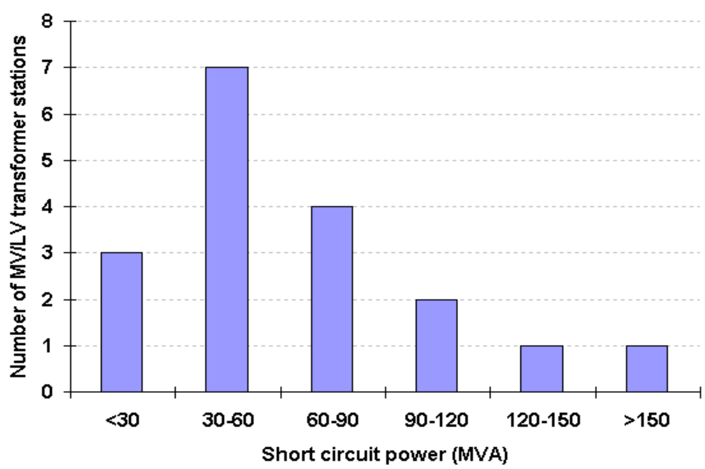


Figure 2.11. Distribution of S_{SC} at various MV substations in the Netherlands

Information on the value of S_{SC} at any point in the network is needed for protection coordination in the network and equipment sizing. Knowledge of the value of S_{SC} at a point is also useful for evaluating PQ levels in the network.

2.4.1.2 Maximum impedance limit for different connections

The maximum impedance at a customer's POC is specified to limit the inrush current during a load start and to restrict the flicker short-term severity contribution

(ΔP_{st}) to 1.0 as per the standard IEC 61000-3-3. In the Netherlands, LV customers can have single-phase 40A and various three-phase connection capacities such as 25A, 40A, 50A, 63A and 80A. The maximum permissible grid impedance values for various current capacities are calculated using the equation (2.9) [Cob02] considering the allowable inrush current equal to the current of the protection device at the POC and the ΔP_{st} to 1.0. Table 2.5 shows the calculated value of maximum impedance for different connection capacities and the repetition rate (r) of load start per minute being 0.1 at the customer's POC.

$$\Delta P_{st} = 36.1 \cdot \frac{I \cdot Z_g}{U_{nom}} \cdot \sqrt[3.2]{r} \tag{2.9}$$

where,

- I: connection capacity at the POC
- Z_g: maximum grid impedance at POC
- U_{nom}: nominal voltage of the installation
- r: repetition rate of the load in a minute

Table 2.5. Maximum impedance for various connection capacities at a POC

Current capacity at the LV installation (A)	Maximum allowable grid (network) impedance per phase (Ω)
25	0.523
40	0.326
50	0.261
63	0.207
80	0.163

Note: It can be remarked here that, this method of impedance calculation at a POC does not consider actual network's situation such as the actual voltage condition. This can cause certain percentage of error in the calculation.

2.4.1.3 Transformer types

Various transformers connected between the different voltage levels play an important role on voltage dip propagation behaviour in the network. Transformers are available with different winding configurations and can influence the propagation of dips at different voltage levels. Different types of voltage dips can be classified as follows:

- Type 1: transformers that have similar type of winding configuration in primary and secondary and both windings are grounded. The example of this type of transformer is star-star connection.

- Type 2: transformers that remove the zero-sequence voltage such as star-star winding with one or both windings ungrounded and delta-delta winding.
- Type 3: transformers that swap line and phase voltages. The examples are delta-star, star-delta and star-zigzag transformers.

For the transformers with different winding types (and clock number) in the primary and secondary sides, there will be phase shifts between primary-side and secondary-side voltages. The phase shift does not affect the voltage dip behaviour experienced by a device. However, the harmonic behaviour of the network can have some noticeable impact because of the phase shift of current and voltage waveforms in the network. Table 2.6 shows the fault propagation behaviour through the transformers [Pat01].

Table 2.6. Fault propagation behaviour through different transformers

Type of transformer	Fault type	Phase with maximum voltage dip
Type 1	ABC_G	A/B/C
	BC_G	A
	BC	B
	A-G	B
Type 2 & Type 3	ABC_G	A/B/C
	BC_G	A
	BC	C
	A-G	C

Note: ‘A, B, C’ are the nomenclatures used to designate the three phases of a 3-phase network connection. ‘G’ represents the ground connection of the system.

Figure 2.12 shows a typical configuration of the Dutch network with various intermediate transformer connections. The HV/MV transformers in the Dutch networks are mainly of ‘Yyn’ type (Type 1) and impedance grounded to reduce the fault propagation impact in the network. However, they cause voltage swell at the healthy phases for unbalanced faults. The MV/LV transformers are mainly of ‘Dyn’ configuration (Type 3) and restrict the zero-sequence current propagation in the higher voltage levels when an unbalance fault occurs in the lower voltage levels.

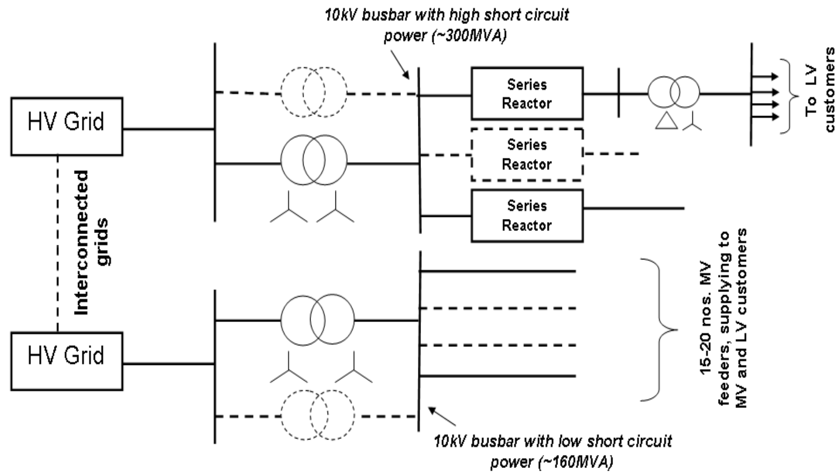


Figure 2.12. Typical configuration of the Dutch networks

2.4.1.4 Protection and earthing strategies in the networks

The earthing (also called grounding) strategy is important mainly for the transfer of unbalanced faults in the network. In the Netherlands, impedance grounding is used in the MV busbars to reduce phase to earth short-circuit current in the network. Moreover, almost every MV feeder in the Dutch network consists of both primary and secondary protection devices. The response time of the secondary protection is generally set as 300ms and that of the primary protection device is 600ms. When faults are generated in a feeder below secondary protection, the customers located above the secondary protection device face a deep voltage dip at their terminals. In contrast, when a fault occurs above the secondary protection of the same feeder, it is cleared by the primary protection device and all customers of the feeder suffer interruptions. The earthing of a grid also plays an important role in harmonics propagation behaviour in the network. In a grounded system, the zero-sequence components of harmonic currents get a path to flow, otherwise it gets blocked for an ungrounded system.

2.4.2 Characteristics of Customer’s devices

The operational performance of a customer’s device depends on the internal arrangement of its different elements (such as capacitors, inductors, resistors, power electronics components, etc). The customer’s devices can have significant impact on the network’s voltage quality because of their mutual interactions with other network components. To investigate PQ performance (in relation to flicker, harmonics and voltage dips) of a customer's device, the following information is considered to be important:

- Inrush current and frequency of starts (for calculating flicker level)
- Harmonic finger prints (for estimating harmonic current emission)
- Immunity of a process / device against a voltage dip event
- Aggregation of customer's loads in the network

2.4.2.1 Inrush current and frequency of starts

Flicker is regarded as a PQ problem in the network as the customers often complain about it. Flicker is produced by rapid voltage changes in the network. The most common type of motor load in a MV and LV network is an induction motor. To start an induction motor, a rotating torque is required that drives the rotor of the machine. Therefore, the motor draws a high current from its supply side to produce the required electromagnetic torque. In most of the cases, the starting current drawn by an induction motor is quite large (varies between 3-8 times) than its nominal current. A large value of inrush current produces a voltage variation at the motor terminal and it disappears after a certain amount of time, depending on the inertia of motor and the characteristics of the electrical network. During the quasi-stable state, the voltage variation at the installation can produce sufficient flicker which may be perceivable by the human eyes. To limit the voltage variations in the installation, various starting methods (for example star-delta start, auto-transformer starting, with electronic soft starters, etc.) are adopted that restrict the motor inrush current to a relatively lower value (within 1-3 times of nominal current) [Roc01].

The frequency of motor starts in a specified time also has an impact on the production of voltage variations and flicker. As per the Dutch Grid Code, the rapid voltage variations should be limited to ≤3% of the nominal voltage. The standard IEC 61000-3-7 [Iec04] gives a restriction regarding the permissible voltage changes per minute (r) based on the ratio of a customer's agreed power (S_i) at the POC and short-circuit power (S_{sc}) of that installation. Table 2.7 gives the limits of relative voltage changes in a minute for various short-circuit power ratios [k= $(S_i/S_{sc})_{max}$], considering that the value of P_{st} should be limited to 1 as per the standard IEC 61000-3-3.

Table 2.7. Limits for relative voltage change per minute for load variations

r (min-1)	k
r >200	0.1
10 ≤ r ≤ 200	0.2
r < 10	0.4

When the short-circuit power at a POC is low, the flicker emission limit should be determined based on the actual network's characteristics.

2.4.2.2 Harmonic fingerprints

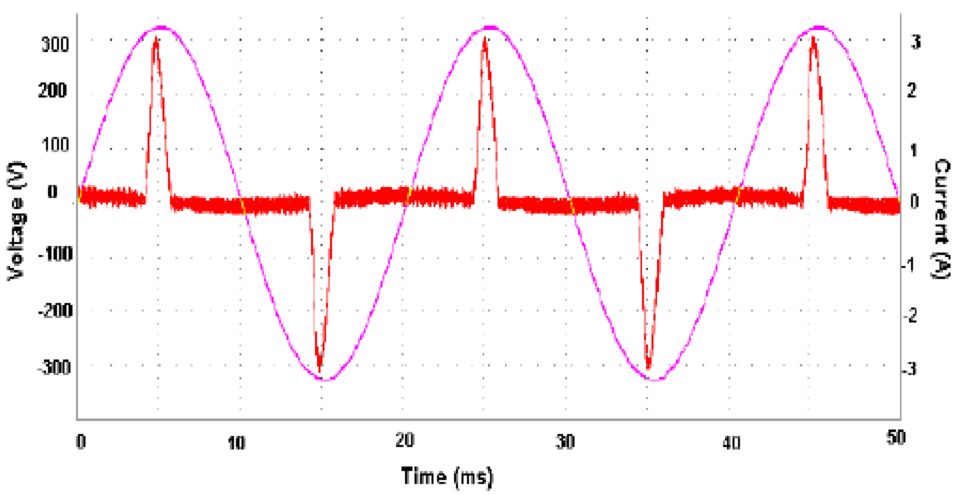
Power electronic devices have non-linear voltage-current characteristics and produce harmonic current emission in the network and consequently distort the supply voltage. At present, a device manufacturer guarantees the harmonic emission of a device for the normal sinusoidal supply voltage condition. However, when the supply voltage is already distorted with some specific types of harmonics the performance of the device is different. Therefore, it is necessary to determine the devices' current emission behaviour under distorted network voltage conditions too to ensure favourable operating conditions for all customers.

- **Discussion on the 'harmonic source model'**

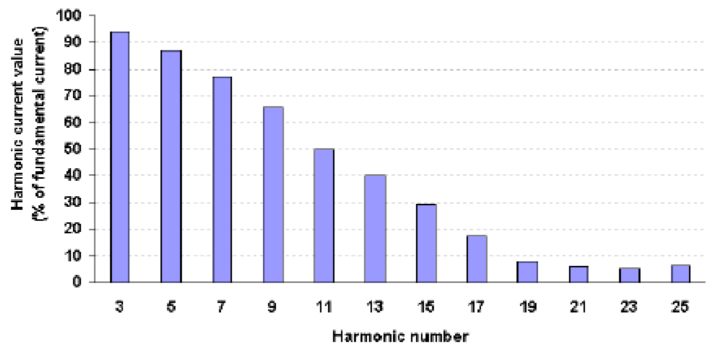
It is often difficult to obtain an average harmonic load model for a LV customer's installation because of the variation of usage and dynamic nature. A household customer has mixed loads (combination of linear and non-linear loads). A non-linear device is commonly represented by an equivalent current or a voltage source model along with an equivalent impedance or admittance. Knowledge of the characteristic of a non-linear device is important to understand its behaviour correctly under various operating conditions. In this research, laboratory measurements of some household devices are done to understand their actual characteristic. Generally, it is accepted that the non-linear devices can be modelled as a simple 'current source' model, when the voltage distortion THD_V in the network is low [Cha01]. On the contrary, reference [Pom01] shows that most of the power electronics used in household applications (e.g. television sets, laptops, compact fluorescent lamps, etc.) are configured with single-phase rectifiers with a capacitive output filter and have predominantly a voltage source characteristic. However, the motor driven loads (e.g. washing machine, refrigerators, air conditioners, etc.) can be represented by a current source model. In such a model, the contribution of a harmonic source is identified by magnitudes and phase angles of harmonic currents for respective harmonic orders.

- **Development of 'harmonic fingerprints'**

A concept is developed by TU/Eindhoven to measure the harmonic fingerprint of a device for estimating its harmonic current emission behaviour under various distorted grid voltage condition. A harmonic fingerprint is a database that contains a large set of harmonic current measurements for a device at different distortion conditions of the supply voltage. In the PQ lab of TU/Eindhoven, various household appliances and lighting devices are chosen for measurement. First, each device is tested separately for a clean sinusoidal voltage condition (230V rms) and its harmonic spectrum is recorded as shown in Figure 2.13. Subsequently, the supply voltage is distorted with various odd harmonics (from the 3rd harmonic up to the 25th harmonic order), having an amplitude variation of 1% to 10% (with a step of 1%) and also a phase shift of 0° to 360° (with a step of 30°) and respective harmonic currents are measured. Thus, for each device two matrices (each of 10x12 dimensions) are formed with new harmonic current amplitude and new phase angle data respectively, for different distorted voltage conditions. It was decided to perform the harmonic fingerprint measurement up to 25th harmonic order as the harmonic current values of the measured devices decrease exponentially with high order harmonics. Additionally, the accuracy of the supply power source and the measuring device becomes low with higher order harmonics (n>25). It is also observed that during a distorted supply voltage condition, the harmonic current emission of a device can change significantly. In the harmonic fingerprints measurement, the fundamental rms value of the supply voltage is taken as 230V. If this voltage is changed within the standard limits, the harmonic spectrum of the measured non-linear device will be changed. Nevertheless, the existing database will still be accurate enough.



(a) Typical current waveform for a sinusoidal supply voltage



(b) Harmonic spectrum under sinusoidal supply voltage condition

Figure 2.13. Current waveform and harmonic spectrum of a typical PC

Figure 2.14 shows an example of the harmonic fingerprint of a PC when a 25th harmonic voltage of different magnitudes and phase angles is applied at its terminal. References [Cob01], [Cas01] give more information on the harmonic fingerprint development method. From the harmonic fingerprint plot/database, it is often possible to identify the internal characteristics of a device. Also, the device's current of a specific order harmonic can be found for the same order harmonic voltage plot. However, the cross-interference among different order harmonics can not be directly distinguished from a harmonic fingerprint plot. The laboratory measurement is compared with the MatLab/SimuLink calculation using harmonic fingerprints. The conclusion was that using the available cross-interference data on different order harmonics hardly influences the accuracy [Yli01]. Therefore, the cross interference effects are not considered in this analysis.

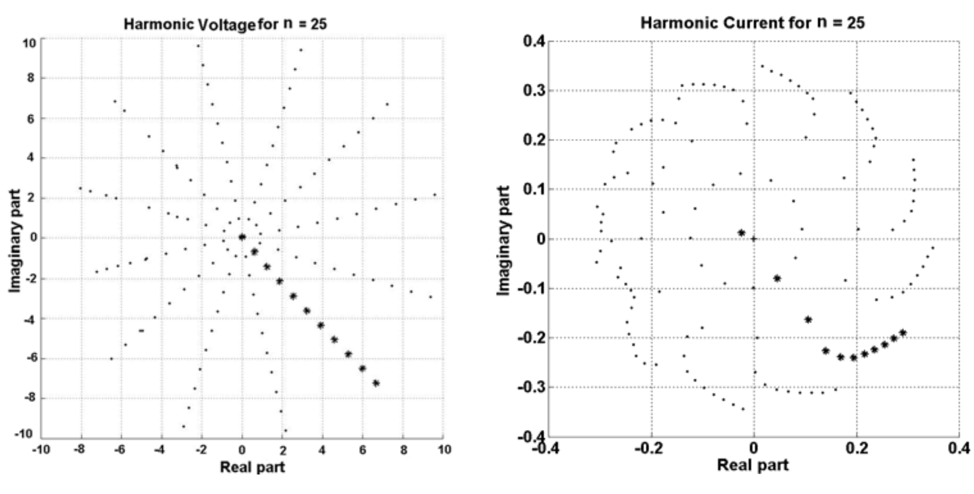


Figure 2.14. Harmonic fingerprint plot for a PC (for n=25)

Figure 2.15 [Bha03] shows the harmonic current emissions for a CFL when the 25th harmonic voltage distortion is increased from 1% to 10% of the fundamental voltage for phase shifts of 0°, -30°, +30°, -180°, and +150° respectively. It shows that the harmonic current emission of a CFL increases significantly when the magnitude of the 25th harmonic voltage distortion (with 0° phase shift) at its supply terminal is changed from 1% to 10%. Also, with phase angle variations of the supply voltage, the respective harmonic currents of a CFL change significantly.

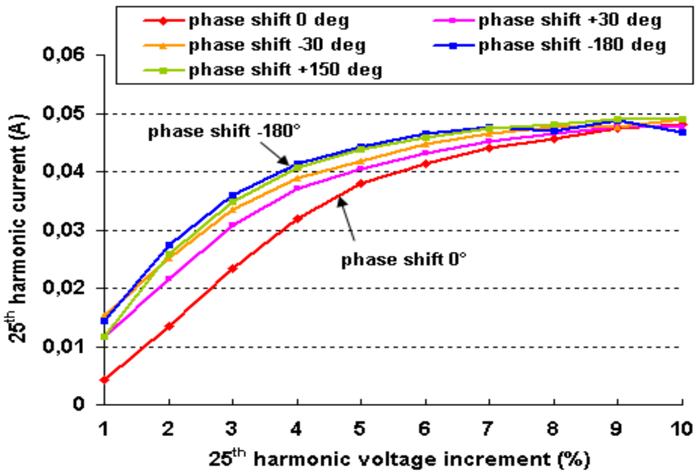


Figure 2.15. Harmonic currents of a CFL for 25th harmonic voltage distortions

In the PQ lab of TU/Eindhoven, the harmonic fingerprint measurements are done for some household devices and are listed in Appendix A-4. The harmonic fingerprint data of those devices are utilized in the harmonic simulation of the modelled network in chapter 4. In a network, mutual interactions occur between the network voltage and current. Moreover, a distorted supply voltage (as background distortion) influences the harmonic current emissions of the disturbing loads. This can have significant impact on the total harmonic currents at a POC.

2.4.2.3 Immunity to voltage dips

A voltage dip at a customer's POC is measured by the magnitude of the voltage drop (or remaining voltage at that terminal) and its duration. Various devices' susceptibilities to voltage dips differ and can be categorised in three groups [Bol02]:

- First group of devices are sensitive to the magnitude of voltage dip only (e.g. process controls, motor drive controls, many types of automated machine) and the dip duration is of secondary importance.

- Second group of devices are sensitive to both the voltage dip magnitude and duration. This group includes equipment with electronic power supplies.
- Third category of device is sensitive to voltage dip characteristics other than its magnitude and duration. It is affected by phase unbalance, the point-on-wave at which the dip occurs, or the transient oscillation associated with an event. Typical examples are actively controlled devices that rely on timing information from the waveforms (such as DC motor drives with controlled thyristors connected to the AC line, relays, contactors, etc.)

Different devices have different sensitivities towards voltage dips and are described by their individual voltage tolerance curves. A device's immunity to a voltage dip event depends on its voltage tolerance (V-T) performance curve. When a voltage dip occurs, the voltage available at the equipment terminal is lower than the nominal voltage. If the available voltage at the equipment terminal is less than its minimum voltage limit for a duration longer than the maximum tolerance time, the equipment will shut down. Proper characterization of voltage dips is quite complicated and is not well defined yet. For example: when a single-phase voltage dip event occurs and interrupts the operation of a process/device partially and if a second consecutive dip occurs (in the second phase or all three phases) within a short interval and has similar effects, it is unclear whether the total number of occurrences of the event will be counted as two or a single event.

A voltage dip event can disrupt the operation of many sensitive process devices in an installation that might lead to partial or complete interruption of the operation of a customer’s plant. In the process industries, variable speed drives (VSD) are widely used because of their dynamic performance, high flexibility and possible energy savings. In contrast, they are quite vulnerable to voltage dips. Their dip behaviours depend mainly on the hardware topology, control algorithm, loading conditions and the type of dip occurring in the network. Other sensitive devices are computers, thyristor fed DC motors, contactors, etc. Various protection devices such as under-voltage relays, contactors are quite sensitive to the point-on-wave of the supply voltage at which a dip initiates. Their responses towards a voltage dip depend on the magnetic energy stored in them before the start of that event. To find out voltage dip related sensitivities of a process plant and to identify the weakest link in the system, it is very important to analyze the whole process chain including its input power supply’s protection and control devices. Voltage tolerance curves (also known as ‘power acceptability curves’) are the graphs of the equipment’s maximum acceptable voltage deviation in a certain duration of time for safe operation. The most widely used 'V-T' curves are the CBEMA (Computer Business Equipment Manufacturers Association) curve, the ITIC (Information Technology Industry Council) curve and the SEMI 47 (Semiconductor Equipment and Materials International Group) curve [Car01]. Figure 2.16 shows typical immunity graph of SEMI 47, commonly used in industries [Sem01].

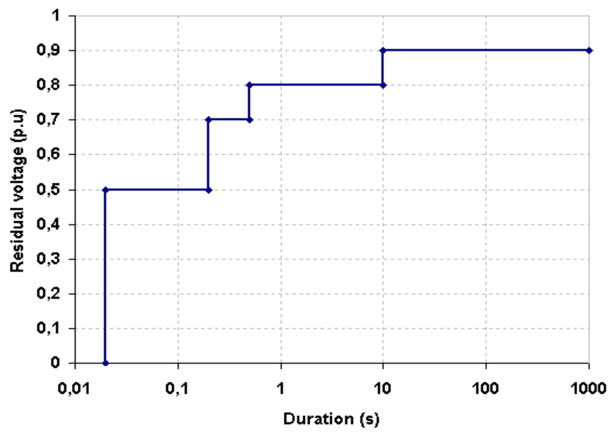


Figure 2.16. 'SEMI 47' curve mainly used in the semiconductor industries

The CBEMA and ITIC curves differ in the way their regions are presented. The CBEMA is a continuous curve whereas the ITIC has a series of vertical and horizontal lines. The ITIC curve has an expanded acceptable region compared to the CBEMA curve. The CBEMA curve is used for defining 'V-T' for computers, electric drives, solid state devices as well as various residential, commercial and industrial apparatus. The devices have to follow the immunity graphs specified by ITIC or CBEMA for computes and the SEMI 47 graph for semiconductor devices.

Large industries (such as: semiconductor industries, paper plants, glass and steel industries, etc.) suffer technical inconveniences and large financial losses when voltage dips occur at their plant sites. It is considered as a critical problem for continuous process operation as the whole plant operation might be interrupted and has to be restarted. Characterization of various types of voltage dips and assessment of their impacts on equipment sensitivity is a complex and time consuming process. The equipment may respond differently depending on dip type, magnitude, duration, point on wave of dip initiation and ending, dip shape, phase shift during dip event, dip energy, etc. Also, it is very important to have clear knowledge about the process under consideration (along with its electric feeding supply and various protective devices) to predict the installation's immunity against a voltage dip. Some processes are capable to operate without supply voltage for a small period of time (e.g. a chemical plant) whereas some processes are very sensitive to even a small duration voltage dip (e.g. paper mills, steel plants). The analysis of the CIGRE/CIRED JWG 4.110 concluded that 'process immunity time' (PIT) is an important indicator for designing a customer's process efficiently to minimize process outages because of voltage dips [Cir01]. The JWG also proposed a flow chart to predict the equipment's failure probability during a voltage dip event in the network. Figure 2.17 shows the maximum and minimum immunity requirements of a process for voltage dip events at the customer's installation.

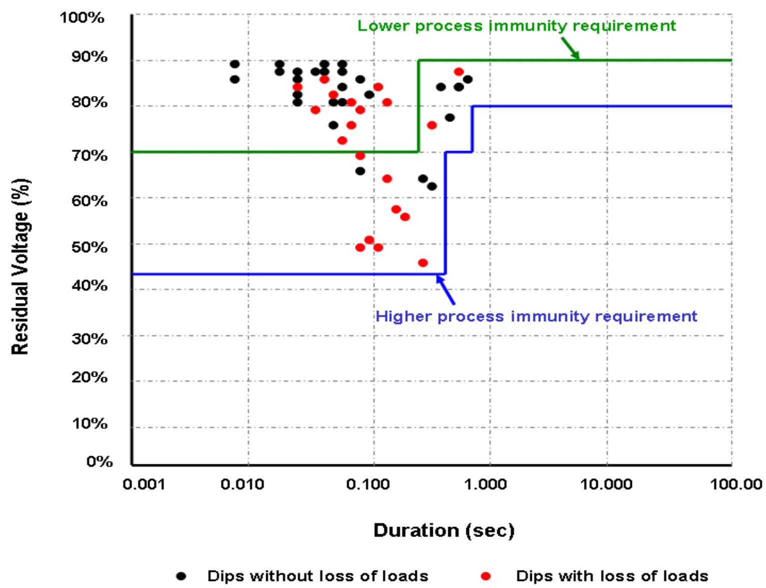


Figure 2.17. An example of selecting process immunity requirements

When a customer chooses the lower process immunity for his installation, then he probably will not be able to protect his process from all voltage dip events. On the contrary, when he selects the higher process immunity, it means that he has to invest more money for the process devices at his installation to make his installation more immune to different voltage dip events. This choice depends on the customer's installation vulnerability to voltage dips and the associated financial consequences.

2.4.2.4 Aggregation of customer's loads

The total connected load of a typical household customer is assumed to be approximately 12kW. A load coincidence factor of 10% is taken as the simultaneous operation of the household loads is quite small. Hence, average peak demand of each household is around 1.2kW and consists of motor loads, electronic loads and lighting devices. From the experiences of various network operators, it is found that simultaneous start of customer's motor load is quite low (average one disturbing load per minute) in a typical LV transformer substation. The short-term flicker severity (P_{st}), caused by the starting of motor loads, can be calculated by using equation (2.1). In a neighbourhood with many households, the harmonic currents are generated mainly by the operation of various non-linear loads such as home consumer appliances. However, the harmonic current spectrums and phase angles of those non-linear loads often cancel out each other and decrease the net harmonic current distortion at the customer's POC. It is also noticed that the aggregation of linear and non-linear loads effectively reduces the total harmonic current in the network compared to if only non-linear loads are present. Reference [Tau01] suggested a methodology (based on field measurements) to determine an aggregate harmonic load model of a household for estimating the harmonic voltage distortion at the POC. The technical report IEC/TR 61000-3-14 [Iec07] gives a formula for calculating the magnitude of resulting harmonic voltage at a POC when many harmonic sources are present in the network, as shown in equation (2.10).

$$U_n = \sqrt[\alpha]{\sum_i U_{n,i}^{\alpha}} \tag{2.10}$$

where,

- U_n: magnitude of the resulting harmonic voltage for harmonic order 'n' at the POC under consideration
- $U_{n,i}$: magnitude of the harmonic voltage for harmonic order 'n', contributed by the i^{th} harmonic source at the POC under consideration
- α: an exponent which depends on the probability of random variation of disturbance (in terms of magnitude and phase angle)

The value of the summation exponent 'α' is taken as 1 for lower order harmonics ($n<5$) when it is known that the harmonics are likely to be in phase; 'α' is taken as 1.4 for harmonic order $10 \geq n \geq 5$; and it is 2 for higher order harmonics ($n>10$). However, these are indicative values. The actual values of 'α' for various harmonic orders can be estimated from the practical field measurement data of a network (refer chapter 5).

2.4.3 Propagation and attenuation of PQ disturbances

For power quality management in the network, along with the information of devices' emission and immunity characteristics, it is also important to know how the devices mutually influence each other. The mutual interactions among various devices can result in amplification or a reduction of total PQ disturbances in the network, depending on their characteristics. The rate of PQ propagation depends mainly on the network configuration and its impedance. Synchronous measurements at different installations give an indication to the PQ propagation behaviour in the network. In this section, the propagation and attenuation behaviour of flicker, harmonics and voltage dips in the network are discussed.

2.4.3.1 Flicker attenuation and propagation

In the MV and LV networks large numbers of customers are connected who often use loads that demand variable power and emit current pollutions. Two main categories of fluctuating loads exist in practice: a) conventional equipment with some controlled duty cycle that results in predictable real/reactive demand fluctuations; b) arcing equipment, perhaps including some duty cycle variations that results in random demand fluctuations. In the LV network, the loads such as compressors used in refrigerators, heat pumps, air conditioners, electrical tools (welding machine, drilling equipment), other appliances (copy machine, lifts etc.), and dispersed generators (micro-combined heat power generators, wind mills, etc.) can cause fluctuations in the voltage and the power supply. A large number of these devices and their simultaneous operation can increase voltage disturbances (mainly flicker) at various customers' installations in the network. The voltage fluctuations generated by the operation of those devices generally get added (as per equation 2.1). It is more significant when the short-circuit capacity of the network is low. The knowledge of the network configuration is essential to analyze flicker propagation. For a radial network, it is sufficient to know the short-circuit levels at each point of the network to estimate voltage fluctuations. The relative voltage variation at the customer's POC can be calculated by estimating the reactive power change relative to the short-circuit power. Reference [Ten01] states that the presence of industrial loads containing a large portion of induction motors can attenuate flicker in the network. It is because the induction motors have relatively smaller effective impedances at flicker related frequencies. Thus, the load composition, transformer's impedance and the action of voltage regulators influence flicker propagation behaviour in the network. For an interconnected system, estimating flicker propagation is rather complicated and the impedance matrix method [Ren01] is found the most appropriate.

The transfer of flicker from one point to another point can be calculated by doing synchronous measurements as suggested in reference [Per01]. The P_{st} values at the source and other measuring points have to be recorded simultaneously and the flicker transfer coefficient can be determined. When only one flicker source is present at 'point 1' in the network and evaluation is at 'point L'; the transfer coefficient can be defined by equation (2.11).

$$T_{Pst,1L} = \frac{P_{st,L}}{P_{st,1}} \tag{2.11}$$

The transfer coefficient ($T_{Pst,1L}$) indicates the propagation of flicker from a source (e.g. point 1) to another point (e.g. point L) in the network as illustrated by Figure 2.18. In a real network, multiple flicker producing sources are present and contribute to flicker emissions in the network. Therefore, the total P_{st} value at a certain point will be the combination of (individual) contributions from different flicker producing sources.

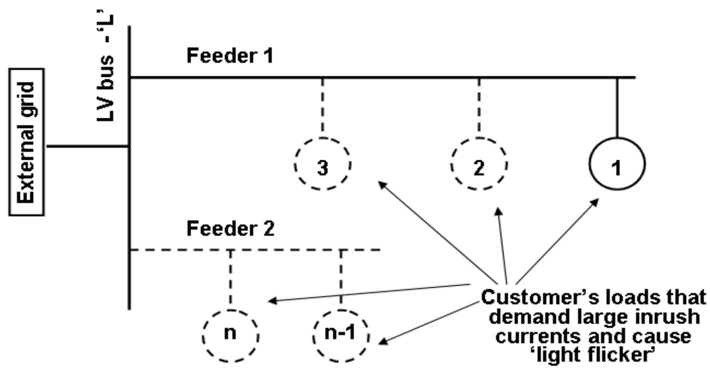


Figure 2.18. Customer's loads that produce flicker in the network

2.4.3.2 Harmonic resonance, propagation and other effects

The harmonic currents in combination with the network impedance produce harmonic voltages in the network. The harmonics problems in the network are mainly related to local resonance effects. Two types of resonance problems can happen: a) series resonance and b) parallel resonance as shown in Figure 2.19. The network components such as the impedances of the transformer and feeders in combination with the capacitance of a power factor corrector capacitor and the customer's load impedance can contribute to harmonic resonance situations in the network. In case of parallel resonance, the impedance of the network will be high seen from the current source (customer's end). This will result in high harmonic voltage conditions in the network. For series resonance in the network, the opposite situation occurs. The total effective impedance will be low when seen from the customer's side and this will lead to a high harmonic current distortion in the network. Detailed frequency response analysis of the network components is to be done to estimate the harmonic resonance points in the network.

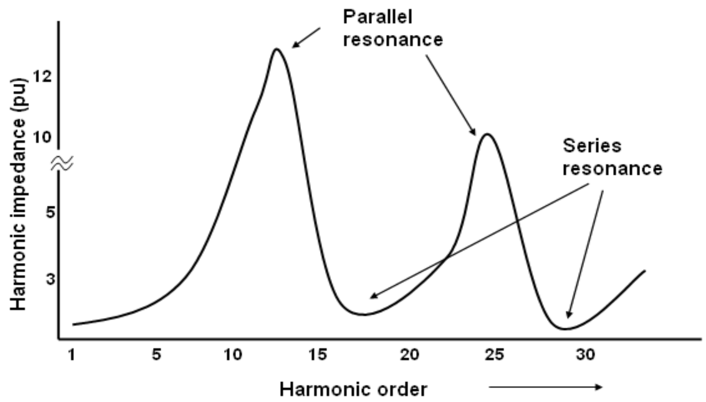


Figure 2.19. Illustration of parallel and series resonances in the network

Reference [Con01] summarizes various active and passive filters and other preventive solutions (such as harmonic cancellation by delta-delta or delta-star transformers, incorporating shunt harmonic impedances, increasing the number of phases in rectifiers or static converters, operating transformers and motors at low saturation curves, etc.) to damp the network harmonics and avoid resonance problems in the network.

Harmonic currents, generated by the operation of various customers' non-linear devices, propagate to different voltage levels in the network. The harmonic propagation in a LV network depends mainly on the location of the observation point, the short-circuit power of the source and the location of the disturbances (as illustrated in Figure 2.20). When the harmonic current source is at point 1 and the observation point is at LV busbar- 'L', the transfer coefficient for harmonic number ‘n’($T_{Un,1L}$) can be defined as shown in (2.12).

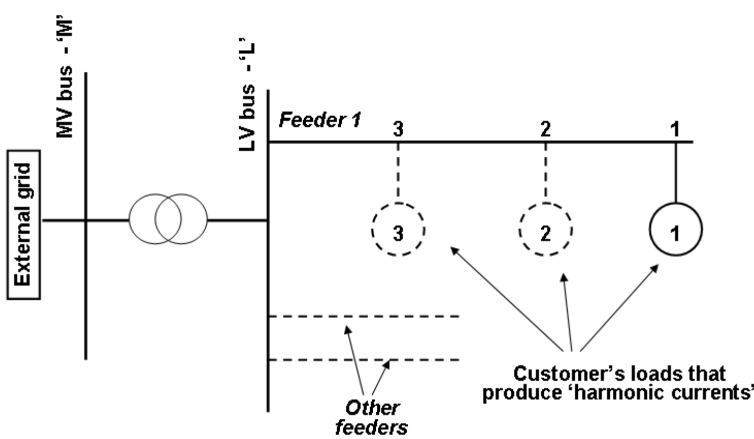


Figure 2.20. Customer’s loads that emit harmonic pollutions in the network

$$T_{Un,1L} = \frac{U_{n,L}}{U_{n,1}} = \frac{Z_{L,n}}{Z_{L,n} + Z_{L3,n} + Z_{32,n} + Z_{21,n}} \tag{2.12}$$

where,

- $U_{n,L}$: harmonic voltage at L
- $U_{n,1}$: harmonic voltage at point l
- $Z_{L,n}$: harmonic impedance at observation point L
- $Z_{L3,n}$: harmonic impedance between point 3 and L
- $Z_{32,n}$: harmonic impedance between point 3 and point 2
- $Z_{21,n}$: harmonic impedance between point 2 and point 1

The harmonic transfer coefficient for different order harmonic 'n' will vary depending on the respective harmonic impedances of various network components. The transfer of a harmonic voltage from the lower to the higher voltage level is generally quite low (especially when short-circuit power at the MV busbar is more than 100MVA) [Cob01].

- **Attenuation and diversity effects**

When many single-phase power electronic loads are present in the network, the harmonic currents for a specific order may increase or decrease depending on the respective phase angles of different devices. It was noticed that when the power demand of a device increases, the supply current waveform becomes wider and taller and a corresponding reduction of the harmonic current magnitude occurs. Reference [Man01] shows that when many identical devices are served through a shared network impedance, there will be a reduction of the net harmonic current magnitude for different order harmonics. This is called the 'attenuation effect' and the attenuation factor (AF_n) is calculated as shown in equation (2.13).

$$AF_n = \frac{I_n^N}{N \cdot I_n^1} \tag{2.13}$$

where,

- I_n^N: resulting current of harmonic order 'n' for N identical devices operating at a busbar in parallel
- I_n^1: harmonic current of order 'n' with only one device
- N: number of identical devices connected in parallel

Reference [Nas01] gives a modified definition of the attenuation factor which considers the effect of supply voltage distortion with respect to a case when there is little or no distortion. It also gives experimental result on attenuation effects of many compact fluorescent lamps (CFLs) in the network. That analysis concluded that with the increase of number of CFLs in the network, the total harmonic current distortion (THD_I) in the network reduces. Also, the effective harmonic current reduces for 3rd to 7th order and also for 17th to 21st order harmonics; whereas it increases for 11th to 15th order harmonics. The 9th harmonic current will increase or decrease, depending on the supply voltage distortion. Another reference [Des01] shows that when many single-phase loads (such as PCs) are supplied from the public distribution supply, the attenuation factor of some order harmonics can increase up to 130% (such as for 15th, 17th and 19th orders). This is due to the high influence of higher order harmonic voltages on harmonic currents.

The phase angle dispersion of individual current harmonics of a device can occur because of the variation of device's power demand, line impedance magnitude and the X/R ratio of the network. When multiple non-linear loads are present in the network, there can be significant phase angle differences among them. This can reduce the effective harmonic current in the network and is called 'diversity effect'. The current harmonic diversity factor is defined as a ratio of the phasor sum of currents of the harmonic order 'n' and the algebraic sum of currents for harmonic order 'n' and is shown in equation (2.14).

$$DF_n = \left| \frac{\sum_{i=1}^{N} I_n^i}{\sum_{i=1}^{N} \left| I_n^i \right|} \right| \tag{2.14}$$

where,

- N: total number of non-linear loads connected in parallel
- I_n^i: $|I_n^i| \angle \beta$: harmonic current of order 'n' injected by the i^{th} load that has magnitude of $|I_n^i|$ and phase angle β

With many different single-phase devices connected together, the total harmonic current distortion can decrease and the power factor at the common terminal point might be improved. Reference [Man01] shows some examples of attenuation and diversity effects with many single-phase non-linear loads in the network. It concluded that when many identical loads (such as TV, PC, etc.) are shared through a common source impedance, significant attenuations of harmonic currents occur for the 5th and 7th order harmonics (AF_n is in the range of 0.3-0.5). However, the attenuation does not occur much (AF_n is around 0.8-0.9) for the 3rd order harmonic. The same reference [Man01] also showed the diversity effects of various single-phase loads. It concluded that for the 3rd and 5th harmonic orders, the diversity effects are low as there is not much cancellation of phase angles among the devices. For higher order harmonics ($n \geq 13$), DF_n can be in the range of 0.4-0.6, depending on the number of devices connected in parallel at a POC. Reference [Cuk01] discussed a laboratory experimental result for CFLs that are connected in parallel. It was found that the diversity effect is more prominent when less numbers of CFLs (e.g. 6 numbers) are connected. The diversity effect gradually reduces when many CFLs (e.g. 30 numbers) are connected at the same POC. For the latter case, the diversity factor varies in the range of 0.85-0.95 for harmonic order $n \leq 11$ and the DF_n is between 0.75-0.85 for $n \geq 13$.

2.4.3.3 Voltage dip propagation

When a short-circuit fault occurs in the network, the customers located at various points (of the same or other voltage levels) in the network experience voltage dips of different characteristics. This phenomenon is called 'voltage dip propagation'. A voltage dip generally becomes less severe at the locations further away from the fault position. The characteristic of a voltage dip can change significantly when a fault occurs in the HV or MV network and its impact is measured at the lower voltage levels. The propagation of a voltage dip event depends on the network's configuration, intermediate transformer's configurations, and earthing strategy of the network. According to the CIGRE/CIRED working group C4.110 group, dips can be classified in three main types [Cir01]:

- Type I (unbalanced fault): a single-phase short-circuit affecting the faulted phase voltage. It is the most common type of fault in the network.
- Type II (unbalanced fault): a two-phase short-circuit fault affecting two faulted phase voltages.
- Type III (balanced fault): a three-phase fault that affects all the three phases. It is the most severe type of dip and has the highest impact on the customers. It can propagate through the transformer without much change in its magnitude and nature.

A balanced voltage dip originated in the HV network propagates spontaneously to the lower voltage levels, without much attenuation. However, when a voltage dip occurs in the LV network, it is mainly noticed by the customers located in the same voltage level. This voltage dip does not propagate much in other higher voltage networks. The magnitude of a voltage dip at a node point in the network is calculated by using the basic fault analysis technique and is shown by equation (2.15).

$$U_{dip} = \left(\frac{Z_f}{Z_S + Z_f} \right) \cdot U_0 \tag{2.15}$$

where,

- Z_f: fault impedance
- Z_S: source impedance at the node point under consideration
- U_0: pre-fault voltage at the node point under consideration

2.5 Summary and conclusions

In this chapter power quality problems in the Netherlands and other countries in the world are discussed. The main sources of origin of flicker, harmonics and voltage dip are described briefly. Also, various measurement indices that are used to represent flicker level, harmonics and voltage dips are discussed. The PQ performance trends of the Dutch networks are summarized from the analysis of the national PQM data (for the years 2005-2008). Also, the results of the PQ monitoring done under the KTI project are briefly described. A typical MV and LV network is developed by using a network analysis tool for simulating various PQ disturbances in the network. Finally, the propagation behaviours of flicker, harmonics and voltage dips in the network are discussed. The main findings of chapter 2 are summarized as follows:

- The national and KTI PQ measurements in the networks of the Netherlands show that the PQ performance of the Dutch networks is quite good and mostly meets the requirements of the standards. However, occasional local problems related to high flicker and harmonics occur in the network and the customers complain about the incidents. Those local PQ problems are often due to the operations of the customer's connected devices in combination with high network impedance at the POC. In the recent years, some parts of the Dutch grid are renovated with higher cross-section cables and over-sized transformers. It is noticed that the customers connected at those parts of the networks are generally more satisfied with the received quality of the electric supply (as the network impedances of their connection points are quite lower than the old parts of the Dutch networks). However, when more loads will be connected in the new network parts (example: large charging current demands due to E-mobility), PQ problems can be increased in these networks too.

- Network structure and network impedances highly influence the PQ level in the network. With high impedance of the network, PQ problems (mainly flicker and harmonics) become more prominent. Various transformers' winding configurations and earthing strategies influence the harmonic propagation behaviour and unbalanced voltage dips propagation in the network.
- Inrush current demands, frequency of starts of customer's devices and the network's short-circuit power influence the flicker severity (P_{st} value) at the customer's POC.
- Harmonic fingerprint of various devices is an important tool to estimate the harmonic behaviour of the network. The total harmonic current in the network is highly dependent on the emission characteristics of the connected devices, their mutual phase angles and the background distortion of the supply voltage.
- Voltage tolerance ('V-T') graphs of the customer's devices are important to calculate an installation's immunity to voltage dips. While calculating the weakest link of the customer's process chain to estimate voltage dip immunity performance of the installation, it is also important to check the voltage tolerance of the supplied power supply which includes various protective and control devices too. A equipment manufacturer can provide the 'V-T' graph of a device/component in line with the voltage dip classification table used (of the EN50160 standard) that is used to present voltage dip statistics of the network.
- At present, most of the PQ indices used in the network indicate average performance over 10 minutes period. Introduction of short-time (such as 1 minute and/or 3 seconds period) indices can identify the actual PQ performance level in the network more accurately. However, it demands large memory of the measuring devices to record and store such huge volume of PQ data.

Chapter 3

Consequences of inadequate PQ and their solutions

3.1 Introduction

Inadequate power quality (PQ) of the electric supply causes many inconveniences to the customers. As discussed in chapter 2, the customers complain to the network operators about various PQ aspects when they suffer techno-economic damages at their installations. In this chapter, various technical and financial consequences of PQ disturbances as perceived by different customers are discussed. The correct financial data on PQ losses are quite difficult to obtain, as they are very case specific. In the recent years, the CIGRE/CIRED JWG C4.107 members proposed methodologies to describe PQ related financial losses for the customers and network operators. Those methodologies are taken as a guiding tool for the financial analysis of this thesis. In addition, various PQ survey results obtained from the literatures are used as reference data to specify PQ related financial losses. In the later part of this chapter, various PQ mitigation measures that can be applied at the network side as well as the customer's installations are discussed. Furthermore, the new developments on PQ mitigation measures that are researched in the 'Theme-2' and 'Theme-3' of the 'KTI' project are briefly described. Finally, a 'cost-benefit' method is discussed which is commonly used as an analyzing tool to decide about (optimal) financial investments for the various involved parties.

3.2 Technical consequences of poor PQ

The customers use large number of devices at their installations that comprise of electronically controlled converter loads. The residential customers use different domestic appliances such as televisions (TV), videocassette recorders (VCR), microwave ovens, personal computers (PC), heating-ventilation-air conditioning equipment (HVAC), lamps, etc. The business and office equipment include computer workstations, copiers, printers, lighting systems, etc. On the other hand, the industrial customers use programmable logic controllers (PLC), automation and data processors, variable speed drives (VSD), soft-starters, inverters, computerized numerical control (CNC) tools and so on. All these different types of devices are quite sensitive to PQ disturbances. From worldwide customer surveys, it is found that the complaints on PQ related disturbances (for example harmonics, voltage dips, flicker, etc.) are increasing every year. The quality of the power (voltage and current) that is provided by the network operator has to comply with reference parameters set in standards like the European standard EN 50160 and other specific standards or the national grid codes. It can be observed that the customer's non-linear loads often distort the network's voltage. Therefore, it is a real challenge for the network operator to maintain the network's voltage quality. Until now, only a few case studies are carried out to analyze the technical and non-technical inconveniences of inadequate PQ for the network operators. Nevertheless, an estimation of technical damage on different network components because of the PQ disturbances can be done to get an indication of possible impacts of inadequate PQ for the network operator.

3.2.1 For the customers

Many case studies and surveys in different countries around the world have been done to estimate the impacts of inadequate PQ to the customers. It was generally noticed that industries are vulnerable to long and short interruptions (that are considered as "reliability issues" in the power system analysis). Voltage dip is the main PQ problem for the semiconductor and continuous manufacturing industries, and also the hotels and telecom sectors. Harmonics related inconveniences are perceived mainly by the commercial and service sectors such as banks, retail, IT, etc. Another PQ problem that draws high attention is the presence of transients and surges at the customer's installation. In 2001, the Leonardo Power Quality Initiative (LPQI) surveyed in eight countries of the

European Union (EU) [Lpq01] and found that the customers complain when they suffer inconveniences at their sites, as shown in Table 3.1.

Table 3.1. Customer's reported complaints in EU-8 as per LPQI survey [Lpq01]

Perceived inconvenience	*Affected devices*	*Reported problem*
Computer lock-ups and data loss	IT equipment	Earth leakage current causing voltage drops
Loss of synchronization in processing equipment	Sensitive measurements of process control equipment	Severe harmonic distortion creating additional zero-crossings within a cycle of the sine wave
Computer, electronics appliances damage	Electronic devices like computer, DVD player, etc.	Lightning or a switching surge affecting supply voltage
Lights flicker, blink or dimming	Lighting devices, and other visual screens	Fast voltage changes leading to visible light flicker
Malfunctioning of motors and process devices. Extra heating, decreased operational efficiency and premature aging of the equipment	Motors and process devices	Presence of harmonics in the electric supply voltage
Nuisance tripping of protective devices	Relays, circuit breakers and contactors	Distorted voltage level
Noise interference to telecommunication lines	Telecommunication system	Harmonics causing interference signals

In 2008, another report was published by the LPQI in which a PQ survey was described that was conducted among the customers of the EU-25 countries [Lpq02]. It was reported that loss of synchronization of processing equipment is an acute problem in the industries, mainly for continuous manufacturing industries. Lock-ups of computers and switching equipment tripping are the second largest problem for industries. For the service and transport sectors, disconnection and data loss are the main problems caused by inadequate PQ. It was noticed that main reasons of PQ disturbances in industries are the motor driven systems and static converters. For the service sectors, these are mainly the electronic apparatuses. Figure 3.1 shows the LPQI survey results that indicate the frequency of occurrence of different PQ consequences in the industries and the service and transport sectors as a percentage of cases analyzed. For example, among the industries that were surveyed, approximately 55% of them reported about computer lock-up problems. Many industries as well as the service sectors complained about more than one PQ related problems at their installations.

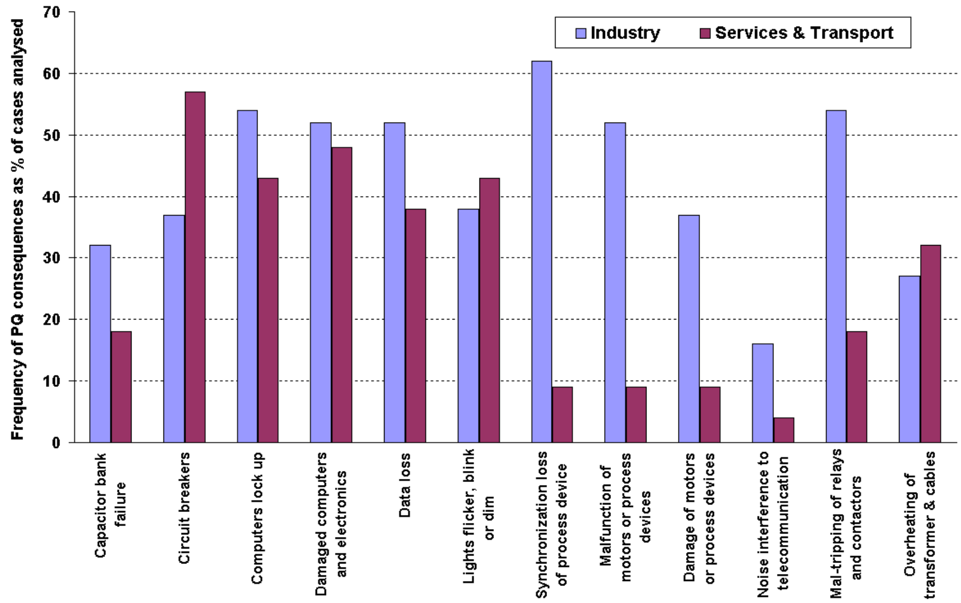


Figure 3.1. Consequences of inadequate PQ as experienced by the customers

Figure 3.2 shows the LPQI survey results [Lpq02] of the devices that mostly get affected by PQ problems in the EU-25 countries.

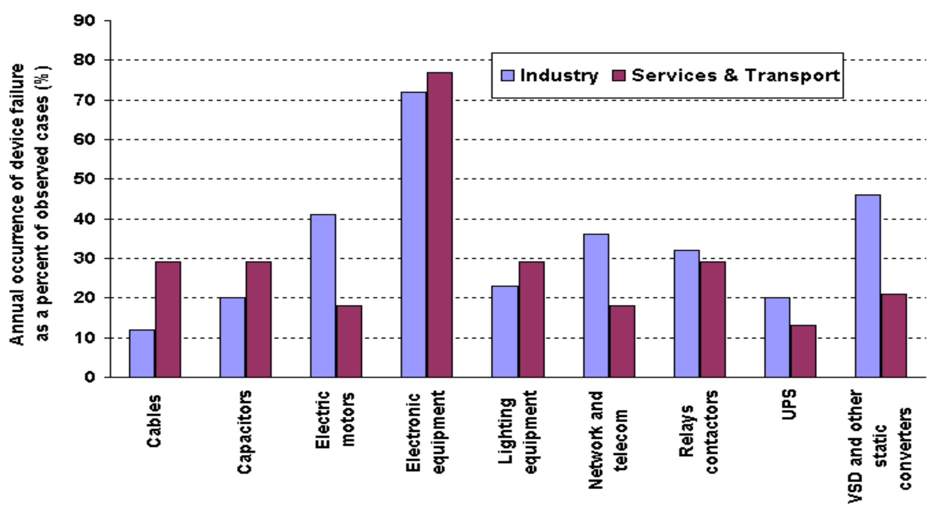


Figure 3.2. Equipment affected by PQ problems in different sectors

It can be noticed from Figure 3.2 that the electronics devices are the most vulnerable to PQ problems in different sectors. More than 70% of the industries and 75% of the service sectors reported problems related to various electronics equipment failures at their installations. In 2000, the Electric Power Research Institute (EPRI) conducted a PQ survey [Epr02] among the industrial customers in the USA. It was found that the most affected devices in the industries because of inadequate PQ are computers and microprocessor based devices (43%), variable speed drives (13%), lighting equipment (8%), motors (5%), relays (1%) and other devices (30%).

3.2.2 For the network operators

Large PQ emissions from the customers' sides can make it difficult for the network operator to maintain a high voltage quality at a customer's POC. Power electronic devices produce harmonic currents that lead to additional harmonic power flow and increase network's total apparent power demand while decreasing the true power factor of the network. Large harmonic current can also cause overloading and extra power losses in the network components. In extreme cases, it can lead to high thermal stresses and eventual early ageing of the network devices. Imposing penalties to the harmonics producing customers is not possible because of the lack of proper measuring devices. Harmonic currents when combined with high grid impedances increase voltage distortions in the network and in extreme situation can shift zero-crossing points of the supply voltage waveform. This increases noise and electromagnetic interference in the network. Transformers, cables, and power-factor correction (PFC) capacitors are the network components that mainly get affected by PQ disturbances. The customers (such as industries and large commercial offices) who own transformers, cables and/or PFCs at their installations also suffer harmonic losses and other PQ related inconveniences.

3.2.2.1 Effects on transformers

Presence of harmonic currents increases losses and the demand of apparent power in the network. Therefore, the network transformers have to supply extra power. Various losses in a transformer are: the core losses, copper losses, and stray-flux losses in a transformer. These losses consist of 'no load losses' and 'load losses'. No load loss is affected mainly by voltage harmonics, although the increase of this loss because of harmonics is small. It consists of two components: hysteresis loss (due to non-linearity of the transformers), and eddy current loss (varies in proportion to the square of the frequency). The load losses of a transformer vary with the square of load current and increase sharply at high harmonic frequencies. They consist of three components:

- Resistive losses in the winding conductors and leads
- Eddy current losses in the winding conductors
- Eddy current losses in the tanks and structural steelwork

Eddy current losses are of large concern when harmonic current is present in the network. These losses increase approximately with the square of frequency. Total eddy current losses are normally about 10% of the losses at full load. Equation (3.1) gives the total load losses (P_T) of a transformer when harmonics are present in the network [Hul01].

$$P_T = P_{CU} \times \left(\frac{I_L}{I_1}\right)^2 + P_{WE1} \times \left(\sum_1^n \left(\frac{I_n}{I_1}\right)^2 \cdot n^2\right) + (P_{CE1} + P_{SE1}) \times \left(\sum_1^n \left(\frac{I_n}{I_1}\right)^2 \cdot n^{0.8}\right) \quad (3.1)$$

where,

- P_{CU}: total copper loss
- P_{WE1}: eddy current losses at 50Hz (full load)
- P_{CE1}: additional eddy current losses at 50Hz (full load)
- P_{SE1}: stray losses in construction parts at 50Hz (full load)
- I_n: rms current (per unit) at harmonic ‘n’
- I_L: total rms value of the load current (per unit)
- I_1: fundamental component of load current (per unit) at 50Hz
- n: harmonic number

Other concern is the presence of 'triple-n' harmonics. In case of a transformer with a Y/Δ configuration, 'triple-n' currents generated in the downstream network circulate in the closed delta winding. All other 'non triple-n' harmonics pass to the upstream network. To minimize the risk of premature failure of transformers, they can either be de-rated (generally applied in the EU countries) or can be made as ‘K-rated’ transformers (quite common in the US). A ‘K-rated’ transformer is constructed to withstand more voltage and current distortion than standard transformers [Cha03]. Such an index is used for rating the transformers based on their capabilities to handle harmonic currents. The purpose of both the 'de-rated' and 'K-rated' approaches is to adapt the transformer to operate in a harmonics-rich environment without overstressing it and limiting the chance of its premature failure.

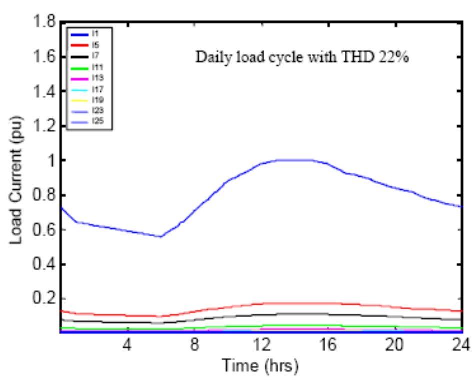
Thermal degradation of an electric device is caused by the temperature rise beyond the rated value. When the operating temperature deviates from the rated hot spot temperature, the life expectancy (i.e. aging rate) of a device is changed and can be calculated by using Arrhenius law as shown in (3.2) [Fuc01]. The aging rate is mainly dependent on the type of insulating material of the device, the surrounding ambient temperature where the device is operating and the elevated temperature rise because of the device operation.

$$\rho = \rho_{rat} \cdot e^{-\left(\frac{E}{K}\right)\cdot\frac{\Delta\theta}{\theta_{rat}(\theta_{rat}+\Delta\theta)}} \tag{3.2}$$

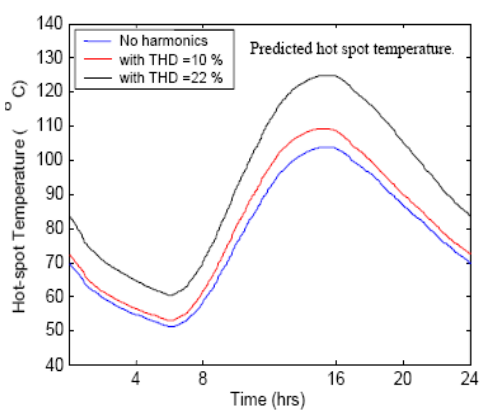
where,

- ρ: life time referred to temperature of $\theta° = \theta°_{rat} + \Delta\theta°$
- ρ_{rat}: life time referred to $\theta° = \theta°_{rat}$
- $\Delta\theta°$: temperature rise in relation to θ_{rat} in Celsius
- θ_{rat}: cable rated temperature in Kelvin
- E: activation energy expressed in "eV", where 1eV= 1.6×10^{-19} joule.
- K: boltzmann constant $= 1.38 \times 10^{-23}$ joule/°K.
- The value of (E/K) depends on the type of insulating material used in the device

With equation (3.2) it can be derived that for every 7° temperature rise above a rated hot spot temperature of 85°C, the life time of a device is reduced by 50% of its normal life time (when E/K=1.1eV). Reference [Elm01] shows that with an increase of THD_I in the network to 20%, the hot spot temperature of the transformer increases (see Figure 3.3). This can cause a reduction of the transformer's useful life time.



(a) Daily load profile (fundamental and harmonic currents) measured at a transformer's terminal



(b) Predicted hot spot temperature rise with increase of THD_I at a transformer's terminal

Figure 3.3. Measurement of hot spot temperature at a transformer's terminal

3.2.2.2 Effects on cables

Harmonic currents have two main effects on cables:

- Additional 'ohmic losses' (I^2R losses) in the line and neutral conductors of a cable because of increased rms value of current due to harmonics. This causes increased operating temperatures in a cable.
- Harmonic currents cause harmonic voltages across various parts of the network that can increase dielectric stress on cable insulation and can shorten its expected lifetime [Mon01].

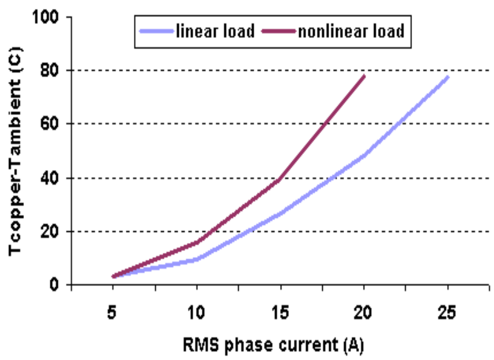
The AC resistance of a cable is determined by its DC resistance value plus skin and proximity effects. The alternating current tends to flow on the outer surface of a conductor where the impedance is the lowest. This is known as "skin effect". This effect is more pronounced at the high frequencies. The "proximity effect" is because of the mutual inductances of parallel conductors. Both the skin effect and the proximity effect are dependent on the power system frequency, conductor size, the resistivity and the permeability of the material. The presence of harmonics in the cables influences conductor's resistance. Hence, in a non-sinusoidal supply condition, the total losses in a cable consisting of 'm' conductors can be calculated by equation (3.3) [Des02]. The extra losses cause additional heating in the cable and further increase its operating temperature which eventually can cause early aging of the cables. Moreover, the presence of harmonics in the network causes extra loading of the cables.

$$P_{cable} = \sum_{m=1}^{m} \sum_{n=1}^{40} R_{m,n} \cdot I_{m,n}^2 \tag{3.3}$$

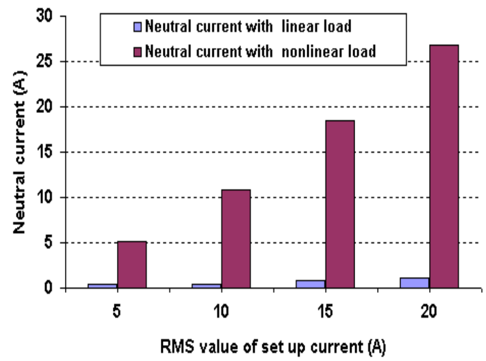
where,

- P_{cable}: active power losses in a cable/unit length
- m: number of conductors in the cable
- n: harmonic number
- $R_{m,n}$: resistance of the mth conductor per unit length for the nth order harmonic
- $I_{m,n}$: rms value of the nth harmonic current in the mth conductor

With temperature rise beyond the rated value, thermal degradation occurs in an electric device. In the reference [Des03], a 4x2.5mm^2 cable with copper conductor, PVC insulation and extruded polyethylene shield was used for testing. This is a common type of installation cable in Belgium. Fixed values of set-up currents (5A, 10A, 15A and 20A) were applied to linear as well as the non-linear loads. Incandescent lamps are used to represent the linear load, and PCs are used for non-linear loads (total harmonic current distortion of 40% approximately). Figure 3.4 (a) shows a comparison of the cable's Cu conductor temperature rise with linear and non-linear loads for different set-up currents. It was found that with increasing set-up currents, the neutral conductor's current (because of 'triple-n' harmonics) increases significantly for non-linear loads as shown in Figure 3.4 (b). This increases total heat content of the cable and raises its temperature. In the test, it was noticed that the temperature of the copper conductor of the cable exceeded its permissible temperature limit for high non-linear loads (while set-up currents are always maintained below the limit of maximum cable current capacity). This can cause life time reduction of the cable.



(a) Relative temperature rise of a cable's conductor with linear and non-linear current



(b) Increase of neutral currents with increasing fundamental current loadings

Figure 3.4. Increased temperature rise in a cable with non-linear loading

3.2.2.3 Effects on PFC capacitors

Power-factor correction (PFC) capacitors are used to draw currents with a leading phase angle to counterbalance the lagging currents drawn by the inductive loads such as an induction motor. The currents in the PFC capacitors cause extra losses when harmonics are present in the network. Furthermore, the impedance of a PFC capacitor reduces as the frequency increases, whereas the source is generally inductive which its impedance increases with frequency. Additionally, the presence of voltage harmonics in the power system increases the dielectric losses in the capacitors at high operating temperature. The dielectric loss in a capacitor is calculated by equation (3.4) [Fuc01]. Thus, the harmonics in a network can cause reduction of operational lifetime of a PFC capacitor.

$$P_{cap} = \sum_{n=1}^{n=40} C(\tan\delta)\cdot\omega_n . U_n^2 \tag{3.4}$$

where,

- $\tan\delta$: $R/(1/\omega C)$ is the loss factor

- ω_n: $2\pi f_n$ = harmonic frequency
- U_n: rms voltage of n^{th} harmonic

In electricity networks, PFC capacitors are used to improve the power factor. However, with the capacitor and the stray inductance of the network components, a parallel resonant circuit can be formed. This causes very large (often localized) harmonic voltages and currents to flow, often leading to the catastrophic failure of the capacitor system. To reduce the chance of resonances in the network, tuned PFC capacitors can be used to limit harmonic components.

3.3 Financial consequences of inadequate PQ

Power quality disturbances can have significant financial consequences for different customers. It is quite hard to estimate the correct financial losses because of inadequate PQ as many uncertainties are involved. The financial losses depend mainly on the customer category, type and nature of the activities interrupted and the customer size. In addition, the representation of the cost data in different surveys is not unique which makes it often difficult to compare financial losses for various customers. Many case studies are published about PQ cost analysis for various types of customers and some of them are discussed in this section. In contrast, very limited information is available on PQ cost for the network operators. For this reason, the CIRED/CIGRE ‘Joint Working Group’- JWG C4.107 has been formed to develop a systematic approach to estimate costs related to various PQ problems [Cir02]. This group proposed methodologies to estimate PQ costs for the customers as well as the network operators. In this thesis, based on that approach, the estimation is done to assess financial losses of PQ disturbances for the network operators.

3.3.1 PQ costs for the customers

Reference [Cir02] describes the proposal of the CIRED/CIGRE JWG 4.107 group that suggests separating various PQ related disturbances into two broad categories: (a) quasi continuous variations and (b) discrete events. Furthermore, two distinct methods of measuring the economic impact of inadequate PQ have been identified.

- The first method is the direct method, which is an analytical approach to consider the probabilities and impacts of the events. This method leads to a precise answer, but mostly it is difficult to obtain correct input values.

- The second method is an indirect method, which considers historical data for the analysis and customer's willingness to pay for solving PQ problems.

The end report of the CIRED/CIGRE JWG C4.107 group gives an overview of various PQ cost data for different countries. The survey results of the LPQI over a two years period (2003-2004) in the EU-25 countries among 62 companies from different industries and service sectors, the PQ related financial losses are estimated 151.7 thousand million euro [Tar01]. Out of this amount, 90% of the financial losses are accounted to the industries. Figure 3.5 shows the percentages of total financial losses on various PQ aspects in the EU-25 countries.

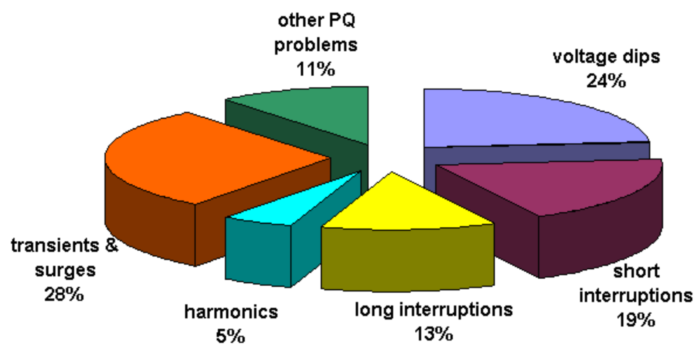


Figure 3.5. Percentage share of PQ and interruption costs EU-25 countries

Figure 3.5 shows that 56% of the total financial loss is a result of voltage dips and interruptions, while 28% of the costs are due to transients and surges. The other 16% of the financial losses are because of harmonics, flicker, earthing and EMC related problems. The cost caused by a PQ disturbance for a company consists of expenditures in various accounts as follows:

- Staff cost – this is the cost because of personnel rendered unproductive for disrupted work flow.
- Work in progress – this category includes the costs of raw material involved in production that is inevitably lost, labour costs involved in the production, extra labour needed to make up lost production, etc.
- Equipment malfunctioning – if a device is affected, the consequences can be slow down of the production process, extra 'idle' time, etc.

- Equipment damage – if essential equipment is affected, consequences can be complete damage of the device, shortening of its life time, extra maintenance, need of stand-by device, etc.
- Other costs – the costs paid for penalties due to non-delivery or late delivery, environmental fines, costs of personal injury (if any), increased insurance rate, etc.
- Specific costs – this category cost includes extra energy bill due to harmonic pollutions produced by the non-linear operation of devices, fines incurred by the utility for generating harmonic distortion at its installation. Reduction of personal working efficiency and related health problems due to flicker can also be included in this cost category.
- Savings – there are some savings in the production because of PQ disturbances. It includes the saving from the unused materials, saving from the wages that are not paid, savings on energy bill, etc.

In a typical continuous manufacturing industry, large financial losses may be incurred by lost work-in-progress (WIP) up to about one third of total PQ costs. Also, the slowing down of processes and labour costs are quite significant in this sector. In other sectors, the situation is not very clear with the labour cost and equipment related costs. In the public services like hotels and retail sectors, PQ impact is noticed as slowing down of their business activities, and can be compared in terms of revenues lost. In the industries, losses are mainly because of voltage dips, interruptions and transient surges. Figure 3.6 shows the distribution of PQ costs in various accounts in the industry and service sector, as estimated in the LPQI survey [Lpq02] for the EU-25 countries.

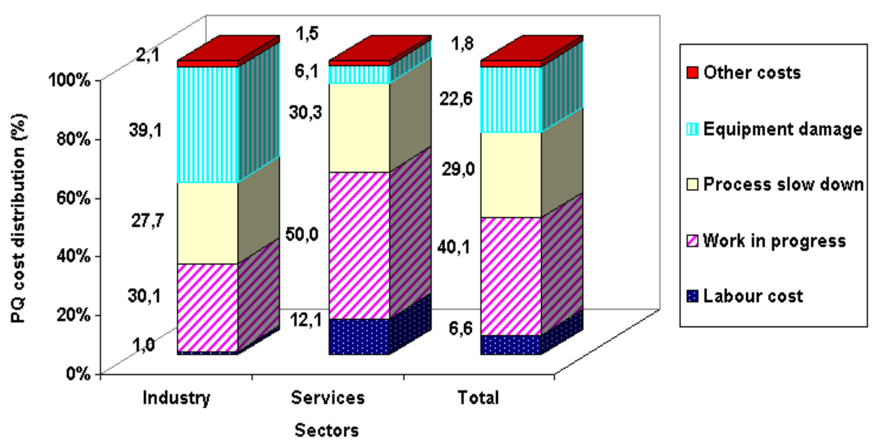


Figure 3.6. PQ cost distributions per sector in EU-25

A PQ survey was also conducted by EPRI [Epr02] through out the USA in 2000. This report stated that the US economy loses between 119 thousand million to 188 thousand million dollars per year because of power outages and various PQ related problems across all business sectors. Digital economy and continuous manufacturing are found to be the most affected sectors. Another report [Epr01] estimated the costs of momentary and 1 hour outages in various sectors of the USA. Similar type of survey was also conducted by UMIST, UK in 1992 [Kar01] to assess the cost of outage for various durations to different customer groups. Both those findings are compared in Table 3.2.

Table 3.2. Costs of outages as experienced by different customer groups [Epr01], [Kar01]

Sector	Survey done for UK customers Costs per outage per customer (€/event/customer)[1]		Survey done for US customers Costs per outage per customer (€/event/customer)[2]	
	momentary	*1 hour*	*momentary*	*1 hour*
Residential	-	0.84	1.63	2.02
Commercial	13.8	127.2	454	664
Industrial	1440	5160	1420	2375

Note: [1,2] Various original cost data are converted to equivalent euro for better comparison. The conversion rates are taken as: 1 £ = 1.20 € and 1 $=0.75 €.

It shows that the outage costs for different sectors in the UK and the US vary significantly, except for the industrial customers suffering momentary outages. It is quite difficult to conclude in general on the financial losses in different industries due to inadequate PQ as the cost of outage due to interruption depend largely on the customer's installation characteristics and the devices involved. Among the industries and commercial sectors, there can be a wide range of variety in device usages and their sensitivity to PQ problems. Therefore, a proper evaluation method is required for correct interpretation and comparison of PQ cost data.

3.3.1.1 Financial losses caused by process failure

When a disturbance occurs in an industrial process plant because of a voltage dip event or a short interruption, it can cause appreciable financial losses for the plant owner. The financial losses for an industrial customer because of a PQ event can be determined by equation (3.5) [Mil01].

$$CL = EE + (RL - VE) \cdot (r + s) + FC \tag{3.5}$$

where,

- CL: combined loss

- EE: extra expenses incurred because of failure (€/per failure)
- RL: revenue lost per hour of plant downtime (€/per hour)
- VE: variable expenses saved during plant downtime (€/per hour)
- r: repair or replacement time after a failure (hours)
- s: plant start-up time after a failure (hours)
- FC: any fixed costs (€/per failure)

Different case studies show that the financial loss due to a voltage dip is highly influenced by the customer's characteristics such as load composition and process layout at the plant site, etc. Moreover, the financial data are presented in different ways in various published case studies. For example, sometimes the basis of representation is 'per event cost', sometimes 'per kVA' or 'total installed capacity' of the plant, and sometimes 'per hour cost' or 'total cost in a year' etc. Figure 3.7 [And01] provides a range of values for the financial losses due to voltage dips in different sectors that can be used for macro-level planning purpose. The 4th bench marking report of CEER [Cee01] summarizes many examples of case studies on indicative values of voltage dip related costs in different countries of the world.

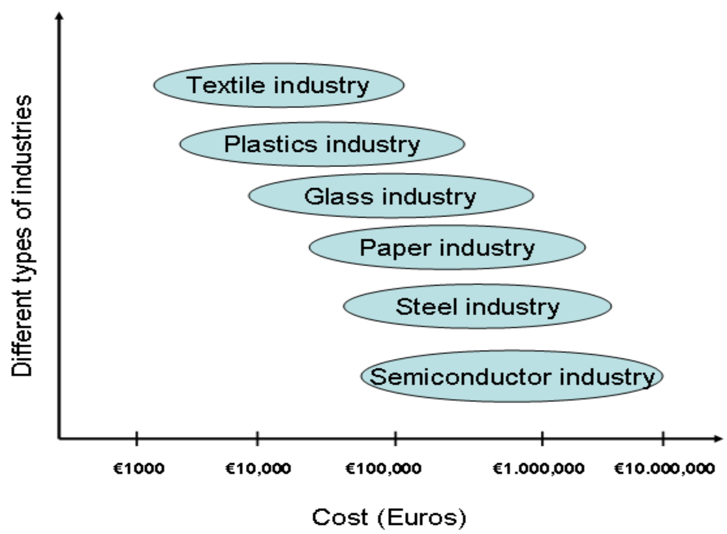


Figure 3.7. Indicative financial losses in different sectors due to various voltage dip related events [And01]

3.3.1.2 Financial losses caused by harmonics

Both the harmonic voltages and harmonic currents can cause failure or abnormal operation of a customer's device and can have financial consequences to the customer. Moreover, when a customer has his own transformer, feeding cable and/or PFC capacitors at his installation, he will suffer harmonics related problems in those devices too. Generally, harmonics cause three types of problems:

- Additional energy losses (in the customer's transformers, connection cables, motors, neutral conductors, etc.)
- Premature aging of a device or a component
- Mal-operation of a device

The present worth of the operating costs of all components (represented as 'Dw') in a considered installation for a period of N_T can be estimated as shown in equation (3.6) [Car01] for a harmonics-rich environment.

$$Dw = \sum_{y=1}^{N_T} (Dw)_{y,pw} = \sum_{y=1}^{N_T} \frac{(Dw)_y}{(1+\alpha)^{y-1}} \tag{3.6}$$

$(Dw)_y$ is the sum of the operating costs for all components at the customer's installation in a specific year 'y' under consideration. 'α' is the present worth discount rate and N_T is the period of years under consideration. Reference [Key01] gives an estimation of harmonics related losses in an office building. In this case, about 60kW electronic loads (mainly computers) were connected that operated 12 hours per day for 365 days in a year. It was found from the analysis that an additional energy loss of 21.9MWh per year was occurring due to harmonics at the customer's installation. Hence, those offices were paying extra energy bills of 2100 dollars each year (which is approximately 8% of the total energy bill). It was also observed that the substation transformer became overloaded when supplying to only 50% of its capacity equivalent non-linear loads.

The premature aging caused by harmonic distortion involves incremental investment costs $(Da)_k$ for the k^{th} device during the observation period. This is shown by equation (3.7) [Car01], where $C_{k,ns}$ and $C_{k,s}$ are the present worth values of total costs for buying the k^{th} device during its life in non-sinusoidal and sinusoidal operating conditions respectively.

$$(Da_k)_{pw} = (C_{k,ns})_{pw} - (C_{k,s})_{pw} \tag{3.7}$$

The evaluation of costs because of abnormal operation is the most complex. Also, it is often difficult to determine if the degradation of a device's performance is only due to harmonics or other PQ disturbances. However, there are references which identify some cases in which device's performance degradation is solely due to harmonics such as electronic equipment operating with voltage zero-crossing, meters, lighting devices, etc. To estimate the cost of a device's mal-operation, it is required to get information of that device's characteristic under harmonic conditions, the activity for which the device is used and the relative importance of it in that process activity.

In most of the cases it is difficult to gather all information related to costs as harmonics have mainly long term impacts and have relatively less visual immediate effects. It involves financial analysis of all the effects that lead to abnormal operation of the process/activity due to the mal-operation of a specific device. Reference [Car01] describes an investigation on a wide range of devices used in the commercial and industrial sectors and has concluded that estimating the cost of abnormal operation requires extensive information on a device's behaviour in the presence of harmonics, the activity in which the device is used and the economic values of all items contributing to lower productivity.

3.3.1.3 Consequences of flicker

Light flicker is considered to be an annoying problem for the customers. Most of the times, it does not have high direct financial impact. However, it causes inconveniences to the people when frequent flickering (of light and computer screens) occurs at their work-places or homes. From field studies it was found that flicker can cause specific effects, leading to severe headache, epilepsy and other vision related illness. Therefore, the affected people have to go for medical supervisions that can involve some monetary expenses. It was found from the LPQI survey [Lpq02] that the cost consequences due to flicker related problems can be up to 10% percent of an organization's employment costs.

3.3.2 PQ costs for the network operators

It is noticed that the network components experience problems of extra losses, additional loading, premature aging and abnormal operation of a protective device or control equipment because of a PQ disturbance (such as harmonics). Light flicker is another PQ problem that has drawn attention even though it has lesser financial impacts than other PQ problems. It can cause bad reputation of the network operator as a service provider in the electricity business. Moreover, when a customer complains to the network operator about flicker problem, then an engineer has to visit the site to analyze the problem to take necessary actions. These activities cause extra cost for the network operator. A voltage dip can cause high financial losses to the customers. A network operator can also have monetary losses when a deep voltage dip occurs in the network. He might have to manually switch in the network parts again and he may have to pay some penalties according to rules set by the regulator.

In an existing network, PQ performance can be improved by rearranging and reinforcing the network. Regular maintenance strategy can also be adopted to reduce failure rate and enhance lifetime of network components. Implementing a mitigation measure is another method to increase PQ performance level in the network. The decision on adapting one of those strategies can be done after analyzing PQ problems experienced by the customers and their relative financial losses in comparison to the actions required. Furthermore, it is also possible to tighten the immunity standard of devices to make them less sensitive to PQ disturbances. This requires regulatory change and will increase their manufacturing costs. PQ cost analysis in the networks would involve the following aspects:

- Network's mitigation cost (such as changes in network infrastructure, implementing an extra feeder, placing a PQ mitigation device, etc.).
- Extra energy losses in the network components (such as cables, transformers etc.) due to inadequate PQ of the network.
- Evaluation of cost of higher quality by introducing individual 'PQ contract' schemes.
- Extra costs to handle customer's complaints (effort in finding the problem, network intervention for modification and improvement).
- Customer's willingness to pay extra money (and tariff) to minimize PQ disturbances at their installations.
- Costs aspects that concern manufacturers to design equipment for improving PQ (emission and immunity of a device).
- Total market size (that means the number of customers involved) for a specific PQ solution under consideration.

3.3.2.1 Harmonics in the network

Field measurements show that most of the components (transformers, cables etc.) in the Dutch network are loaded quite below their nominal value. De-rating, mal-operation or premature failure of the network devices happens seldom in the Dutch networks, except at few local incidents. However, it is clear that extra losses (and reduction of energy efficiency) are occurring in the network components because of additional harmonic currents in the network. In future, with the usage of more power electronic devices, harmonics can become a problem in the networks. Regular PQ monitoring can probably indicate actual changing PQ situations in the network.

The cost of nuisance tripping of a protection device (because of harmonics) can be significant as it can cause unplanned supply interruption. The costs of reduced equipment lifetime can also be very high, especially for the expensive equipment such as transformers, network cables etc. A transformer is expected to have a lifetime of 30-40 years. It might be the case that it has to be replaced 10 years earlier due to its early aging because of harmonic distortions in the network. Most of the time, effects of harmonics are hidden and not immediately visible. Various costs of harmonics are: a) operating cost (e.g. increased power losses), b) aging cost, and c) cost due to device's mal-operation. All these harmonics related costs can be calculated as described in section 3.3.1.2.

When large harmonic currents flow into the network, the network operators can notice its impacts immediately as the network components may get overloaded and overheated leading to excess apparent power demand and/or a mal-operation of network relays. Reference [Pap01] estimates around 0.15%-0.20% increase in total losses in the network components (lines and transformers) because of existing level of harmonics in the Greek networks. A field measurement was conducted in the Hydro-Quebec's distribution network of Canada during 1998-2000. It was estimated that the harmonic losses in their MV and LV distribution networks would be around 0.15% of the total energy used [Cir02] under the condition of a harmonic voltage distortion of 100% of the IEC 61000-3-6 [Iec11] standard planning level value. A field survey was done for a test LV network in the Netherlands too [Hod01]. It was estimated that the harmonic energy losses in the LV cables were approximately 5.2% of the total fundamental losses in a year, whereas that for the MV/LV substation transformer was 2.2% of its fundamental losses. Also, it was found that the total harmonic losses for that LV network were 0.06% of the total demand (of 860MWh) in a year. However, this estimation is done only for a small part of the LV distribution network that is newly built and consists of high capacity underground cables. In chapter 6 of this thesis, harmonics related losses in a typical Dutch LV network are further discussed.

3.3.2.2 Consequences of voltage dips

A voltage dip event can disrupt the operation of sensitive devices that might lead to partial or complete interruption of the customer's power supply. The effects of voltage dips mainly depend on the type of customer, the usage of the power supply and the electricity demand of the installation. A voltage dip event can cause substantial financial losses to the industrial customers as described in section 4.3.1. Depending on the real process outage time, their type of operation and size of the industry, the financial losses can vary largely. Generally, the industrial customers demand large quantities of electricity. Therefore, when a voltage dip event in the network disrupts the power supply of many industries in a specific part of the network, it can have significant financial impacts to the respective electricity service providers (due to loss of 'kWh units' of electricity tariff).

3.4 Commercial quality aspects

Another aspect that has grown interest in the electricity service sector is the ‘customer satisfaction’ index. It depends mainly on the customers’ and the network operator’s mutual relationships and indicates the commercial quality of the electric supply. The commercial quality generally relates to the individual agreement between the network operator and the customer (about an electric supply). However, only some of these relations can be measured and regulated through standards or other legal instruments. When more customers are not satisfied with the PQ of a supply, the network operator may lose the trust of customers. Under a certain situation, the national regulators might take action against the network operator. Presently, in many countries, the network operators are obliged to verify PQ complaints of an individual customer. They should provide a voltage at the customer’s POC that fulfils the applicable standard requirements. Thus, it is a challenge for the network operator to maintain both the technical and commercial quality to satisfy a customers’ need. However, the customer's responsibility regarding PQ requirements at a POC are not yet well defined.

When a customer buys a service, product or component from the market, the ‘brand name’ plays an important role in decision making of his purchase. For a device when sold in the market, the device manufacturer should guarantee its performance as per the relevant product standards (of IEC or other internationally recognized standards) under defined voltage condition. However, in reality, the devices have to operate in a network environment with distorted supply voltage condition. Therefore, the connected devices generate different harmonic currents than at a clean voltage condition. In certain situations, some specific order harmonic current can exceed the limit of standard. Also, it produces extra losses, may operate abnormally that leads to the decrement of its lifetime. All these can bring doubts in the customer’s mind about the quality of device that may affect the commercial quality aspect of the product manufacturer.

3.5 Available mitigation measures

A vast range of potential solutions, with varying degrees of cost and effectiveness, are available in the market to mitigate various PQ problems. The solutions can be applied at different voltage levels and locations within the power system: at the network utility level, at the end user’s point of connection or within the customer's installation. In Figure 3.8 [Bha04], various locations where mitigation measures can be implemented are shown.

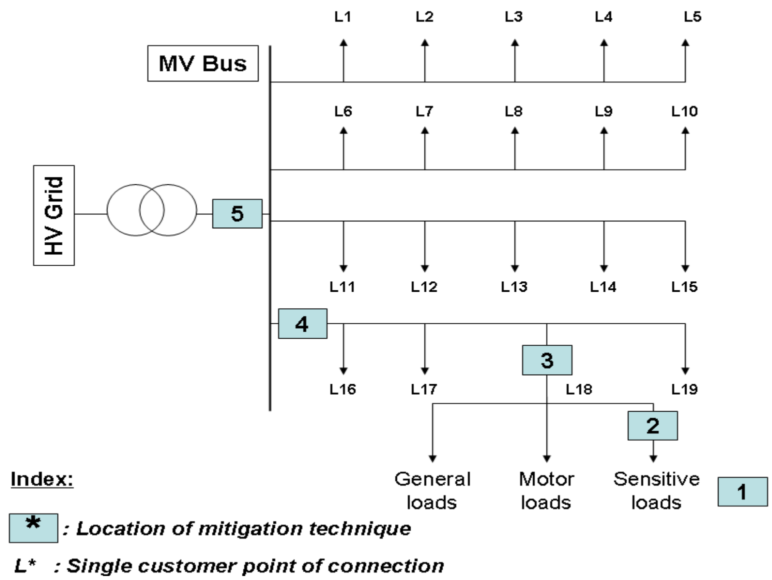


Figure 3.8. Mitigation measures used in various locations in a power system

Modification in the device itself (location 1 of Figure 3.8) is the easiest solution to solve a PQ problem. It means that the device is more immune to PQ disturbances. Also, it can be designed to produce less PQ emission. This is not always a feasible option as it demands a stricter specification, and custom-made device that might not be readily available in the market. But, if more numbers of similar types of devices suffer from a particular PQ problem or produce significant PQ emissions or if more customers require a particular type of device, the device manufacturer would probably be ready to manufacture it. The PQ mitigation measures that are commonly used in the industries and service sectors of the European countries [Lpq02] are as follows:

- Uninterrupted power supply
- On-site generator
- Harmonic filters
- Isolation transformers
- Line conditioners / active filters
- Multiple independent feeder
- Oversizing equipment
- Shielding and grounding

- Static transfer switch
- Static Var compensator
- Surge protection
- Dynamic voltage stabilizers and restorers

3.5.1 Customer-side solutions

Mitigation measures can be taken at the source of problem, which is in many cases in the devices located at the customer's installation. This refers to the mitigation measure at 'location 1' of Figure 3.8. When a (heavy or fluctuating) load starts, it often causes large voltage drops in the installation, leading to flicker problem. To solve this, the following measures can be taken:

- Decrease the inrush current of the load start to keep the amplitude of voltage drop with in the allowable limit (adopting soft-starter)
- Avoid fast voltage change by flattening the rise time of a motor start
- Fly wheels for compensation of impulsive load changes
- Upstream connection of a shunt reactor or parallel connection of controlled reactive loads
- Interlocking to avoid overlapping effect (prevents starting of multiple loads simultaneously)
- Load balancing in the installation - by adopting step by step method to compensate voltage fluctuation cause by different types of loads

A customer may wish to implement a PQ solution at his installation to protect all critical loads ('location 2' of Figure 3.8) that are fed by a common connection feeder. He may also choose to limit the flicker problem for the whole installation ('location 3' of Figure 3.8). The following options are possible as a solution at the customer’s side for flicker:

- Install a dynamic flicker compensator (DFC) at the installation. The tasks of the compensator are to reduce relative voltage fluctuations to zero and dynamic load balancing. It simultaneously superposes a pulsed voltage change with a compensating pulsed voltage change of opposite polarity to bring voltage fluctuation to zero. A dynamic flicker compensator also controls the starting instances of various loads to optimize 'overlapping' effects of several flicker generating sources in the installation.
- Use a thyristor controlled reactor (TCR) as a flicker compensation method. In this method, reactive power of a load is supplemented with switchable inductances to a maximum inductive reactive power, and

that can further be compensated with fixed capacitor batteries. The compensation power can be made available through filter circuits. A system consisting of TCR and filter circuits is known as SVC (static Var compensator). The quality of a SVC for flicker compensation is determined by the dynamic behaviour. The response time is in the range of millisecond.

- Having thyristor switched capacitors (TSC) is another flicker compensation method. The demand for capacitive reactive power in the installation can be met by dynamically switching the capacitors. The capacitors are pre-charged to a suitable start voltage to reduce their switching mode current demands. Therefore, generally a switching delay happens that can limit the operational dynamics of a TSC as a flicker compensator.
- An alternative option can be the replacement of all incandescent lamps of the customer's installation by energy saving lamps, or using modern lighting technologies that are less sensitive to flicker. Figure 3.9 [Cai01] shows the flicker response characteristics of an incandescent lamp and that of a fluorescent lamp, and some energy saving lamps. It shows that energy savings lamps can tolerate higher voltage variations in comparison to an incandescent lamp and thus are (5 to 8 times) less sensitive to light flicker.

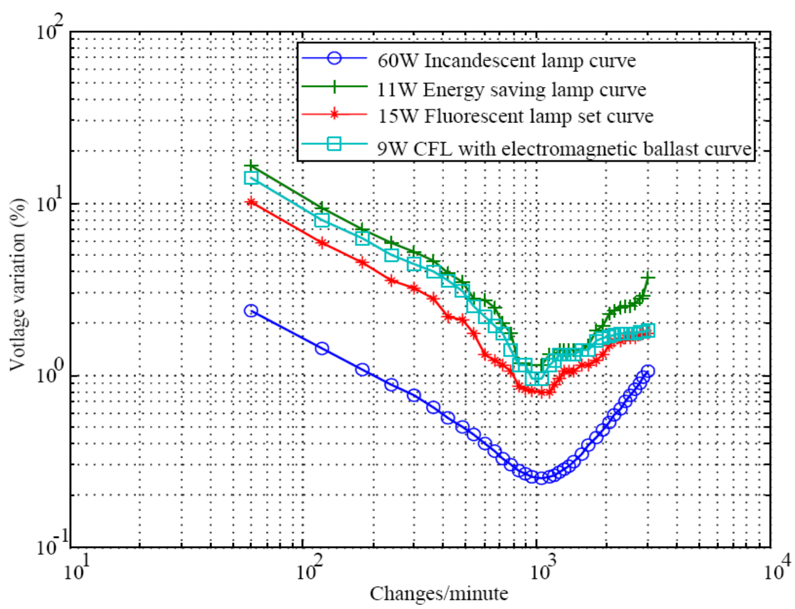


Figure 3.9. Instantaneous flicker sensation curves for different lamp types due to sinusoidal input voltage modulation

Harmonic currents are mainly produced by the customer's non-linear devices. Therefore, remedial measures are taken mainly at the customer's installation. Various harmonic mitigation measures are possible such as:

- Limiting the harmonic currents by using equipment with low harmonic emissions. This will reduce the total harmonic current distortion (THD_I) at a customer's installation. This refers to a mitigation measure applied at 'location 1' of Figure 3.8.
- Separation of non-linear loads and sensitive loads and supply them from different feeders can be an option to avoid mixing up harmonic currents in the installation. Further, the harmonics produced by the non-linear loads can be mitigated by adopting suitable mitigation measure.
- De-rating or over-sizing of equipment can also be done to allow harmonic currents to flow through them, without exceeding their capacity limits.

Harmonic mitigation measures can also be applied at locations 2 and 3 of Figure 3.8 as follows:

- Harmonic currents leaving a POC can be controlled by implementing a harmonic absorption system at the installation. It is a series-resonant circuit with a resonance frequency close to or equal to the considered harmonic frequency. Absorption systems consist of several such circuits, which are tuned to various harmonic frequencies of order ($6n\pm1$, where 'n' is harmonic number). It is used to absorb power at an unwanted signal frequency by providing low impedance to ground at that frequency. The purpose of an absorption system is to reduce the distortion of the network voltage.
- Active harmonics compensators can constantly analyse the load current and accordingly feed a remedial compensation current to smoothen the total supply current drawn by the installation at its POC. Figure 3.10 shows typical configuration of an active filter. It consists of a coupling reactor (for higher network voltages also a coupling transformer), an IGBT power circuit and a DC intermediate circuit capacitor. The IGBT-inverter and controller with fast digital signal processors enable the dynamic compensation of harmonics and reactive power too. Active filters can generate both inductive and capacitive reactive power as per demand and thus can control the power factor at the connection point. It can also reduce flicker severity at the installation.

- Harmonic filtering can be done by using a ‘hybrid filter’ which is a combination of an active and a passive filter.

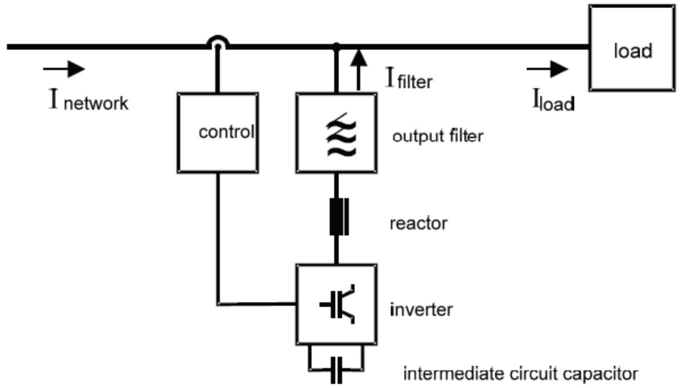


Figure 3.10. Schematics of a typical active filter

To avoid voltage dip related inconveniences at an installation, several measures can be applied (at location 1 and 2 of Figure 3.8) as discussed below:

- Process modification is the cheapest solution to reduce process outage costs [Did02]. Automatic restart of equipment after a voltage dip event can be used for motors that are not speed critical (such as fans, pumps). A variable speed drive equipped with 'restart on the fly' detects the voltage recovery moment after a voltage dip event and reaccelerates immediately. This option can be applied to motors that can tolerate only small speed deviation. Further, it is noticed that a slight adjustment of the under-voltage relay protection setting can eliminate many outages of process devices. However, the high charging current drawn from the supply terminal during voltage recovery can damage sensitive device (such as a variable speed drive). Therefore, extra reactance must be connected in series with the protection device to avoid damage.
- Kinetic buffering is a mitigation measure that can be applied at a VSD terminal that has a DC bus to which many motors are also connected. During a voltage dip event, one or more of the motors can be operated in generator modes and feeds back energy to the DC bus to keep its voltage at a level higher than that of the settings of an under-voltage protection relay. Thus, process outage can be prevented. Similar type of mitigation measure is DC-bus buffering through an additional energy storage source (such as capacitors).

- Boost converters are used to keep up the DC bus of a VSD at its rated value. A boost converter module consists of a rectifier and an actual boost converter which is connected in parallel to the VSD's original rectifier. Commercially available boost converters with a power rating equal to the active power demand of the VSD are available to withstand voltage dips of 50% magnitude for duration of 2 seconds.
- An active front end (AFE) is a voltage rectifier containing active components such as IGBTs. Bi-directional power flow is possible in an AFE and it can enhance the immunity of a system for voltage dips (by providing active power). The maximum voltage dip that can be mitigated by an AFE depends on the short-time overload current factor of the IGBTs. Implementation of an AFE can also reduce harmonic distortion at the installation.

A mitigation measure can be applied at 'location 3' of Figure 3.8 too for protecting the whole installation from voltage dips.

- Immunization against all dips can be achieved by implementing flywheel or a static UPS at the installation.
- When a customer wants to immunize his installation against some of the dips (that are very critical for his plant), series controller such as a dynamic voltage restorer (DVR) with or without a storage device can be used. A DVR monitors each phase voltage at the POC. In case of a dip, it calculates the required correction voltage needed to minimize the voltage dip and to keep the operation of the process in a safe region of operation. A typical DVR with a transformer but without energy storage can compensate a maximum of 30% voltage dip. Therefore, if a process can operate at 80% of its normal rated voltage, a DVR can support up to 50% of voltage at the installation. Thus, it can enhance the process's voltage dip immunity. Figure 3.11 shows a DVR with energy storage that is generally used to support large loads (>1MW). The transformer is connected in series with the connection cable of the installation.

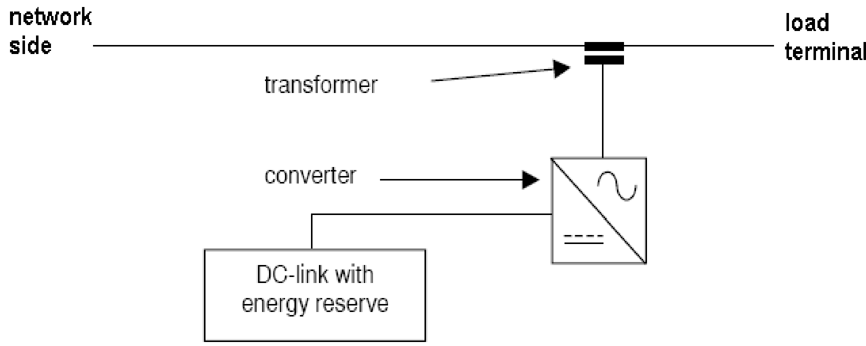


Figure 3.11. Scheme of a typical DVR with an energy storage unit

- Shunt controllers can be installed in parallel to the load to mitigate shallow voltage dips. A statcom is a typical application of a shunt controller that injects current at the POC during a voltage dip event. However, a statcom without active storage has limited dip immunization capability as its operational performance depends on the network's impedance and its own current injection capacity. If a statcom cannot supply the required power to mitigate a voltage dip, active energy storage can be added to the statcom, resulting in an increase of its voltage dip immunization performance. Alternatively, a shunt connected synchronous machine can be used to supply large reactive power and to mitigate voltage dips at the installation.
- Further, the on-site generators can be used as back-up emergency generator to provide power to the loads in case of islanded operation from the network. However, it requires additional control and protection devices for its operation.

3.5.2 Network-side solutions

A mitigation measure can also be applied in the network to improve the PQ performance of many customers. Referring to Figure 3.8, a mitigation measure can be implemented in a feeder at 'location 4', when many customers connected at the same feeder complain about PQ problems. On the other hand, if customers of different feeders (but fed from the same substation) in the network, complain about PQ disturbances, the network operator might adopt mitigation measure at 'location 5' of Figure 3.8. PQ mitigation measures in the network often require major reconfiguration and rearrangement of the network topology and are quite expensive too. The following options are possible:

- Incorporating energy storage devices (such as: battery, super capacitor, flywheel, etc).
- Implementing an extra parallel cable or increasing the cross section of the feeders.
- Implementing an additional transformer or replacing the existing transformer with a lower impedance transformer.
- Changing in the protection strategy of the network.
- Increasing the short-circuit power level in the network by changing the point of common coupling to a higher voltage level.
- Installing a zig-zag transformer that has cancellation effect for the 'triple n' harmonics.

All the above possibilities are challenges to the network operator to improve the PQ in the network. The remedial measure should be accompanied by careful network investigations. Therefore, adequate planning and design analysis is essential to adopt a suitable solution.

3.5.3 Mitigation measures developed under KTI project

The ‘Theme-2’ [Hes02] of the KTI project investigated possibilities to minimize the impact of resonances and harmonic distortions by using additional functionalities of the power electronics inverters that are connected in the low voltage network. A control strategy is developed for grid connected DG that minimizes harmonic voltage distortion. A versatile inverter with a ‘digital signal processor (DSP)’ structure is programmed and built, and validated in laboratory. The results of the simulations show that the studied extra services perform satisfactorily. These services virtually shift resonances towards a higher harmonic range and damp the resonance peaks to a lower level.

In the ‘Theme-3’ [Wan02] of the KTI project, the flexible operation of grid-interfacing converters in distribution networks was investigated for the purpose of voltage quality enhancement at both the network and the customer sides. The research is carried out in a bottom-up fashion: from the low-level power electronics control, through the realization of individual system functionality, finally arriving at system-level concepts and implementation. The introduction of multi-level control objective made that the proposed system can ride through voltage disturbances, enhances the network's voltage quality for local loads, and continues power transfer to and from the network during shallow dips.

Both proposed methods developed in the above two researches can be applied as mitigation measures to solve various PQ related problems in the network and at a customer's POC respectively.

3.5.4 Cost of mitigation measures

Each PQ solution technology needs to be evaluated in terms of cost and effectiveness. In broad terms, the solution cost should include initial procurement and installation expenses, operating and maintenance expenses, and any disposal and/or salvage value considerations. A thorough evaluation would include other costs such as real-estate or space-related expenses and tax considerations. Table 3.3 gives an indication of the approximate costs of various PQ mitigation measures.

Table 3.3: Approximate costs of some PQ mitigation devices [Hul02], [Did03], [Sod01], [Ash01]

Problem	Measure	Estimated cost
Voltage dip	Sensitive devices can be protected by DVR or an AFE	• DVR (50% voltage boost): 190 €/kVA • AFE (75kVA - 250kVA): €15,000-35,000
	Sensitive equipment / installation can also be protected with a static UPS	• 270-400 s/kW
Flicker	Static Var compensator (SVC)	30 €/kVAr
Harmonics	Install filter	The 25A filter costs €3,500 (approx.) + installation charge. Reference [Ash01] indicates the costs as follows: • Active filter (150-225 €/A) • Passive filter: detuned €30/kVAr, and tuned €90/kVAr

Besides the costs, the solution effectiveness of each alternative must be quantified in terms of the performance improvement that can be achieved. To attain the most economic solution to solve a PQ problem, various costs and returns must be analyzed in detail and the pay back period, internal rate of return or net present values for each solution should be calculated. The economic analysis of a network's PQ cost can be done at two levels:

- Individual level – investment required to provide a desired PQ level at a customer’s or a group of customers’ terminals (at a point of common coupling or at a POC).
- Global level – investment requirements to maintain a specified PQ level in the network.

Hence, it can be concluded that finding out the most economical solution for a PQ problem is an important but very difficult decision. A detailed cost-benefit analysis for all the involved parties should be done to reach at an optimum solution.

3.6 Costs and benefits of PQ solutions

Various available PQ mitigation options need to be evaluated in a systematic manner considering the economical impacts to all parties involved and the costs associated with different alternatives to improve the PQ performance. When PQ problems arise in the network and customers complain about them, the network operator should first do a survey to locate the sources of problems. When a single or a few customers complain, the network operator can handle the situation by performing a local field survey and consult the customer to take a suitable action. However, when the network operator receives many complaints from customers, he should analyze the problem more in detail. After the analysis, it may be possible to determine the parties that are responsible for the problem in the network. Depending on the situation, the network operator may ask the affected customer(s) either to install a mitigation device(s) at the installation(s) or to pay for the solution. The network operator must invest money on a mitigation measure if the PQ disturbance is caused by a network's internal problem (such as large network impedance, high background distortion or if the network is connected to a weak grid) and it is affecting (a large group of) customer(s) in the network. Thus, the following situations are possible while deciding on an investment for a PQ solution:

- A mitigation measure is chosen at the affected customer’s installation and the investment is also done by the customer.
- The mitigation measure is adopted at the customer's installation, but the investment is done by the network operator.
- A mitigation measure can be implemented in the network (such as: network reconfiguration, laying an extra cable, installing storage or

filters, etc.), while the investment can be shared by the network operator and the customer, depending on mutual agreements.

A ‘cost-benefit’ analysis using the ‘net present value (NPV)’ method is commonly used to make a decision on an investment. NPV is the difference between the investment’s present market value and its cost [Did03]. The NPV calculation uses a discount rate, which is the rate at which the capital needed for the project could be returned if it is invested in an alternative venture. It is also called ‘opportunity cost of the capital’. The calculation of NPV for an initial investment C_0 to solve a PQ problem is shown in (3.8) [Cir02]:

$$NPV = -C_i + \sum_{t=0}^{n} \frac{(C_{b,t} - C_{c,t})}{[(1+r)\cdot(1+i)]^t} \cdot (1+e)^t \tag{3.8}$$

where,

- C_i: initial capital investment
- $C_{b,t}$: benefit component occurring at the beginning of time period ‘t’
- $C_{c,t}$:cost component occurring at beginning of time period ‘t’
- n: number of time periods, usually in years
- e: escalation rate of money that occurs due to inflation or the percentage of annual change for service prices or cost of goods
- r: discount rate adjusted for inflation
- i: inflation rate

To make a decision on an investment for a PQ mitigation measure, a detailed economic analysis has to be done considering various cost reduction possibilities. All the alternative mitigation options have to be compared on an equal basis. This decision process is called ‘capital budgeting’. In this method, all the project’s cash flows are calculated considering the ‘time value of money’. It is also important to identify all critical factors that influence the cash flows and the degree of accuracy in forecasting various cost figures. The main elements of an investment to be investigated are:

- The capital cost or initial investment (for PQ mitigation).
- The actual cost of capital (that depends on discount rate).
- Cost saving (because of PQ mitigation measures).
- Operating and maintenance cost for the investment.
- Economic life time of the investment.

The main purpose of the ‘cost-benefit’ analysis is to look at the project’s performance over time. The typical value of the discount rate lies between 5-15%.

The projects with a positive NPV are expected to increase the value of investment and are considered to be economically feasible. When choosing among mutually exclusive projects, the project with the largest positive NPV should be selected.

Alternatives to the NPV method are the payback method and the internal rate of return (IRR) method [Did03]. The payback method is a very simple analysis tool but it is considered to be inferior to the NPV method. The payback method does not take into account any cash flow after the payback time. Thus, this method can lead to a wrong financial decision for a project investment plan. The IRR method considers all marginal cash flows during an investment project. The IRR is defined as the discount rate at which the NPV is equal to zero. The IRR method gives an equivalent result as the NPV method when deciding on an investment for a project.

A decision on an (economically) optimum PQ solution can be taken after comparing the investments of the customers and the network operator, with reference to one customer. Let's assume that a single customer's investment is '$NPV_{customer}$' for solving a PQ problem at his installation. On the other hand, when the PQ mitigation is done in the network and the investment required is '$NPV_{network}$' that can solve PQ problems of 'x' number of customers connected to the network. The parameter 'x' also includes the customers that can probably be benefitted in the future because of the implementation of a mitigation measure in the network that can improve PQ of the supplied electricity. Equation (3.9) [Lab03] shows that both the above NPV values should be compared to reach an optimum decision about an investment.

$$(NPV_{network} \cdot K_{exp})/x \Leftrightarrow NPV_{customer} \tag{3.9}$$

K_{exp} is a factor which gives a weighting value based on the network operator's experience for handling and solving similar kind of network related problems. Therefore, 'K_{exp}' value is taken smaller than '1', considering that PQ mitigation in the network side is more effective and will be less expensive (on 'per customer' basis) as it can benefit many installations in the network. Hence, network based PQ mitigation investment per benefitted installation will generally be smaller than that of PQ mitigation applied at a single customer's installation. From a societal point of view, this mitigation measure is commonly the most optimum solution.

Reference [Did02] illustrates some case studies on cost-benefit analysis in solving voltage dip problems with variable speed drives and various mitigation measures. At present the available standards do not give any specific limit for voltage dips in the network. Also, it is expensive to eliminate voltage dip events completely from the network. When a customer complains about a voltage dip, often he is advised to install a mitigation device in his installation (at his own cost). If a group of customers in a specific region of the network often suffer voltage dip problems, they can ask the network operator for a better power supply (such as a special ‘PQ contract’), install PQ mitigation devices in the network, or they can improve their own installations' voltage tolerance limits by installing more immune devices. The dispute between the network operator and the customers can be solved only after conducting a detailed technical and financial analysis. PQ related responsibility sharing issues in the network is further discussed in chapter 6 of this thesis.

Cost-benefit analysis on harmonics in the network is given in references [Key01], [Ash01]. Various harmonics mitigation options are evaluated and the optimum solution is proposed. Presently, introduction of a harmonics related penalty cost is considered as an option by some of the network operators in the world. However, no such clause is yet defined in the regulation or any standard. In chapter 6, some example case studies are described where cost-benefit analyses are done for the selection of a suitable PQ mitigation device.

3.7 Summary and conclusions

PQ problems such as voltage dips and harmonics can have significant techno-economic impacts to the customers and the network operators. It was found from the LPQI survey (2004) in the EU-25 countries that electronic equipment, electrical motors, variable speed drives and static converters are the most affected equipment in the industries. The other affected devices are network cables, capacitors, lighting equipment and relay contactors. Estimating the financial losses of a customer because of inadequate PQ is quite complicated as it includes various direct (immediately visible) costs and indirect (long-term) costs. In this chapter, theoretical estimations of costs related to voltage dips and harmonics at a customer's installation are described. It was noticed that the network operators can also have significant inconveniences because of inadequate PQ in the network. The network components suffer extra losses, overloading, reduced operational efficiency, abnormal tripping and premature failure because of harmonics in the network. Some reference case studies are mentioned where inadequate PQ related financial losses for the customers and network operators are analysed. It was noticed that flicker is technically not a significant problem for the network. However, when the customers often complain about light flicker problem to the network operators, it can lead to some financial consequences. The ‘commercial quality’ aspect of the electricity is also briefly discussed that indicates a customer’s satisfaction on the quality of electricity service provided by the network operator.

In this chapter, various PQ mitigations measures are briefly described. As most of the PQ mitigation measures are quite costly, any investment decision requires a detailed cost-benefit analysis, considering the impacts on different affected / interested parties in the network. In the present electricity business, diseconomy of PQ is an important discussion topic. In many cases, the customers (have to) invest for the mitigation measure at their installations to avoid PQ related inconveniences. However, the source of problem can be elsewhere in the network or at some other customer's premise or from a specific device connected to the network. Therefore, in certain situations, the affected customer may not be responsible for the originated PQ disturbance. In the last couple of years, electricity regulators of different countries of the world have observed such type of conflict situations. Also, some cases were noticed where the involved parties have approached the legal court to have justice about their rights. Therefore, PQ has become a legal issue too. The responsibility sharing of a PQ disturbance, its techno-economic impacts and the choice of suitable mitigation measure are very complex and require detailed investigation. In chapter 6, PQ responsibility sharing among the involved parties is discussed in more detail. Additionally, example case studies are shown in which the ‘net present value’ method is utilized as a decision making tool for investment analysis on a PQ mitigation measure at a customer's installation.

Chapter 4

An evaluation of PQ in the Dutch networks

4.1 Introduction

This chapter consists of various simulations results and field measurements that are done for the Dutch network. The modelled LV and MV networks of the Netherlands, discussed in chapter 2, are used for simulation purposes. The flicker and harmonic problems are simulated on the modelled LV network to analyse the worst and average PQ situations in the Dutch networks. Further, the simulation results are compared with the field measurements obtained from the national Power Quality Monitoring (PQM) campaign and the PQ data obtained from the KTI project. In addition, voltage dip simulation is done on the modelled MV network to estimate the expected number of voltage dips in a year at a MV customer's installation. Field results on the number of voltage dips experienced by some customers are also presented. All the simulations results can be utilized as indication for the (future) PQ situation at the customer's POC of a typical network. Furthermore, the simulation results are compared with the limits of the present standards.

4.2 Flicker simulations

In this section, the simulation and some measurement results regarding flicker severity in a network are discussed. The simulation is done on the LV model network described in chapter 2. In a real network, flicker is generated by the operations of industrial loads in the MV and HV network and from various disturbing loads (such as elevators, air conditioners, welding device, etc.) in the LV network. It propagates along the network and is perceived by the customers as light flicker (depending on lamp types). In the flicker simulations of this thesis, firstly only a flicker source is considered in the LV network. A typical three-phase induction motor model is used as a flicker generating source at the LV customer's terminal. Next, it is assumed that the upstream network also produces flicker pollution and affects the customers of the LV network too. Therefore, a background (MV) flicker source is considered in the simulation. The network's impedance is found to be a very important parameter that has influence on the flicker severity in the network. The values of flicker transfer coefficients between different voltage levels are found out from network simulations and field measurements. These are further utilized in chapter 5 to determine various planning level values of flicker in the network. Finally, the simulation results are compared with the field measurements on similar types of network to obtain a clear insight about flicker severity in the network.

4.2.1 Analysis procedure

The flicker simulation is done on the modelled LV network using the network analysis tool 'Power Factory'. When a motor starts, an instantaneous voltage fluctuation occurs at different nodes in the network. These instantaneous voltages during the motor switching operations (e.g. pre-start, during start and post-start conditions) can be recorded to calculate the short-term flicker severity level (P_{st}) at different nodes. In the modelled LV network, an induction motor is chosen to simulate the flicker problem in the network. Motor start simulation is done on that network and the rms voltage wave-shapes at different points in the network are recorded. Each voltage step magnitude and time duration of each step-change are noted to calculate the short-term flicker severity analytically (refer equations (2.2) and (2.3) of chapter 2) at some specific points in the network under consideration.

The motor start voltage change and flicker severity can also be calculated using a flickermeter model. For that purpose, the instantaneous voltage variations during motor start-ups are recorded as input to the flickermeter for analysis. The flickermeter is developed in 'Matlab/Simulink'. The concept is based on UIE/IEC flickermeter that is built for a coiled filament gas-filled 230 V, 60W or 120 V, 60W incandescent lamp. A detailed description of flickermeter model is given in the reference [Cai01]. The analysis steps used for estimating the P_{st} are as follows:

- Record instantaneous voltage changes during motor start-ups (from network simulation).
- Convert voltage changes to equivalent light variations of an incandescent lamp, weight them according to frequency to account for human perception (by using flickermeter model).
- Determine instantaneous flicker perceptibility and derive short-term flicker severity P_{st} over a 10 minutes period (from flickermeter model).

Reference [Bar01] describes an procedure to estimate flicker severity at an installation (POC). According to this method, first it is required to know the short-circuit power (S_{sc}) and network impedance angle (θ_k) at the POC. Next, the apparent power demand (ΔS_i) and power factor (α_i) during load change (motor start) is to be estimated. From these values, the maximum relative voltage change (d_{max}) during motor start condition is calculated by equation (4.1). Further, the limit value of the voltage change (d_{limit}) for a specific repetition rate (r) of motor start can be found from the emission limit curve as shown in Figure 4.1. The calculation method is further described in Appendix B-1.

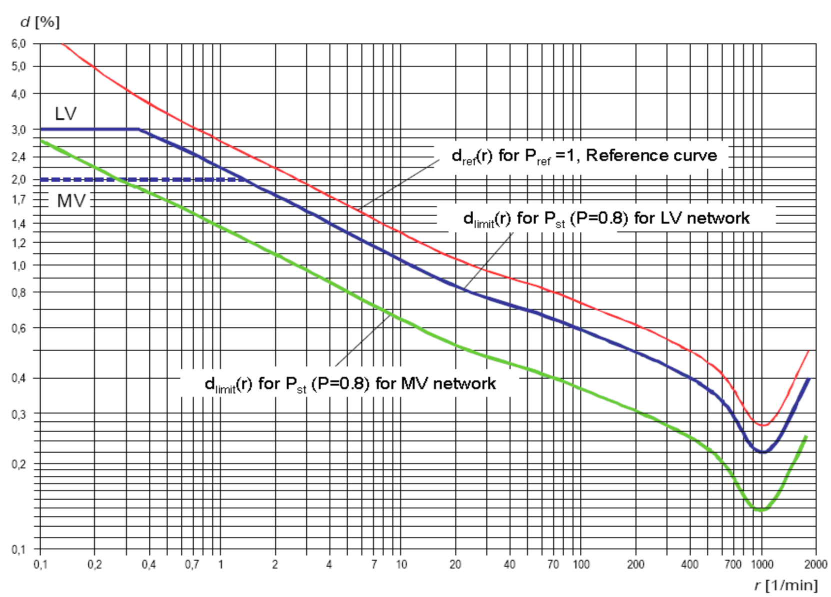


Figure 4.1. Flicker severity limit curve for rectangular voltage change [Bar01]

Figure 4.1 is proposed by the associations of distribution network operators from Austria, Czech Republic, Germany and Switzerland in the report on 'technical rules for assessment of network disturbances' [Bar01]. This report (from now onwards called as 'TR/DNO' in this thesis) describes methods for calculating network disturbances in the LV and MV networks. According to this report, a motor is approved for connection at a POC if the 'd_{max}' (calculated by using equation (4.1)) is below the value of 'd_{limit}' (as found from Figure 4.1). Finally, the P_{st} can be calculated by comparing 'd_{max}' with the reference value 'd_{ref}' (shown by red line in Figure 4.1), as per the standard IEC 61000-3-3. The reference curve for 'd_{ref}' is calculated based on the flicker severity reference limit of P_{ref}=1.

$$P_{st} = \frac{d_{max}}{d_{ref}} \cdot P_{ref} \quad ; \quad d_{max} = \frac{\Delta S_i}{S_{sc}} \cdot cos(\theta_k - \alpha_i) \tag{4.1}$$

The report of TR/DNO also suggested a two-stage assessment procedure to define connection rules for a load at a POC. In 'stage-1', the required values of the ratio of short-circuit power and the rated power of the customer's installation for various types of installations are given (refer Table 4-3 of the report TR/DNO [Bar01]). If the 'stage-1' connection rule is not fulfilled, a detailed evaluation is needed as per 'stage-2' procedure shown in Table 4.1.

Table 4.1. 'Stage-2' assessment procedure of the report TR/DNO

<table>
<tr><td colspan="6">A. First gather detailed data of customer's installation:
• Change of apparent power demand during load start-up
• Repetition rate (r) of load start-up, shape of voltage change curve</td></tr>
<tr><td colspan="6">B. Determine 'd_{max}' as per equation (4.1) and compare it as per the limits given below for the specified repetition rate. Further, estimate the P_{st} from Figure 4.1.</td></tr>
<tr><td colspan="2">r ≥0.1 min^{-1}</td><td colspan="2">0.01 min^{-1} ≤ r < 0.1 min^{-1}</td><td colspan="2">r < 0.01 min^{-1}</td></tr>
<tr><td>LV</td><td>MV</td><td>LV</td><td>MV</td><td>LV</td><td>MV</td></tr>
<tr><td>d_{limit} ≤3%,</td><td>d_{limit} ≤ 2%</td><td rowspan="2">d_{limit} ≤ 3%</td><td rowspan="2">d_{limit} ≤ 2%</td><td rowspan="2">d_{limit} ≤ 6%</td><td rowspan="2">d_{limit} ≤ 3%</td></tr>
<tr><td colspan="2">$P_{st,lim}$ ≤ 0.8, $P_{lt, lim}$ ≤ 0.5</td></tr>
</table>

4.2.2 Case studies for flicker simulation

Simulation is done for three cases that represent three different network situations. The motors under analysis are shown in the respective figures of the considered study cases:

- A 'worst case' situation: when every minute two motors are starting simultaneously in the same LV feeder (see Figure 4.2). This case is simulated for 2 minutes to calculate the P_{st} values at different points in the network.

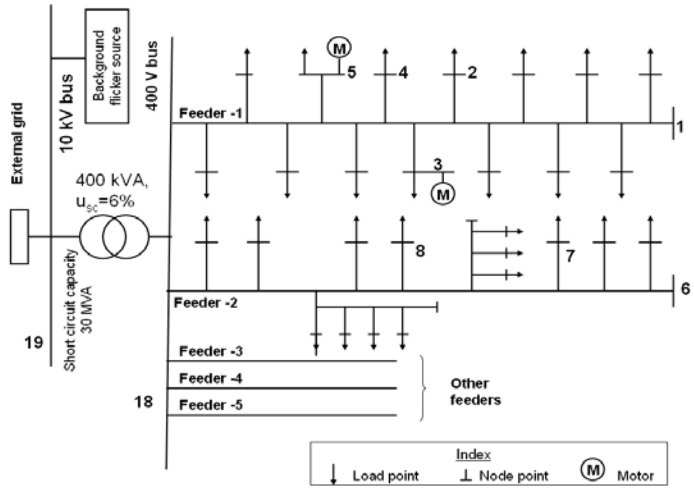


Figure 4.2. LV network for 'worst case' study

- An 'average grid' situation: when every minute one motor in a LV feeder is starting. Thus, in 10 minutes time 10 motors are starting in five different LV feeders of the network (see Figure 4.3). This situation happens only for some specific periods (such as morning and evening peak load demand periods) of a day in a typical household neighbourhood. Simulation time for this case is taken as 10 minutes.

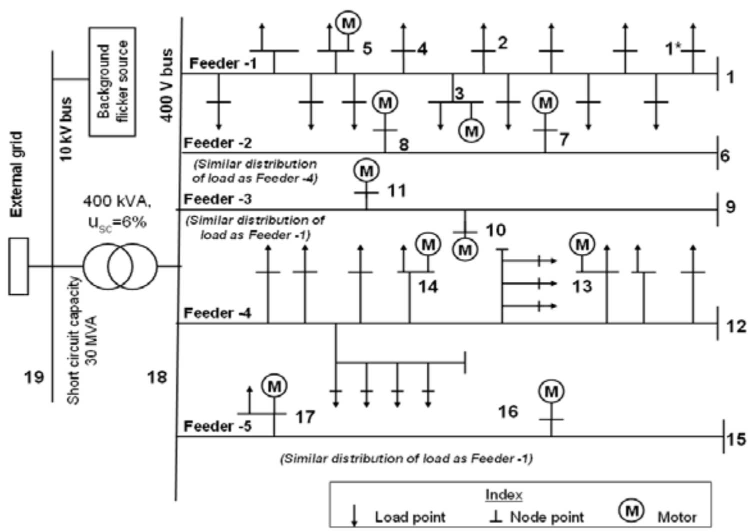


Figure 4.3. LV network for 'average grid' situation

- A 'pessimistic situation': motor start conditions are same as in the ‘average grid' situation with the difference that the motors are connected at other locations. Figure 4.3 is also modified by changing the network impedances at different connection points and replacing the existing 4kW motors by other motor types that demand different inrush currents. For different LV installation capacities, the maximum grid impedances are estimated to restrict maximum flicker severity (P_{st}=1) in the network (refer Table 2.5). The following changes have been adopted in Figure 4.4.
  a) One motor is located at the end of each LV feeder where network impedance is increased to 0.261 **Ω**. This motor demands 50A inrush current while starting.
  b) Second motor is located at the middle of each feeder where network impedance is 0.207 **Ω**. This motor has an inrush current demand of 63A at starting.

  Under such a pessimistic network condition, an installation demands the inrush current equal to its connection capacity with maximum network impedance at the POC.

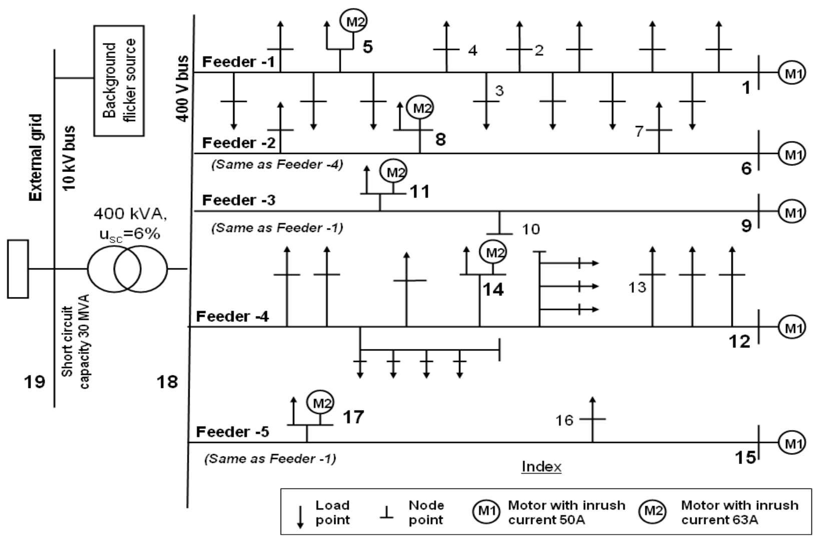


Figure 4.4. LV network for ‘pessimistic case’ study

The influence of background flicker pollution is considered in all the cases. So, each case is simulated for two conditions:

a) no background pollution to LV network from the upstream networks
b) with background flicker pollution contribution from the upstream networks

4.2.2.1 Motor start simulations for 'worst case' situation

This case is simulated considering the worst possible situation that may arise in the network when every minute two motors in a LV feeder start instantaneously. The short-circuit power at the 10kV MV bus is considered 30MVA. Five outgoing LV feeders supply power to different LV customers. Figure 4.2 shows two induction motors at node points '3' and '5' in the 'Feeder 1' that start simultaneously. These are three-phase, 4kW, two poles, star connected induction motors which have a power factor of 0.85 and an efficiency of 83%, and an inrush current of 6.3 times the nominal current. The synchronized voltage variations are measured at different nodes to estimate flicker severity at different points in the network. The verification of the flickermeter model is given in reference [Bha05].

First, no background flicker from the upstream networks is considered in the simulation. The generated voltage fluctuations at different nodes are solely because of the disturbance generated by simultaneous motor start-ups (at point '3' and '5') in the LV network. About 0.5s after the motors start, voltages at different nodes are stabilized. Afterwards, both the motors are switched off. The motor-start instantaneous voltage variations at different points are recorded. Those data are fed to the flickermeter to calculate the P_{st} values (refer Figure 4.5).

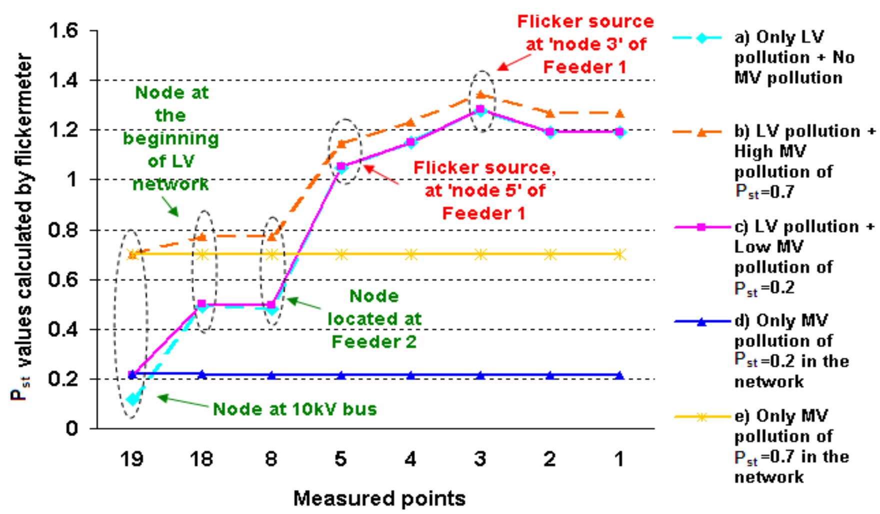


Figure 4.5. P_{st} values with and without background flicker pollution

Next, the influence of background flicker is considered in the simulation. In this analysis, it is assumed that in the MV network big motors are starting that produce voltage variations in the network. Two different conditions are studied:

- low background pollution (with P_{st}=0.20)
- high background pollution (with P_{st}=0.70)

Figure 4.5 shows that the P_{st} values at different measured points increase when the MV background flicker level is high. However, the upstream level background pollution has quite less influence when the LV network also has many disturbing loads. Further, it is found that P_{st} value at '3' is higher than that of '5' when same type of disturbing loads is present at both locations. This is because of two reasons: a) the network impedance at point '3' is relatively higher than at point'5'; b) the generated flicker is transferred from point '5' to point '3' at a higher rate than the other way round. Furthermore, the P_{st} value at the end of the LV feeder (at point '1') is not attenuated much, whereas it is relatively more attenuated at point '18' (near to the MV/LV substation). When the flicker pollution is transferred from the LV to the MV side of the network (at point '19'), it gets largely attenuated.

4.2.2.2 Motor start simulations for 'average grid' situation

Figure 4.3 shows the network used for simulation of the 'average grid situation'. Every minute one motor in one of the LV feeders is switching on. Therefore, in 10 minutes time total 10 motors located in five different LV feeders of the network, are at least once switched on. The flicker sources are located at a distance of 150m and 350m from the MV/LV transformer substation. Next, the simulation is repeated considering an average background flicker pollution of 0.50 from MV network. Figure 4.6 shows the P_{st} values calculated by the flickermeter for this case and the network impedances at different observation points. It can be noticed that there is slight decrease of the P_{st} value at the customers' POCs that are located at the end of a LV feeder (450-500m). This is because of additional impedance of the LV connection cable up to the customer's POC.

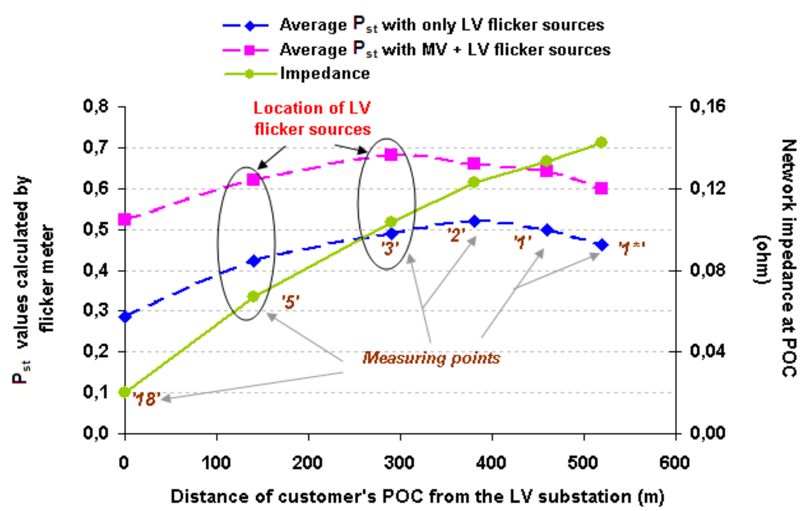


Figure 4.6. P_{st} values and network impedances at different POCs in a LV feeder

4.2.2.3 Motor start simulation in a 'pessimistic situation'

Motor start simulation is done for a pessimistic situation of the network. In this case, the network impedances at various points of the LV network are increased to the maximum permissible value described before (refer chapter 2). In each feeder, every 10 minutes two motors are switched on at two different instants. Thus, it is assumed that each motor runs for 10 seconds and then it is switched off. Thus, in ten minutes time total ten different motors are started in the modelled network. No simultaneous motor start event is considered in this case study.

In Figure 4.4, the motors are connected at locations 1, 6, 9, 12 and 15 (indicated as M1) where the network impedance is 0.261 Ω. These motors demand an inrush current of 50A each during their start-ups at the nominal voltage condition. On the other hand, the motors (indicated as M2) connected at locations 5, 8, 11, 14 and 17 have network impedances of 0.207 Ω. They draw starting inrush current of 63A each at the nominal supply voltage condition. The motor start voltage variations are measured at various points to estimate flicker severity at a POC. In the first analysis, no MV background flicker pollution is considered in the simulation and the P_{st} values at different LV nodes are because of the distortions introduced by different LV motors only. When motor starting occurs at a node in a LV feeder of the network, it causes a high voltage drop at different nodes of its own feeder and a relatively smaller voltage drop at various nodes of the other feeders in the network. In this analysis, it is assumed that in 10 minutes time only two motor are starting in each of the LV feeders and thus the repetition rate (r) is 0.2/minute.

From Figure 4.1, it can be found that the reference voltage drop (d_{ref}) is 4.9% when the repetition rate is 0.2/minute. Table 4.2 compares the P_{st} values estimated by the flickermeter model and analytical calculation for two different installations (connection capacities of 50A and 63A respectively). It shows that the P_{st} values calculated by the flickermeter are higher than that of the analytical method. The reason is that the flickermeter model considers all instantaneous voltage changes occurring during the evaluation period. Hence, all voltage changes associated with the switching on and off of different loads in other feeders (during the evaluation period) of the network are considered. In contrast, the analytical method is done by considering the largest voltage changes at a point in the feeder due to the contribution of that feeder's loads only. Therefore, the values estimated by the flickermeter model can be considered more accurate than the analytical method results. Another observation is that the P_{st} values at various installations have not yet reached 1.0 as per expectation (see section 2.4.1.2). This is because of the presence of other loads in the network and the associated voltage drop in the LV feeders. When the pre-start voltage at a motor terminal is lower than the nominal value, it demands a lower inrush current. This is because a reduced supply voltage at an induction motor's terminal causes less flux in stator and a reduced value of the induced rotor current. Therefore, the electromagnetic torque developed at the motor terminal is also lower than the nominal value. This, in turn, causes a relatively lesser voltage drop during the motor start and leads to a lower flicker severity at the POC than at a nominal voltage condition. Hence, the motor start voltage drops and the P_{st} values at different POCs of the network are lesser than the expected values. Simulation is repeated by considering a pre-start motor terminal voltage the same as the nominal value. Under such a condition, the inrush current of the motor is the same as the connection current capacity at a POC and the P_{st} value reaches 1.0. Another simulation is done considering high MV flicker pollution ($P_{st, MV}$) of 0.70 and transfer coefficient between the MV and LV network as 0.84. The obtained P_{st} values are shown in Figure 4.7.

Table 4.2. Estimation of P_{st} values at the installations (without MV pollution)

Installation capacity / network impedance at POC	Short-circuit power and phase angle at the POC (kVA/deg)	Change of apparent power during motor start (kVA/deg)	Maximum voltage drop calculated (% of nominal voltage)[1]	P_{st} value estimated	
				by flickermeter	using equation (4.1)
50A / 0.261 Ω	578 kVA / 22.4°	30.4 kVA, 73.7°	3.3%	0.76	0.67
63A / 0.207 Ω	732 kVA / 20.7°	38.4 kVA, 73.7°	3.2%	0.73	0.65

Note: [1] Calculated by using equation (4.1) and are verified with simulation results

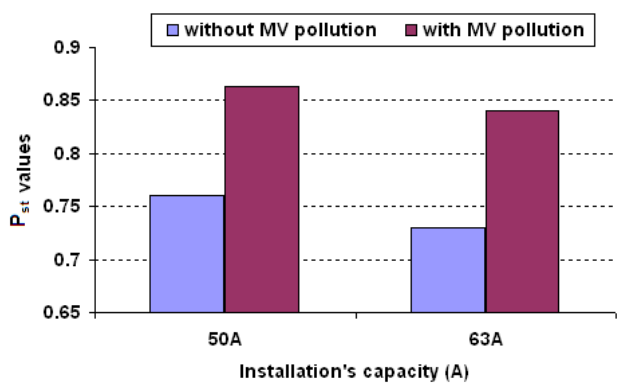


Figure 4.7. P_{st} values found from simulations at different types of LV installations

Figure 4.7 compares the P_{st} values at the 50A and 63A installations, as obtained from the simulations for the cases without and with MV background pollution.

4.2.2.4 Discussion

The simulation results show that the P_{st} values at different points increase largely when motors in the network start more frequently. The values are even higher when motors are started simultaneously. Therefore, the generated P_{st} is related to both the percentage of voltage change during motor-starts and the frequency of voltage variations. The short-circuit power level at a POC is quite important and influences the flicker severity (P_{st} value) at a customer's point in the network. In a real situation, the 'worst case' (described in the simulation) seldom happens in the network. This special case is studied to estimate the maximum flicker level in the network and to derive the maximum flicker contribution (ΔP_{st}) of a load at a POC. The analysis of 'average grid situation' shows that P_{st} values at a LV customer's installation varies between 0.55-0.66 (with the assumption of MV background flicker pollution P_{st} of 0.5), depending on the location of flicker source in the network and the impedance at the observation point. It was noticed that the MV background flicker pollution increases the flicker severity at a LV customer's terminal. Motor start simulation for the 'pessimistic situation' shows that the P_{st} values at a 50A installation is 0.86 and that for a 63A installation is 0.84, when the background flicker pollution (P_{st}) level is 0.70. This study results are further utilized in chapter 5 to estimate the flicker emission limits at the LV customer's installations and for proposing planning level values for flicker at different voltage levels.

4.2.3 Network's impedance and flicker severity

The network impedance plays an important role in determining the flicker level in the network. Two similar flicker sources can have different impacts when the network impedance at an installation differs (see Figure 4.6). A high network impedance (along with a high inrush current) at a customer's installation would produce large voltage variations and high flicker severity at the POC. To connect a new load at a customer's installation, it is recommended to calculate the maximum allowable voltage variation at the POC during the load start if the network impedance of that point is known.

Transfer of flicker emission from a high to a low voltage level depends on the load composition of the downstream network and gets somewhat attenuated when inductive motor loads are present in the LV network. In contrast, the transfer of flicker emission from the low to the high voltage levels is generally very low because of the increase of short-circuit power. In this analysis, a flicker transfer coefficient from the LV to the MV network is found 0.25 (from ‘point 18’ to ‘point 19’) for the simulated network. On the other hand, the transfer coefficient from the MV to the LV network is found 0.84 when the LV network consists of motor loads (25% of the total load) and other passive loads (75% of the total load).

Transfer of disturbance from the HV to MV network becomes attenuated too because of the damping effect of rotating machines connected at MV levels. The standard [Iec04] specifies the value of transfer coefficients from the HV to the MV network as 0.9 and from the MV to the LV network as 1.0. Generally, the MV network consists of many motor loads and the LV network has a combination of motor and passive loads. A field survey [Per01] indicated that the flicker transfer coefficient from the MV to the LV network is around 0.84. Another study [Yan01] showed that the transfer coefficient from the HV to MV network is 0.8. In this thesis, following values of transfer coefficients are considered for further analysis:

$$T_{HV \to MV} = 0.80$$

$$T_{MV \to LV} = 0.84$$

$$T_{LV \to MV} = 0.25$$

4.2.4 Field measurement data on flicker severity

Figure 4.8 illustrates an hourly distribution of the P_{st} and P_{lt} values on a day at a LV busbar near to a MV/LV transformer substation in the Netherlands.

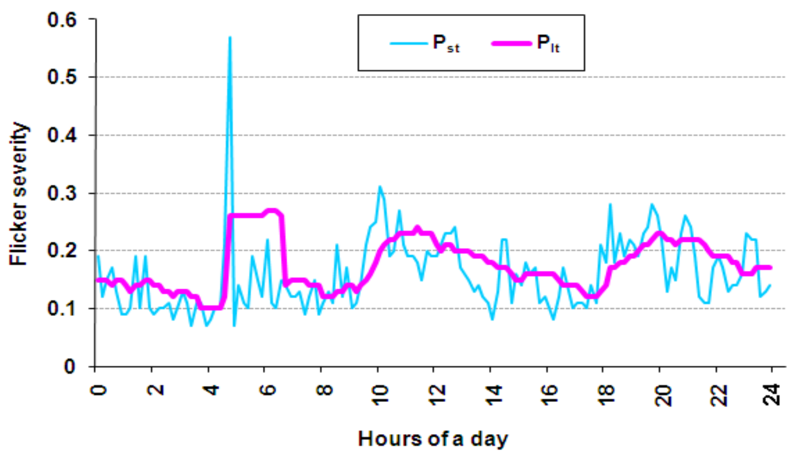


Figure 4.8. Flicker severity measured at a terminal in a LV substation

Figure 4.8 shows that most of the time on a day both the P_{st} and P_{lt} values in the LV network remain in the range of 0.2-0.3. Only occasionally, the P_{st} values became high at around 0.55. It is probably due to the starting of some local disturbing loads.

Figure 4.9 shows the annual frequency of occurrence of flicker severity at a terminal of a household in a typical Dutch neighbourhood. It shows that most of the values remain within 0.2-0.6. It represents the 'average grid' situation of the simulation case study. Some of the flicker severity values stay between 0.6-0.9 that resembles to the 'pessimistic situation' simulation case. Further, it is also noticed that few of the flicker severity values exceed the EN 50160 standard limit of P_{lt}=1 that indicates the 'worst case' situation of the simulation case study.

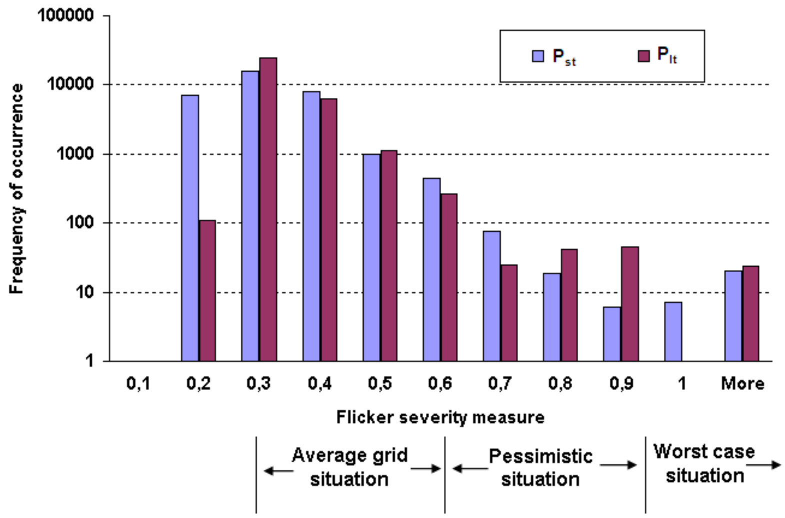


Figure 4.9. Annual distribution of flicker severity at a customer's POC

To compare flicker severity of the Dutch grids with the networks of other countries, some reference examples are discussed here. A measurement campaign in the LV networks of Denmark [Eur01] showed that average P_{lt} values are 0.45 in the urban networks and 0.50 in the rural networks. In general, it was noticed that the P_{lt} value in different networks of Europe is less than 0.70. A P_{lt} trend is recorded for the LV networks in Buenos Aires [Iss01] that showed a slight decrease of flicker severity over last ten years of measurements. It was also mentioned that the utilities have installed flicker mitigations measures at different points in the networks which made the network more powerful and less sensitive to distorting loads. The 95% probability value of the P_{st} value remains within the range of 0.3-0.4.

4.3 Harmonics simulations

In a network, many harmonics producing devices are connected. They produce current harmonics that propagate along the network depending on the network’s impedances. It is also noticed that mutual interactions between the network voltages and currents influence the net harmonic current production in the network. In this research, several laboratory measurements and simulations are done to analyse harmonic behaviour of the network and various connected devices under sinusoidal and distorted network voltage conditions. Four common types of households are modelled to represent different loading conditions at the LV domestic customer’s terminals:

- high load (current demand of 7.5A)
- average load (current demand of 5.6A)
- low load (current demand of 2.3A)
- average load with solar panels connected (net current demand of 3.7A)

In the Power Quality laboratory (PQ lab) of TU/Eindhoven, various household devices are tested to find out their individual harmonic current spectrums under different network voltage conditions. Further, simulations are done on the modelled LV network in which several types of households are connected. Finally, the simulation findings are compared with field measurements that are done under this research to predict the harmonic characteristic of a typical LV network consisting of many households.

4.3.1 Methodology

The network analysis tool ‘Power Factory’ is used to perform harmonics simulations on the LV network model. Figure 4.10 shows a typical household with its various linear (such as cooking element, electric iron, etc.) and non-linear loads (examples: TV, PC, CFL, fridge, PV inverter, etc.). A household customer commonly uses single-phase loads at his installation. In the Dutch network each customer gets a three-phase connection of 25A or a single-phase connection of 40A, depending on the customer’s requirement. To analyse the harmonic behaviour of the LV network, first harmonic fingerprints are measured in the PQ lab for some of the household devices. Next, a combination of various devices is made to form different household terminals (see Table 4.3). Further, a harmonic fingerprint is recorded at each modelled household's terminal (along with its devices) for different network voltage conditions.

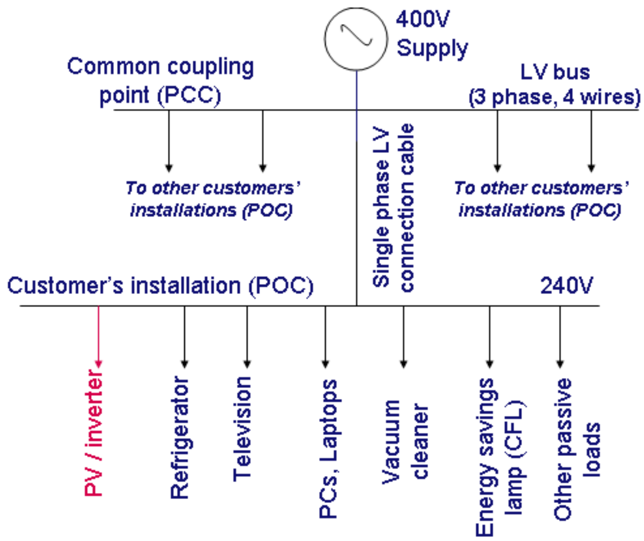


Figure 4.10. Typical schematic of a household terminal with various devices

All the harmonic fingerprint measurements are brought into the simulating software's database. Finally, each type of household is modelled in the network analysis tool and all the required harmonic fingerprints data are taken from the software's database. Figure 4.11 shows the stepwise procedure for the harmonics analysis of this research.

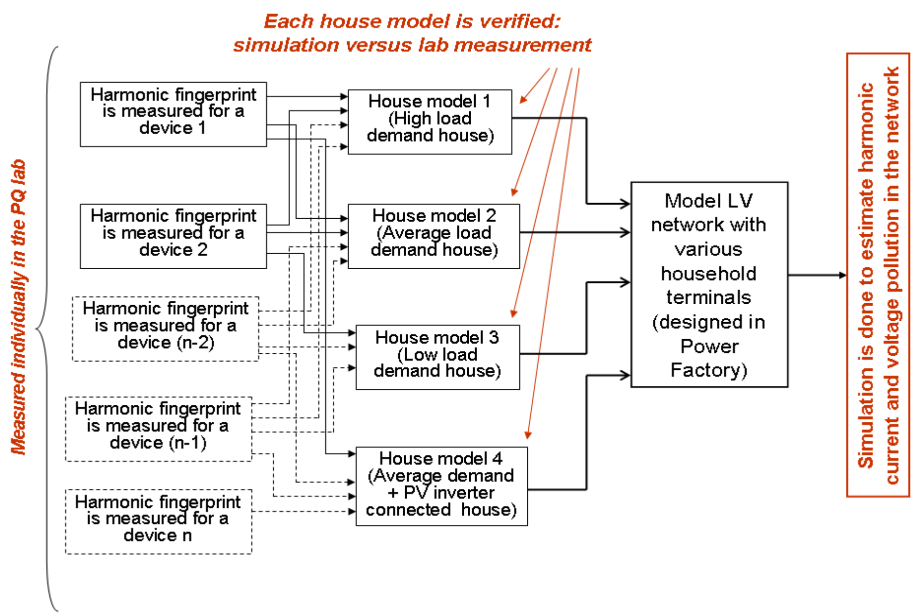


Figure 4.11. Methodology used for harmonics analysis of the modelled network

4.3.2 Household models and simulation cases

In the harmonics simulation, four types of household load models are considered as described in Table 4.3. The typical current demand considered for each model is taken from various load profile measurements conducted by the Dutch network operators over a reasonably long period of time.

Table 4.3. Household models used in simulation

Model name	Devices used	Rms current load (A)	Percentage of non-linear loads with respect to total kVA load (%)
High load case	TV- 1 no PC- 2 nos. Fridge - 1 no. CFL - 10 nos. Vacuum cleaner - 1 no. (at full load condition) Resistive load - 125W	7.5	93
Average load case	TV- 1 no PC- 2 nos. Fridge - 1 no. CFL - 6 nos. Vacuum cleaner - 1 no. (at half-load condition) Resistive load - 125W	5.7	90
Low load case	TV- 1 no PC- 1 no Fridge - 1 no. CFL - 2 nos. Resistive load - 125W	2.4	75
Average load case with PV inverter loads	TV- 1 no PC- 2 nos. Fridge - 1 no. CFL - 6 nos. Vacuum cleaner - 1 no. (at half-load condition) Resistive load - 125W Inverter load - 1 no.	3.8	93

Each household model is simulated separately to check its accuracy with the PQ lab measured data. It was found that all the models give comparable results with the lab measurements (an example is given in reference [Bha03]). Loads in a real network are quite dynamic and time variant. From Table 4.3, it can be noticed that the average resistive load at the customer's POC is taken quite low. In reality, when more customers in the network use resistive loads for their daily activities (such as cooking, ironing, etc.) for a specific period of a day, the total current harmonic distortion level in the network gets significantly reduced (as can be observed from the field measurements). In this analysis, mainly worst-case scenarios are considered to estimate the maximum harmonic distortion level in the network. From the field measurement in the Dutch networks, an average daily peak loading of a LV feeder is found around 70A. Hence, different combinations of houses in a LV feeder of the network model are selected in such a way so that the peak current loading of each LV feeder is around 70A. Table 4.3 shows that the non-linear loads in different households vary in the range of 75%-93% of total load. This indicates that modern houses use a significant amount of non-linear loads for their daily usage. Four cases are simulated with the following combinations:

- Case 1: Combination of high and low load demand houses (50% each type) in the LV network. This is close to a realistic situation.

- Case 2: All LV feeders have houses with average load demand in the network. This is an extreme case to study the effect of similar type of loads in the network.

- Case 3: This case simulates a situation when some customers (60%) have high load demand; and others have average load demand and have a solar inverter installed at their homes (40%). This case is a possible future representation of the network when many houses in the neighbourhood have PV panels and export power to the network.

- Case 4: It is found that the normal average loading of a LV feeder is approximately 40A in the Netherlands (which is only 30% of the capacity of a feeder). To simulate this situation and compare it with field measurements, this case study is formed. In this case, different load demand houses are combined in such a way that the average loading of a LV feeder can be restricted to 40A. Thus, in the model LV network three LV feeders have houses with high and low load demands, one feeder has 30% houses with low load demand and 70% houses with average load and solar inverter connected, and one feeder has 30% houses with high demand and the other 70% houses are with average load and PV inverter connected (see Figure 4.12).

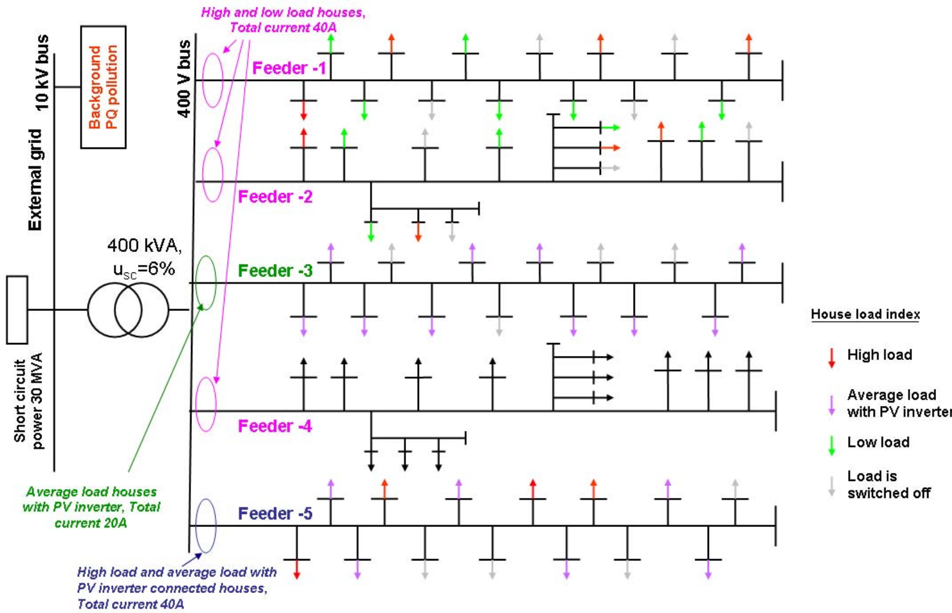


Figure 4.12. LV network load distribution for 'Case 4'

4.3.3 Background harmonic distortions

The simulations are also done under different distorted network voltage conditions. Therefore, first an overview of harmonic voltage levels in different countries of the world is given. A report of the Union of the Electricity Industry – EURELETRIC [Eur01] of 2002 on power quality described the harmonics measurement results (mainly for the MV and LV networks) of different countries. It was observed that in most of the European networks, in general, a 1% increase of the THD_V and the 5th harmonic voltage occurred (with respect to the fundamental voltage) in every ten years period. Moreover, a significant percentage (around 5%) of 5th harmonic values is around or even higher than the compatibility level value as specified in the IEC 61000-2-2 standard [Iec06].

A routine survey in a household neighbourhood in the UK [Eur01] showed that the maximum THD_V is around 4.5%, the 3rd harmonic voltage 1.4% and the 5th harmonic voltage 4.4%. In the urban networks of Denmark [Eur01], it was observed that the 3rd harmonic voltage is in the range of 3-4% of the fundamental voltage, while some measurements of the 5th harmonic voltage have exceeded the value of 6% during the observation period. A harmonics survey is also done for the

French networks [Ber01]. It was found that the 95% probability data for the 5th harmonic voltage is between 4-6% for about 20% of the measured points in the LV networks. It was also found that the 3rd and 9th harmonic voltages at the MV/LV transformer substations are generally low. However, some of the values exceeded the compatibility level values when measured at the end of LV feeders. Harmonics measurements in Australian medium voltage networks [Gos01] show that the THD_V values are in the range of 1.5%-3.8% of the fundamental voltage. Also, it has a predominant 5th harmonic voltage component. A harmonics survey is conducted for a period of ten years in the LV distribution networks of Buenos Aires [Iss01]. It was concluded that the harmonics level remained quite steady throughout the 10 years of measurement period. It was also reported in the same survey that on an average 1.2% of the measured sites is penalised per year for violating the standard limit, especially for the 15th harmonic voltage limit.

From the field measurements in the Dutch MV networks, two typical distortion conditions are estimated: a) average distortion and b) high distortion conditions. Table 4.4 shows a detailed description of the two distortion conditions. The total harmonic distortion recorded for the average case is 3.2% and that for the high case is around 6%.

Table 4.4. Harmonic voltage distortions in Dutch MV networks [Pqm01]

Harmonic number	*Average distortion*		*High distortion*	
	Magnitude (pu)	Phase angle (deg)	Magnitude (pu)	Phase angle (deg)
3rd	0.007	0	0.017	15
5th	0.026	180	0.047	200
7th	0.016	180	0.030	180
9th	0.003	180	0.008	180
11^{h}	0.005	180	0.009	150
13th	0.003	180	0.010	180
15th	0.001	180	0.002	180
17th	0.001	180	0.005	135
19th, 21st, 23rd, 25th	0.001	180	0.003	180
THDv	*3.2%*		*6.0%*	

4.3.4 Harmonic spectrum for devices

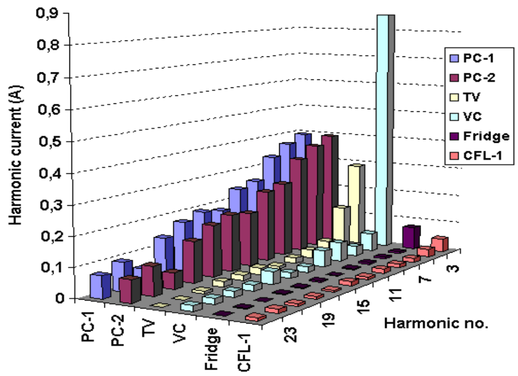
In the laboratory, devices used in household models are measured to identify their individual harmonic emission pattern under various grid voltage conditions. It is observed that during a distorted grid condition, the harmonic current emission of a device can change significantly compared to a nominal sinusoidal voltage condition. From a harmonic fingerprint plot, it is often possible to identify a device's internal characteristic [Cob02], [Yli01]. Table 4.5 compares simulation results of THD_I values for various devices at a (low load demand) household's POC under clean and distorted supply voltage conditions [Bha03].

Table 4.5. THD_I values of different devices in 'low load' demand case

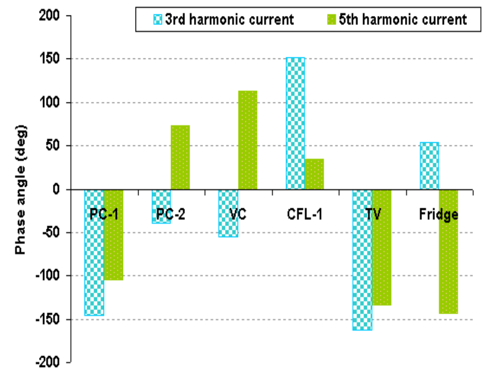
Device	THD_I	
	under clean voltage condition	under distorted grid condition*
TV	54%	66%
PC-1	180%	201%
Fridge	10%	19%
CFL-1	106%	131%
CFL-2	105%	130%
Combined load	*46%*	*55%*

Note: * Tested with high background distortion in the supply voltage (refer Table 4.4).

Figure 4.13 shows the harmonic spectrum of different devices connected at a house terminal that has high load demand. The typical household appliances should meet the general requirements for 'class A' devices in the IEC 61000-3-2 standard [Iec05], as shown in Appendix C-3. It can be noticed that the 3rd harmonic current emission is quite high for a vacuum cleaner (VC). A VC has a universal motor and a phase shift technique is used for its speed control. It produces a relatively large amount of 3rd harmonic current at low power stand. It was also found from lab measurements that for some specific order harmonics, a VC can produce significant amount of current emissions exceeding the limits (for 'class A' devices) of standard IEC 61000-3-2. Other devices such as PC and TV also produce significant harmonic currents. A CFL produces a high percentage of harmonic currents too but its contribution is relatively low (as it demands a very low fundamental current) in comparison to other harmonics producing devices in the network. In Figure 4.13 (a) the measured values of harmonic currents for various household devices are plotted. The device 'PC-1' is a relatively old-model PC as compared to the 'PC-2' which is relatively new-model. It can be noticed from Figure 4.13 (b) that the 3rd and 5th harmonic currents phase-angles of various connected devices vary significantly. If the contribution of 'PC-1' is neglected then it can be noticed that the phase angle differences between different devices are quite large (more than 90º). Therefore, a large amount of diversity does exist even in the low order harmonics at different LV terminals.



(a) Harmonic current magnitudes



(b) 3rd and 5th harmonic current phase angles

Figure 4.13. Harmonic currents of different devices under clean supply voltage

Figure 4.14 shows harmonic currents profiles of the devices such as PC and CFL, as found from the simulation under three supply voltage conditions:

- No background distortion
- Average background distortion (THD_V =3.2%)
- High background distortion (THD_V = 6%)

The harmonic fingerprints measured in the PQ lab for each of these devices and combinations of them are brought in the network simulation tool. The background distortion in the simulation is placed at the LV main busbar. From the analysis, it is found that in many cases the devices emit relatively more harmonic currents (for almost all order harmonics) when background harmonics pollution is present in the supply voltage. Another observation was that the phase angles of each harmonic component in the supply voltage influence the harmonic currents emissions of a device (refer also Figure 2.15). Hence, for some specific conditions, the harmonic current emission of a device can be lower too with a background distortion condition as compared to the case with no background distortion in the supply voltage. Appendix B-2 shows the PQ lab measurement results for some household devices under the above described three conditions of supply voltage as well as for other supply voltage conditions. With the harmonic fingerprint data, simulations are done to find out harmonic current spectrums of different devices under distorted supply voltage conditions, as described above. From Figure 4.14, it can be noticed that the device's harmonic current emissions for a specific order harmonic vary significantly depending on the supply voltage magnitude and phase angle relative to the device’s current phase angle. For example: for the 9th order harmonics, CFL has higher current value at high background distortion condition than at average and no distortion conditions. The opposite situation occurs for the PC which emits lower current at high background distortion condition than at average and no distortion conditions at the 9th order harmonics. Again for 11th and 15th order harmonics, the harmonic currents of CFL are lower at high background distortion condition than at average and no distortion conditions.

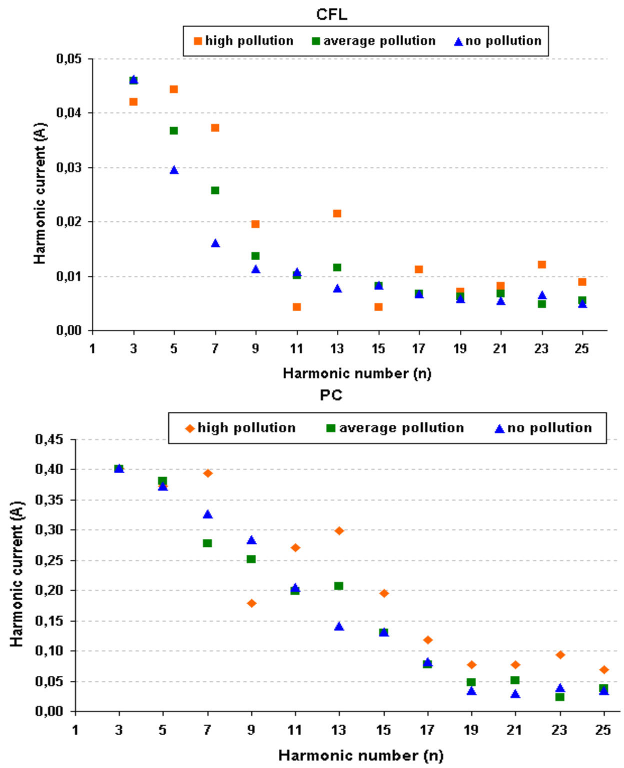


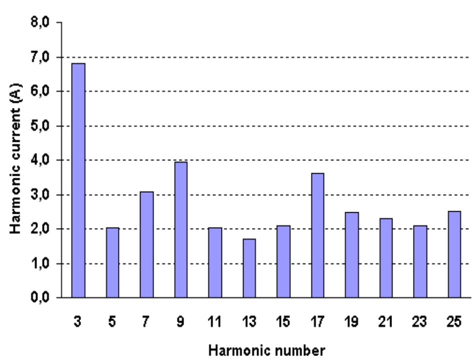
Figure 4.14. Emissions of devices under different supply voltage conditions

4.3.5 Simulations with modelled LV network

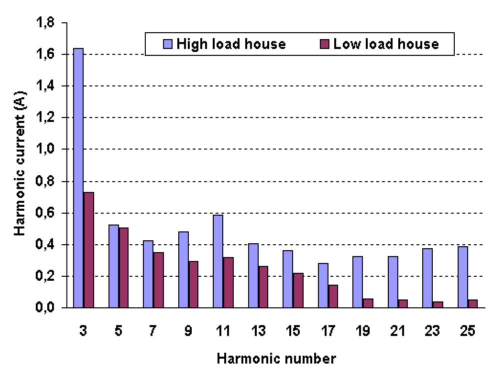
The harmonic load flow simulation is done on the LV network model by combining various household devices as described in Table 4.3. The case studies considered for the analysis are described in section 4.3.2. Each case is simulated first under clean voltage condition and later with the MV background (average / high) harmonic voltage distortion condition.

4.3.5.1 ‘Case 1’

A mix of high load and low load household terminals is selected at different node points of the modelled LV network so that a total fundamental current of 70A is found at the beginning of the LV feeder. The harmonic current spectrum at beginning of a LV feeder is shown in Figure 4.15 (a). The THD_I value at the beginning terminal of a LV feeder is around 16%. The THD_I value at a high load demand house terminal varies between 26-28% and at a low load demand house terminal is between 46-48%. It can be noticed that the harmonic currents for higher order harmonics at a high load house terminal do not decrease as much as a house with low load demand. This case study considers a particular network load situation when the current demand of each LV feeder is quite high (70A). During the considered condition, there are many harmonic producing sources present in the feeder. Depending on their relative phase angles at different POCs, harmonic currents of each order at a house terminal can increase or decrease. Figure 4.15 shows a situation when the harmonic currents in the network are additive for some order harmonics such as 9th, 17th, 19th to 25th; whereas the 5th, 7th and 13th order harmonics have relatively lower values. It can be remarked that in the network load situations are very dynamic and the harmonic spectrums at different house terminals can vary significantly with time. The THD_V values at different LV household customer's POCs are found in the range of 3.7-4.1%. The harmonic spectrum at two house terminals with high load and low load are compared in Figure 4.15 (b). The simulation is repeated by considering an average MV background distortion contribution into the LV network. The THD_I value at the beginning of a LV feeder is around 17% and it varies between 27-50% at different household terminals depending on their load types. The high load demand house has quite a large 3rd harmonic current contribution, which is mainly because of the emission from the vacuum cleaner. Other order harmonic currents are comparable in both types of house installations. It was noticed that the THD_V at different LV terminals varies between 4.9-5.5%.



(a) At the beginning of a LV feeder



(b) At different house terminals

Figure 4.15. Harmonic current spectrums for 'case 1' (no background distortion)

4.3.5.2 'Case 2'

This case study considers only average load models for all houses in the simulated LV network. All harmonics values are found higher than those of the 'case 1'. It is because of the presence of similar type of loads at all POCs (for 'case 2') in the simulated network. In 'case 1', there are two different types of house models that mutually compensate harmonic distortion in the network because of diversity effect (which is due to the variation of phase angles among the devices at different POCs). The simulation results show that for 'case 2', the THD_I values at different house terminals and the beginning of LV feeder are in the range of 31-39% and the THD_V is in the range of 3.5-7.0% at different household's terminals. This case study is repeated by adding an average level of harmonic voltage distortion from the MV network. Under such a condition, the THD_V values at different POCs vary between 4.4-7.9%.

4.3.5.3 'Case 3'

This case considers that 60% houses in the LV network have high load and 40% houses have average load and a solar inverter (2.5kW) installed at their house terminals. The THD_I value at the beginning of LV feeder is found 24%. The THD_I values at houses with high load vary between 26-28%, whereas those of houses with inverter are in the range of 58-61%. The THD_V is found in the range of 1.6-3.7% at different household's terminals. The simulation is repeated by considering an average MV background pollution contribution into the LV network. Under that condition, the THD_V values at different terminals vary between 3.8-5.3%. The simulation results are found comparable to the 'case-1' results. The only noticeable thing is that the houses with average load demand and PV inverter connected have a high THD_I as compared to other type of household installations. It is because the PV inverter connected houses export current to the network and have less net current demands which makes the THD_I high.

4.3.5.4 'Case 4'

This case study is done considering average loading of a LV feeder around 40A (as found from field measurements, see Figure 4.20). This case simulates an average network situation by combining houses demanding different loads as shown in Figure 4.12. In the simulated network, three LV feeders supply houses with high load and low load demands. One feeder supplies to houses that demand either high load or average load with PV inverter connected. Each of these four feeders' current loadings is taken as 40A. The 5^{th} LV feeder supplies to the houses with average load and solar inverter connected and the total current loading is 21A.

The first simulation is done with average MV background distortion. Figure 4.16 shows the harmonic currents at the beginning of five simulated LV feeders.

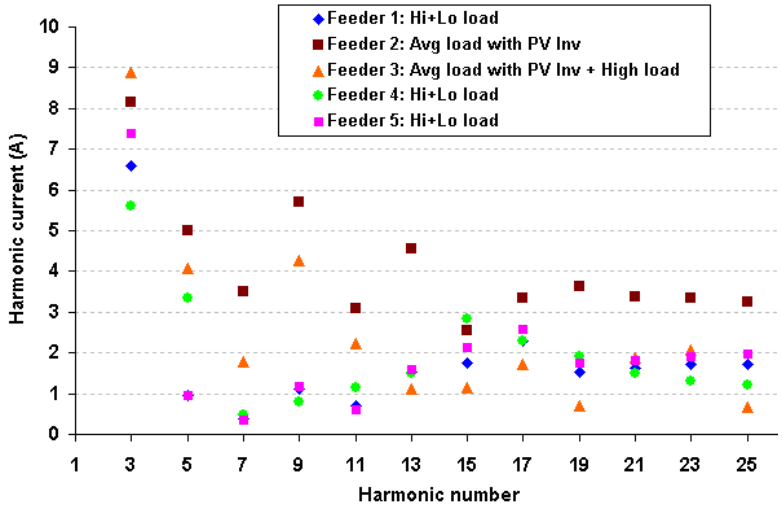


Figure 4.16. Harmonic current in different LV feeders with average MV distortion

The total harmonic current found for a feeder supplying to high and low load demand houses is 8A (where the fundamental current is 40A). On the other hand, the total harmonic current for the feeder supplying to the PV inverter connected houses is 15A (where the fundamental current is 21A). The THD_I values at different households' POCs vary between 20-80% depending on the installation's current demand. The THD_V values at different LV points are in the range of 5.6-7.5%.

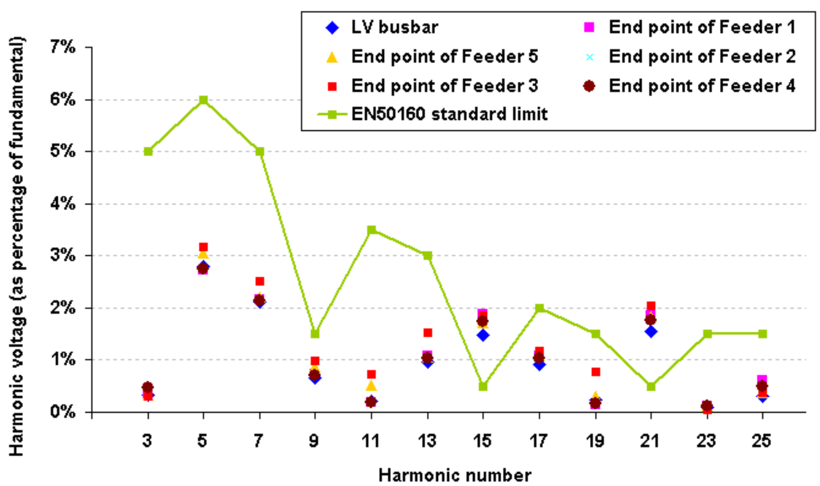


Figure 4.17. Harmonic voltages in different LV points with average MV distortion

Figure 4.17 shows the harmonic voltages at different points of the simulated network. The 15th and 21st harmonic voltages are found high, exceeding the EN50160 standard limit values. It is mainly because of two reasons. Firstly, the limit values are very low in the EN50160 standard as compared to the other consecutive harmonic orders. The other reason is due to the 'triple n' harmonic currents that are flowing through the neutral conductors and are contributing to the increase of harmonic voltages at different points in the network. Another simulation is done with high (MV) background distortion, and the harmonic currents of various installations are shown in Figure 4.18. Further, the harmonic voltages at the main LV busbar are compared for different supply voltage conditions in Figure 4.19.

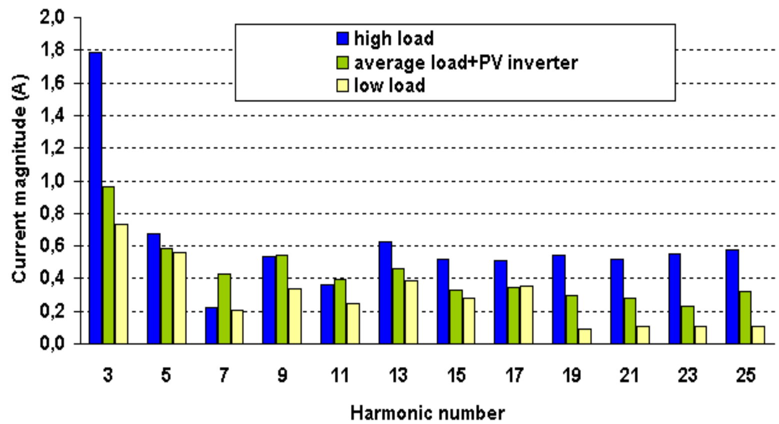


Figure 4.18. Harmonic currents at different households' POCs with high MV background distortion condition

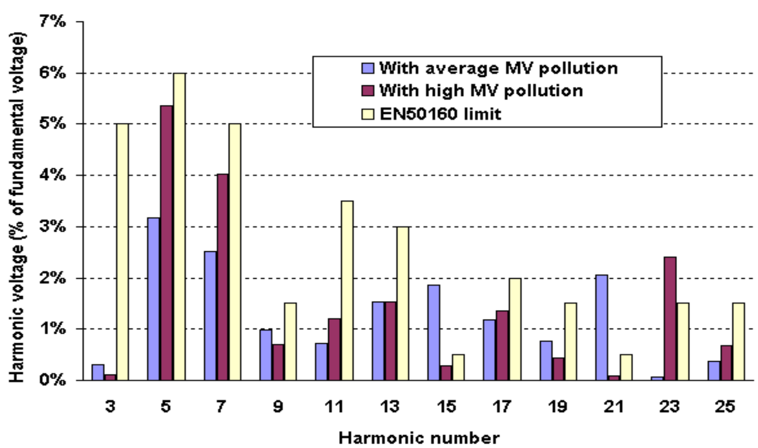


Figure 4.19. Harmonic voltages at LV substation bus with different MV distortions

From the simulation results, it can be noticed that the 15^{th} and 21^{st} order harmonic voltages for average MV distortion condition and the 23^{rd} order harmonic voltage for high MV distortion condition exceed the limit values given in the EN50160 standard. Hence, it can be stated that the harmonic currents and voltages at the POCs are highly dynamic and are quite dependent on the background distortion present in the supply voltage along with the combination of various devices connected at different installations.

4.3.5.5 Discussion

All the simulations are done considering a MV short-circuit power of 30MVA, which is almost the lowest value in the Dutch networks. The X/R ratio is taken as 0.5 as per reference [Pro01]. Three case studies are simulated considering LV feeder current loading as 70A that happens in the Dutch networks only for a small period of a day. These simulations are done with an average MV background distortion condition that corresponds to a worse scenario of the LV network in the Netherlands at this moment. It was found that when the network has a mix of high and low demand houses, maximum THD_V can reach around 5% and no harmonic voltage exceeds the limit of the EN50160 standard. However, when a LV feeder supplies houses with an average load demand and PV inverters connected, the maximum THD_V can be as high as 8%, and some harmonic voltages can even exceed the limits of the standard EN50160.

The ‘case 4’ is a situation that is more common in the Netherlands. The current loading of a LV feeder is taken as 40A. This case is also analysed for average and high MV background distortion conditions. The analysis of harmonic voltages at different installations shows that the THD_V is in the range of 4.5-5.5% for average MV background distortion condition and between 7-8% for high MV background distortion condition. All the THD_V values are within the limit values of the EN50160 standard, but it is noticed that some specific order harmonic voltage components can exceed the standard limits under specific circumstances (because of the influence of the background distortions in the supply voltage). These simulation results are again utilized in chapter 6 to estimate harmonic related losses in the networks. Harmonic current emissions of different installations found from the above four cases will be compared with the values recommended by the IEC/TR 61000-3-14 [Iec07] report in chapter 5 and further harmonic current emission limits for the LV customer will be proposed.

4.3.6 Field measurements on harmonics

Field measurements in the Dutch networks have shown that a LV feeder has an average current loading of 40A with a maximum current of around 70A, when it supplies mainly households and small industrial installations (see Figure 4.20).

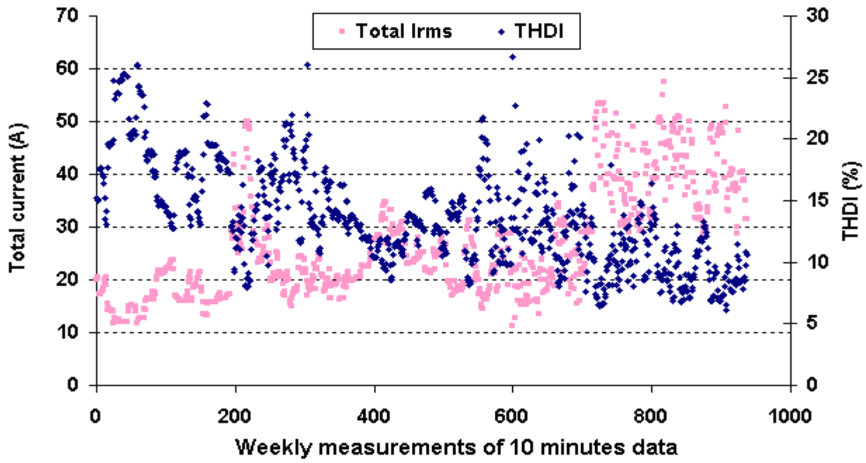


Figure 4.20. Current and THD_I distribution in a LV feeder in a week

Field measurement is, for example, done in a LV feeder with many households, having similar type of load demand as considered in the simulation ('case 4'). The measured harmonic voltage spectrum, harmonic currents, and THD_I variation for a specific day of the year are shown in Figure 4.21, Figure 4.22, and Figure 4.23 respectively. The current and voltage harmonic distortions derived from the measurements show that the THD_I at different house terminals varies in the range of 20-60% and the THD_V values at different LV points vary between 2.5-4.5%. These results of the field measurement are in close match with the simulation results of 'case 4'. However, there is some mismatch between the field measurement and 'case 4' simulation regarding the voltage harmonics values. In the field measurement, harmonic voltages of all orders comply with the limits of the EN50160 standard. In contrast, the simulation results of 'case 4' showed that the 15th and 21st harmonic voltages for average background distortion and the 23rd harmonic voltage for high background distortion condition exceed the EN50160 limits. This is mainly due to the harmonic current contributions from the feeders containing many houses with PV inverters. So, it can be remarked that the case study indicates one of the 'worst-case' load situations of the real network (this was also found in section 2.3.2.2).The field measurements of Figure 4.21 and Figure

4.22 show the harmonic voltage and current spectrums of a typical LV feeder for a day in a year.

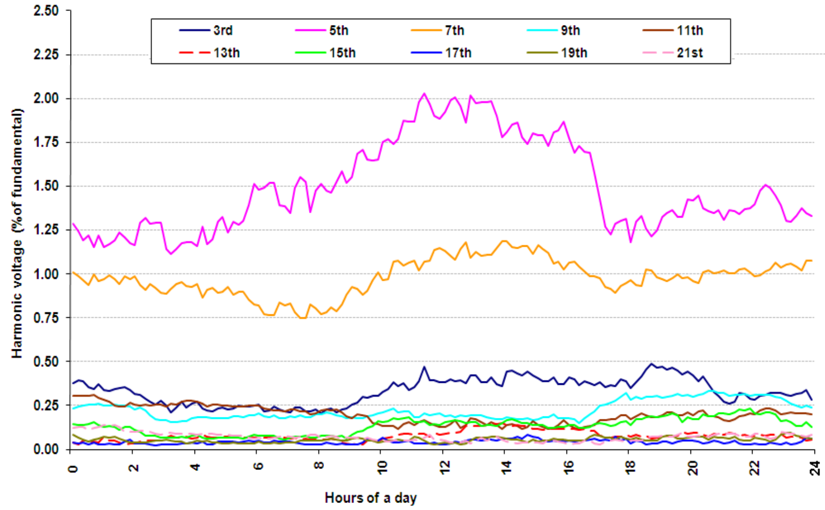


Figure 4.21. Harmonic voltage spectrum at a LV feeder (with PV) on a day

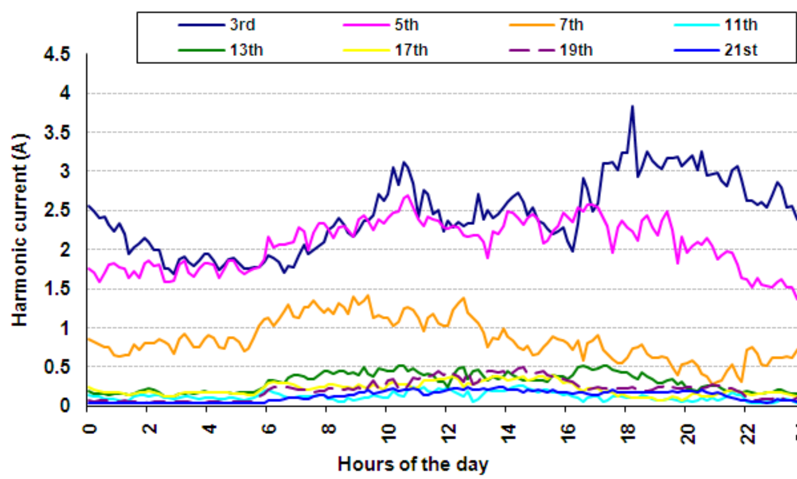


Figure 4.22. Harmonic current distribution of a LV feeder (with PV) on a day

The load demand in a LV feeder (supplying different households) is dynamic and time variant. Hence, the simulation result of 'case 4' is comparable with the field measurement of a situation when the current loading of the LV feeder is around 40A. From field measurements, it was found that the background harmonic pollution contribution of the upstream networks into the LV network during the measurement period was comparable to the 'average distortion' condition (see Table 4.4). Figure 4.23 shows a situation with many households having PV panels at their respective installations. The field measurement shows that the average THD_I in the beginning of the LV feeder is around 28% and that at the household's POC (with PV installation) is around 60%. The THD_V at the LV main busbar is found in the range of 2.5-3%.

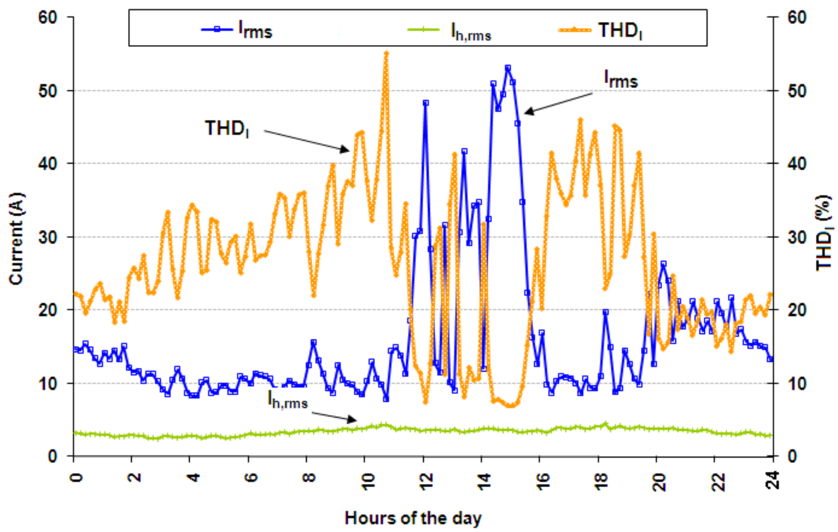
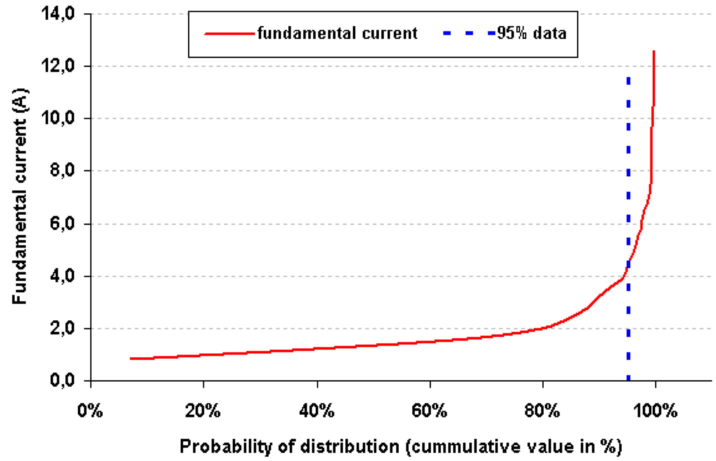
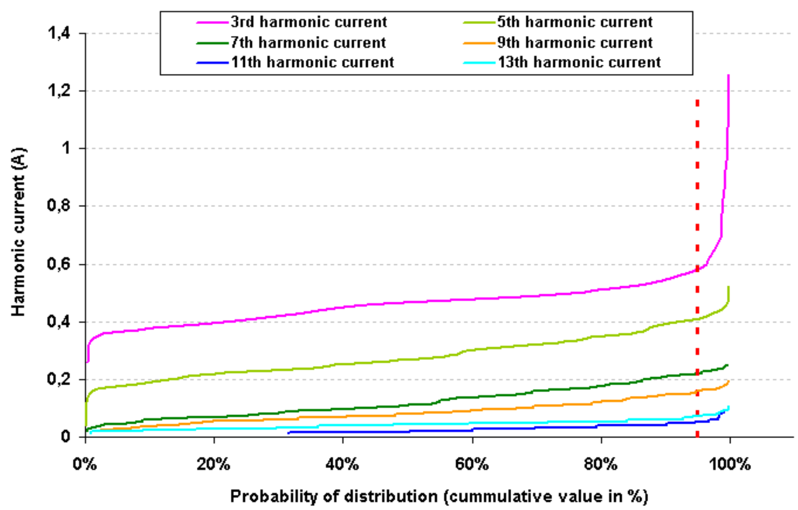


Figure 4.23. Current and THD_I of a LV feeder with many PV installations

The weekly measured field data (10 minutes rms value) are usually compared with the 95% probability value of the standard limits to evaluate the performance of a real network. Field measurement is done at a household customer's POC which is located at the far end of a LV feeder. One week's 10 minutes rms data is analysed to find out the probability distribution for the values of the fundamental and each order harmonic current at the POC as shown in Figure 4.24 (a) and Figure 4.24 (b) respectively. Field measurement shows that the 95% probability value of the fundamental current demand at the installation is 4.2A, with a maximum demand of 13A. Similarly, the 95% values of various orders of harmonic currents can be estimated from Figure 4.24 (b). The THD_I value at the POC is found 18% and the THD_V value 2.4%. These data are comparable to the simulation results that were found for a house with average load.



(a) Fundamental current component



(b) Harmonic current components

Figure 4.24. Current probability distributions at a household customer's POC located at the far end of a LV feeder (measured data for one week)

4.4 Voltage dip profiles

It is common that a voltage dip originates in the network and propagates to various customers' installations. A voltage dip can cause mal-operation of sensitive process devices and the protective devices in the customer's installation, and (in an extreme situation) can lead to a stop of a customer's process operation if it is not properly mitigated with effective measures. Therefore, for an industrial customer (who has sensitive process at his installation), it is necessary to know the yearly voltage dip profile of the network. According to this information, it is possible to take the necessary action such as:

- Changing the customer's process operational sensitivity by installing high immunity devices.
- Incorporating suitable mitigation devices to protect the installation from damage caused by voltage dips.
- Other alternative measures.

Hence, a methodology is to be developed for identifying voltage dip problems and the necessary means needed to overcome it. Next, voltage dip simulation is done on a typical MV network to estimate the number of voltage dips expected at an industrial customer's POC that are causing operational problems in the installation. The network's fault statistics and the customer's devices voltage-time tolerance characteristics are needed for the analysis.

4.4.1 Methodology for voltage dip problem mitigation

Figure 4.25 shows a flow chart that describes a methodology to tackle voltage dip problem at an installation.

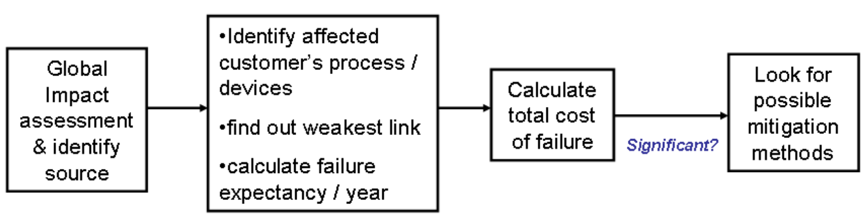


Figure 4.25. Methodology to mitigate voltage dip problem at a customer's POC

First, it is necessary to know the frequency and severity of voltage dips occurring in the network on a yearly basis. Also, it is important to identify the origin of voltage dips in the network. Next question arises how frequent a specific customer's POC gets affected by voltage dips in the network. Therefore, it is required to assess the vulnerability of the customer's installation against different types of voltage dips. The customer can keep an account of each potential voltage dip that causes financial losses to his installation. Thus, the total annual cost of voltage dips can be calculated for the customer. Depending on the severity of the customer's financial losses, mitigation measures need to be taken to prevent voltage dip related damages. The optimum solution can vary significantly depending on the characteristics of voltage dips, the related damage costs of the affected customers and the investment for the mitigation methods to protect the installations against voltage dips. The cost of mitigation could be shared by a customer, or a group of customers and the network operator depending on the situation and mutual agreements between them on the provided electricity service.

4.4.2 Voltage dip simulation

Voltage dip simulation is done on the MV network model that is discussed in chapter 2. Various failure frequencies of the MV network components (such as MV cables and terminals) are taken from the Dutch network's reliability report [Com01]. The following failure rates are considered for estimating fault frequency in the network:

- Line failure rate (λ_l): 0.0243/km cable/year
- Terminal failure rate (λ_t): 0.012/connection/year

In Dutch networks, the majority of faults in the distribution network occur due to ground digging, component erection work, and ageing effects of the network components. When compared with other European networks, the failure frequency in Dutch networks is much lower because of the underground cables used in the MV grid. The fault probability data (number and types of short-circuits) are taken from the yearly statistics of the Dutch network operators. Different types of voltage dips are described in chapter 2. It is found that in the MV network 50% of the faults are of 'type I', 25% of them are 'type II' and the rest of 25% are of 'type III' [Cob02]. However, these fault distributions can vary largely among different networks. All those information are utilized to simulate the voltage dip problem in the MV network model of Figure 4.26.

4.4.2.1 Simulation case

A case study is defined to simulate short-circuit faults and to estimate the voltage dip profile at a typical MV industrial customer's POC in the network. Figure 4.26 shows a typical MV feeder with a series coil at the beginning, and the locations of primary and secondary protections in the network. It is assumed that an industrial customer is located at ‘Node 7’ at which the voltage dip profile is to be estimated. In the simulated network, total 15 outgoing feeders are present in the MV substation.

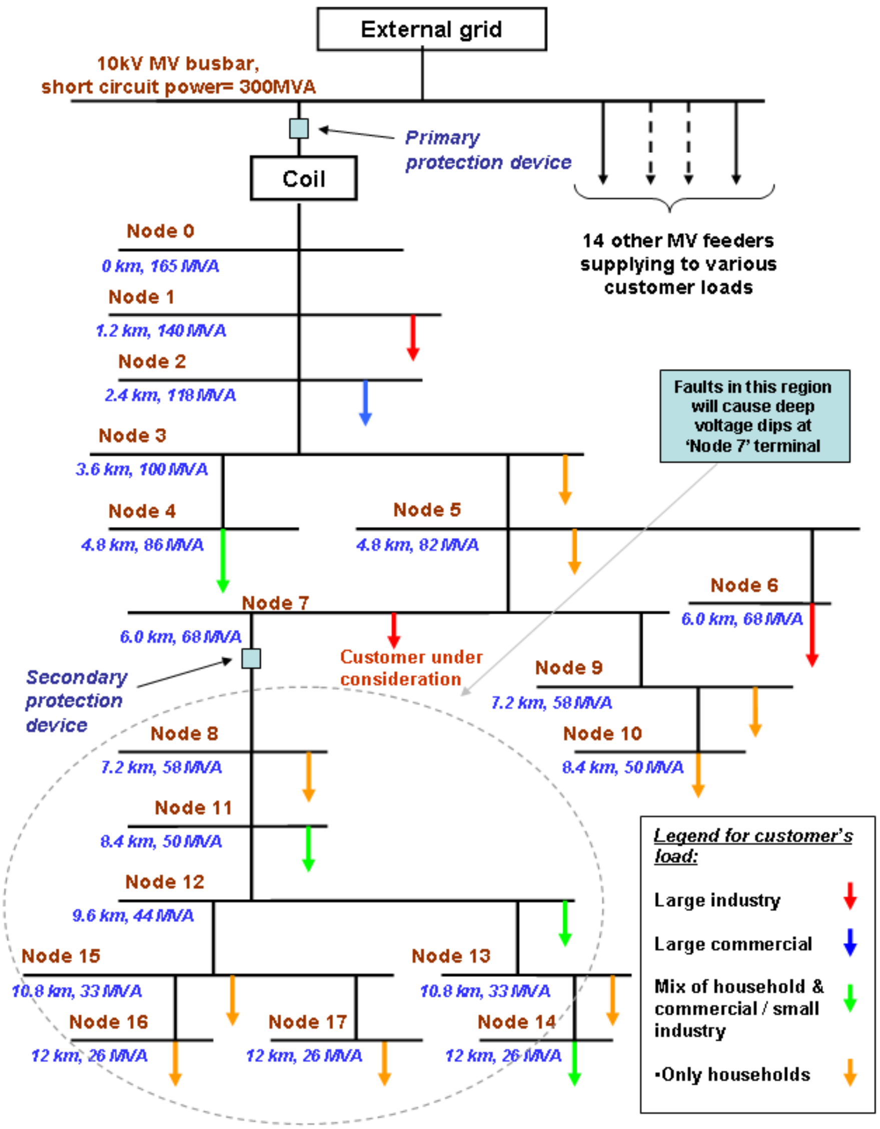


Figure 4.26. MV network used for voltage dip simulation

In this case study, different types of short-circuit faults are initiated at different terminals and in the middle of each feeder sections. Therefore, a short-circuit location in the simulation can, for instance, be a point which is 600m away from 'Node 5'in the line segment connecting the busbars 'Node 5' and 'Node 7'of Figure 4.26. The standard IEC 61000-4-30 (2003) [Iec08] states that in a three-phase system the residual voltage is calculated based on the lowest half-cycle rms voltage in any of the three phases. Therefore, it is assumed that the selected customer (or the customer's sensitive device) is connected to the faulted phase. In the simulation, short-circuit faults generated below 'Node 7' are cleared by the secondary protection device and consequently the customer at 'Node 7' faces a deep voltage dip at his terminal. However, when a fault occurs above 'Node 7' of that feeder, it is cleared by the primary protection device in the feeder and all customers of that feeder suffer interruption. Thus, the customers located below the secondary protection device will face more interruptions than the customers located before 'Node 7'. The main purpose of secondary protection in the network is to improve reliability of the network operation. In the Dutch networks, most MV feeders do not have a series coil connected at the MV substation. Those substations have relatively lesser short-circuit power (for example 160MVA as compared to 300MVA used in the present analysis). A MV substation with short-circuit power of 300MVA and a series coil connected at the beginning of a MV feeder has an equivalent voltage dip performance as that of a MV feeder without coil and connected to a 160MVA capacity substation. The presence of a series coil restricts the short-circuit current and voltage drop (and hence, the impact of the voltage dip) at different installations on the network.

4.4.2.2 HV networks fault statistics

In the HV networks, majority of the faults are of single-phase ('type I') faults. In the Netherlands, it is found from statistics that only one-third of the recorded faults are balanced three-phase faults. The HV/MV transformers are mostly of 'Yyn' type and impedance grounded to reduce fault propagation along the network. In contrast, it can cause voltage swell at the healthy phases for unbalanced faults. As a pessimistic approach ('worst case' study), it is assumed that all faults generated in the HV network are propagated to the MV network without any change. In reality, only the three-phase 'type III' faults occurring in the HV and other upstream networks propagate to the MV and other downstream networks without any significant modification. Table 4.6 shows the average number of voltage dip events recorded with respect to various residual voltage levels and duration of dips in the HV networks (for the year 2008) [Hes01]. This statistic includes all type of faults in the HV networks. In the present analysis, it is assumed that all the faults recorded in the HV networks are of 'type III' only. Hence, all faults are propagating into the MV network. The voltage dip profile of 2008 is utilized in the simulation to estimate the number of voltage dip events at a MV customer's POC. From Table 4.6, it can be found that the total number of voltage dips because of faults in HV network is 7.8 in a year and most of them are cleared with in 0.5s.

Table 4.6. Voltage dip profile of HV networks (2008)

Residual voltage (pu)	Duration of dips (s)				
	0.01-0.02	0.02-0.1	0.1-0.5	0.5-2.5	2.5-5
0.8-0.9	0.05	2.05	0.95	0.1	0.1
0.7-0.8	0.05	2.05	0.95	0	0
0.6-0.7	0	0.17	0.07	0	0
0.5-0.6	0	0.17	0.07	0	0
0.4-0.5	0	0.17	0.07	0	0
0.3-0.4	0	0.125	0.08	0	0
0.2-0.3	0	0.125	0.08	0	0
0.1-0.2	0	0.125	0.08	0	0
<0.1	0	0.13	0.09	0	0

4.4.2.3 Fault simulation on MV networks

The fault simulation is done on the network of Figure 4.26. First, the voltage dips frequency at the selected MV customer's terminal ('Node 7') because of different faults initiated in the MV network (considering the contributions of all 15 MV feeders) is estimated. Table 4.7 shows the voltage dip profile at the selected MV customer's POC due to various faults occurring in the MV network (as found from simulation).

Table 4.7. Voltage dip events occurring in MV networks

Residual voltage (pu)	Duration of dips (s)				
	0.01-0.02	0.02-0.1	0.1-0.5	0.5-2.5	2.5-5
0.8-0.9	0	0	0.074	1.525	0
0.7-0.8	0	0	0.065	0.372	0
0.6-0.7	0	0	0.082	0.288	0
0.5-0.6	0	0	0.029	0.204	0
0.4-0.5	0	0	0.006	0.084	0
0.3-0.4	0	0	0.021	0	0
0.2-0.3	0	0	0.007	0	0
0.1-0.2	0	0	0.006	0	0
<0.1	0	0	0.015	0	0

From Table 4.7, it is found that the total number of voltage dip events in the MV network is 2.78 in a year due to various faults occurring in the MV cables and terminals. It shows that about 1.6 voltage dips/year are occurring with a residual voltage of 0.8-0.9 pu (of the nominal voltage), whereas a voltage dip with a residual voltage less than 0.4 pu occurs seldom at the customer's POC. From the analysis, it was found that the customer, under consideration, suffers around 0.304 voltage dip events in a year due to the faults in its own feeder. Rest of the voltage dip events (approximately 90% of the total events originated in the MV networks) are contributed by the other 14 parallel feeders connected to the same MV substation.

4.4.2.4 Combined voltage dip profile at the customer's POC

As discussed in the previous sections, the voltage dips events originated in the HV network are assumed to be transferred to the MV network. Moreover, the MV network produces voltage dips due to various fault events in the MV network. Therefore, by combining the fault contributions of the HV and MV networks, the total voltage dip frequency at a customer's POC (such as 'Node 7') can be calculated. From the present analysis, is found that the considered customer can expect yearly total 10.6 voltage dips at his installation. All the voltage dip events found from the simulation for various voltage magnitudes and durations are grouped accordingly to compare them with the voltage dip table of the EN50160 standard (refer Table 2.2). An example of the number of voltage dip events calculation of voltage dip table is discussed in Appendix C-4.

Table 4.8 shows the voltage dip events at the 'Node 7' customer's POC when all the dip events are presented in the equivalent 'voltage dip table'. In addition to that, Figure 4.27 [Bha06] shows the three-dimensional plot of various voltage dip events occurring at 'Node 7' of the simulated network.

Table 4.8. Voltage dip events from simulation presented in the EN50160 format

Residual voltage U [%]	Duration t [ms]				
	20 ≤ t ≤ 200	200 < t ≤ 500	500 < t ≤ 1000	1000 < t ≤ 5000	5000 < t ≤ 60000
90>U≥80	2.10	1.02	0.80	0.92	0
80>U≥70	2.10	1.01	0.18	0.19	0
70>U≥40	0.51	0.32	0.27	0.28	0
40>U≥5	0.46	0.31	0	0	0
5 >U≥0	0.06	0.04	0	0	0

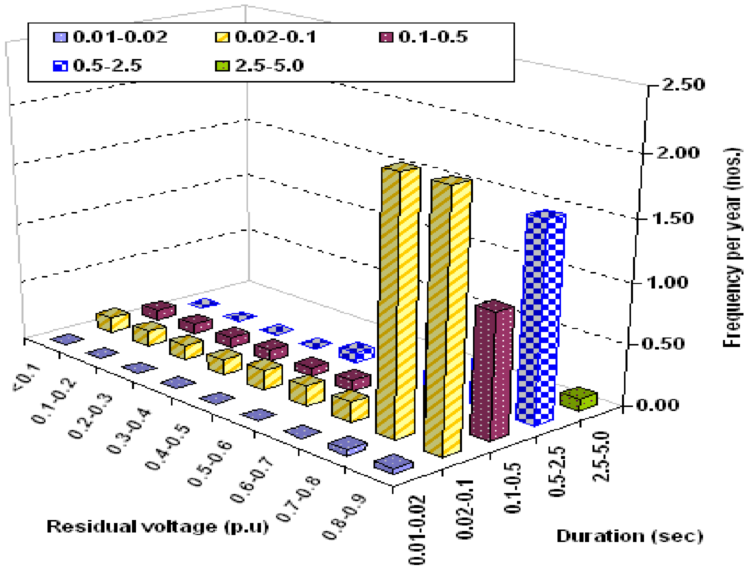


Figure 4.27. Annual occurrence of voltage dips at 'Node 7'

4.4.3 Estimation of process failures at a customer's POC

Not all the voltage dip events that occur at a POC lead to an interruption of the customer's (process) installation. As found in the previous section, there would be 10.6 voltage dips in a year at the customer's POC ('Node 7') of the simulated MV network due to various fault events in the network. This number includes all the voltage dips of different magnitudes and durations. However, only a few of the voltage dip events will cause actual process stoppage at a customer's installation. This depends largely on the 'voltage-time tolerance' (immunity) characteristics of the customer's devices (or total process immunity characteristics of the installation). In the following section, it will be discussed more in detail.

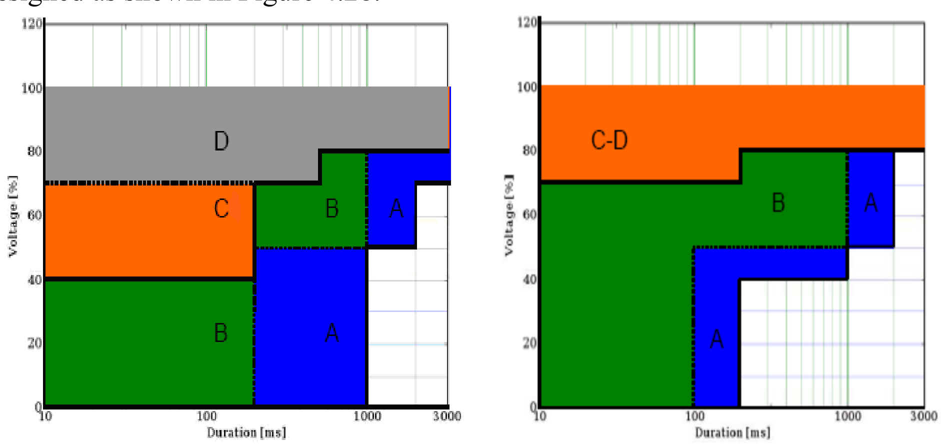
4.4.3.1 Devices sensitivities/immunities to voltage dips

Many customers are connected to the electricity network. Each of them is unique in terms of their sensitivities to voltage dip. From different case studies, it was found that the industrial customers are the most sensitive to voltage dips and associated financial losses. The main factors for calculating the sensitivity/failure risk of a customer's installation are:

- The voltage tolerance graphs of the connected devices and their tripping probability/chance due to a voltage dip.

- Respective locations of sensitive devices and their relative importance level in the installation.
- Characteristics and number of the occurring voltage dips (its magnitude, duration, point on wave, phase angle jump, etc.).
- Interdependence of various critical devices from the operational point of view of the complete process.

A detailed analysis is to be done to find out the most vulnerable devices that can stop the process operation. A customer's process immunity can be estimated by analyzing the process layout and failure risks of important devices. Typical devices used by an industrial customer are AC contactors, personal computers, programmable logic controller (PLC), or variable speed drives (VSD). Three electromagnetic environment classes are specified in the IEC 61000-4-11 standard [Iec03]. The 'class 1' applies to protected supplies and has compatibility levels lower than public network levels. Therefore, this class relates to devices that are very sensitive to disturbances in the power supply (such as computers, automation and protection devices, etc.). A 'class 2' refers to the devices that are connected to a POC or a PCC in an industrial environment. The compatibility levels in this class are identical to those of the public networks. The 'class 3' devices have higher compatibility levels than that of 'class 2' for some disturbance phenomena. Examples of such type of devices are welding machines, large motors that start frequently, etc. According to the proposal of the CIGRE/CIRED JWG C4.110 [Cir01], various immunity labels of devices for different types of dips can be assigned as shown in Figure 4.28.



(a) For unbalanced dips (b) For balanced dips

Figure 4.28. Immunity classes recommended for different voltage dips [Cir01]

The immunity requirements for balanced faults are less severe as they do not occur very frequently in the network. The immunity class 'A' holds for the best immunity class and the class 'D' for the least immunity class device. The class 'C' can again be divided in two: C1 and C2. Both the 'C1' and 'C2' labelled devices are tested based on the requirements for 'class 3' environment of the IEC 61000-4-11 standard. There is a little difference between the 'C1' and 'C2' classes in defining the immunity limits for the unbalanced voltage dips. The 'C1' class gives voltage limit up to 40% of the nominal value (as shown in Figure 4.28), whereas the class 'C2' is meant for 50%. The class 'D' devices are meant for usage in a 'class 2' environment. When a device manufacturer sells a device (of a specific 'class mark') he should guarantee the performance of it for the immunity requirements shown in Figure 4.28. Further, the customer can buy the appropriate device from a device manufacturer, depending on his installation's process immunity requirements.

4.4.3.2 Customer's process sensitivity to voltage dips

An important step to voltage dip performance analysis is to identify the customer's process performance requirements. The customer has to decide about the acceptable maximum number of process stoppage possibilities in a year due to voltage dips. First step is to identify the process immunity time (PIT) by including all devices in the process chain and estimate the maximum duration (of a voltage dip) for which the process can survive without a normal voltage at its terminal. When a voltage dip occurs at a customer's installation, one or more sensitive devices may trip immediately; but because of their self-recovery actions they could come back in operation and the process may not be interrupted. Therefore, a failure risk analysis of the whole process chain is needed to identify the weakest link. Reference [Cha02] describes a procedure to identify the most vulnerable device in a process by analyzing various sensitivity indices and respective process immunities to voltage dips.

By analyzing individual device and its impacts to the whole process chain, the process immunity time and respective voltage tolerance curve for the complete process can be determined. It is also possible that by incorporating some changes in the production chain such as modifying some devices with high immunity class or implementing a mitigation measure in the installation, the process immunity to voltage dips can be increased. The desired immunity requirement for the selected process device can be obtained after analyzing the network's yearly voltage dip profile. It is to be noted that with high immunity requirements of a device, the cost of manufacturing also increases.

The draft version of IEEE P1564 [Iee02] recommends the SEMI curve [Sem01] as a reference for specifying the voltage dip tolerance of a device. For this research, the SEMI curve is taken as the ‘immunity graph’ of the considered customer's installation (including the immunity requirements of the protection devices connected at the supply terminal of the customer’s POC). Figure 4.29 shows a method to count the voltage dip events that are causing process problems by combining the information of Table 4.8 along with the SEMI graph (shown by ‘pink line’). The number of events that fall in the danger zone can be counted to estimate the frequency of process failures in a year. In this case, the number of voltage events that leads to process failure is 2.1 (=0.46+0.06+ 0.31+0.04+0.32+0.18+0.29+0.28+0.19), as can be counted in Figure 4.29. Therefore, approximately 2.1 voltage dip events per year are likely to cause process problems at the customer’s POC. Thus, by applying this procedure, the annual financial losses due to voltage dips for a customer can be estimated.

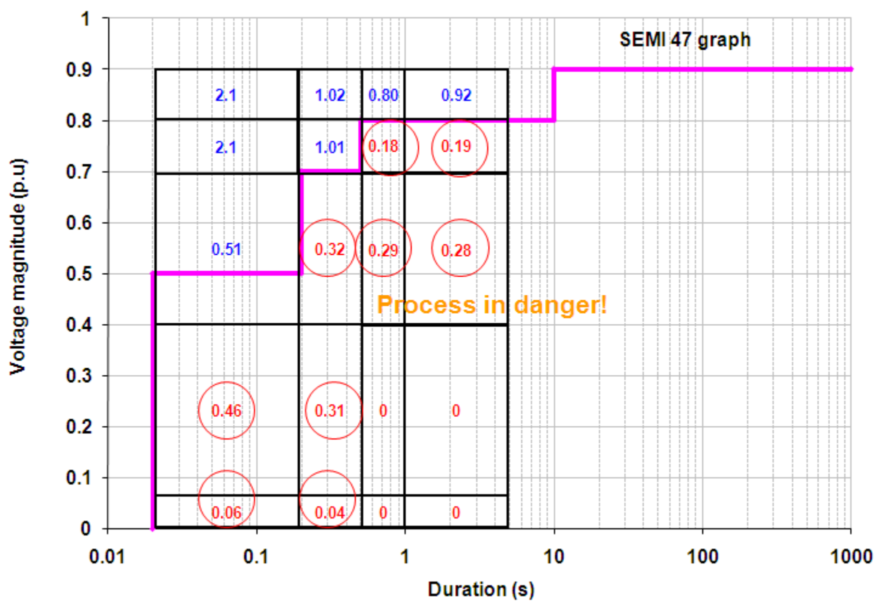


Figure 4.29. Voltage dip profile at the simulated MV customer’s POC in EN50160 standard format along with the SEMI graph

4.4.4 Field measurement data on voltage dips

In the Netherlands, voltage dip measurements are done mainly in the HV networks. Under the KTI project, measurements are conducted in the MV network for specific customers. Figure 4.30 shows the recorded voltage dip events (all types) at a MV customer's POC (stone factory) over a period of two years. However, no financial loss data are known for this customer.

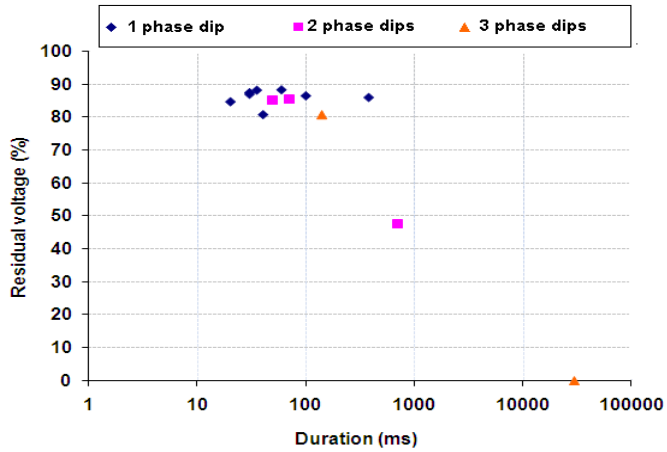


Figure 4.30. Recorded voltage dips at a MV customer's POC (2 years period)

Figure 4.31 shows the results of another voltage dip measurement campaign conducted at an automobile customer's installation over a five years period. From the records, it can be noticed that many three-phase voltage dips have occurred at the customer's POC. Most of the three-phase dips were of either small duration or small magnitude (voltage dip with a residual voltage of 80% or more) and did not cause much damage to the customer's process operation. However, it was found that the customer suffered approximately three process outages in a year that caused significant financial losses.

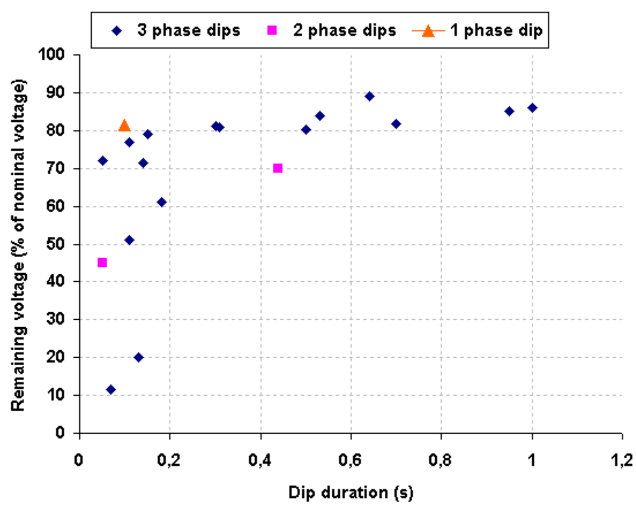


Figure 4.31. Recorded voltage dip-data at a customer's POC (in 5 years period)

Reference [Lum01] describes a detailed technical and financial analysis for the voltage dip example case of Figure 4.31. There are three departments (the metal operation, spray coating, and assembly) in the considered (automobile) installation where process interruptions occurred due to voltage dips. The damage was due to the failures of many programmable logic controllers and variable frequency drives present in the process. This case and its financial impacts are again discussed in detail in chapter 6 of the thesis.

4.5 Summary and conclusions

In this chapter various simulations are done on the modelled networks to estimate flicker severity and harmonic distortion level at different customer's installations. Also, voltage dip simulation is done to estimate the expected number of voltage dips in a year at a MV customer's POC. Moreover, some field measurements are discussed that indicate the existing PQ performance in the Dutch networks. Various findings are summarized below:

Flicker simulation with an 'average grid' situation shows that the maximum P_{st} values at a LV customer's installation are in the range of 0.55-0.66 (with the assumption of MV background flicker pollution P_{st}=0.5). Flicker severity varies depending on the location of the flicker source in the network and the impedance of the observation point. This analysis is in close match with the field measurement results. It was observed that MV background pollution has some influence on the P_{st} values at a LV customer's terminal. Motor start simulation for a 'pessimistic situation' shows that P_{st} value at a 50A installation is 0.86 and that for a 63A installation is 0.84, when the MV background flicker (P_{st}) level is 0.70. This case considered maximum network impedance at the observation points with a motor start inrush current equal to the connection current capacity. The P_{st} values at the observation points are found less than the expected value of 1.0. It is because of the fact that the actual voltage drops at the observation points are less than the reference value given in the 'IEC/UIE flickermeter curve'. The obtained results are compared with the proposed method of the technical report of TR/DNO and are found comparable. The analysis results of the simulation case are further utilized in chapter 5 to estimate flicker emission limit at different LV customer's installations and for proposing the planning level values of flicker severity in different voltage levels.

Harmonic simulation was done for four different cases. In the first three cases, each LV feeder's current loading is considered as 70A (which is a heavy loading condition for Dutch LV networks). All cases considered different combination of houses in the LV network. Among the simulated cases, the worst situation occurs when the LV network consists of houses with similar type of loads. Two different MV background distortion conditions are considered: average and maximum background distortion. The fourth case is a situation that is found more common in the Dutch networks in which LV feeder's current loading is 40A. This case is analysed considering the above MV background distortion conditions. The analysis of harmonic voltages at different installations shows that the THD_V is in the range of 4.5-5.5% for the average MV distortion case and 7-7.8% for the high background distortion case. Thus, all values found are within the EN50160 standard limit of 8%. However, it was noticed that some specific order harmonic voltage components exceed the EN50160 standard's limit values. Harmonic currents of different installations found from the simulation case studies will further be compared with the standard values in chapter 5 to specify harmonic current emission limits for a LV customer.

The voltage dips analysis was done on the modelled MV network. The network components' fault statistics were derived from the network's reliability report of the Netherlands. It was found that the failure probability of a customer's installation depends largely on the 'voltage dip immunity' characteristics of critical devices of the customer's process. From analysis, it was found that an industrial MV customer experiences yearly 10.6 voltage dips at his installation. However, the installation will face process voltage dip related problems approximately two times in a year (for the considered dip profile) when the process's voltage immunity characteristic is based on the 'SEMI 47' curve. When a customer's process immunity graph and the network's voltage dip statistics are known accurately, it is possible to find out the yearly failure rate of a customer's process. Eventually, a suitable mitigation method can be adopted to solve voltage dip problems as they often cause large financial losses. In chapter 5, the approximate number of voltage dip events in a year for the Dutch network is estimated.

Field monitoring is an important step to evaluate the present PQ situation in a network. Further, simulations of the present and future scenarios can indicate the possible problems in the network. PQ regulation can be effectively applied by the regulators when the network operator, the customer and the device manufacturer are aware of the network performance and the consequences of various PQ related inconveniences.

Chapter 5

Guidelines for Optimal PQ at a Point of Connection

5.1 Introduction

A number of PQ related standards exists at national or international levels. The International Electrotechnical Committee (IEC) has created a group of standards for defining, measuring and testing different power quality (PQ) aspects. Also, regional standards (e.g. the Australian standard AS/NZS 61000 series, the European standard EN50160) are available that give limiting values for different PQ parameters. Furthermore, many standards are available at the national level (e.g. British standard - BS, American standard - ANSI, the Dutch 'Grid Code'), at industrial associations (e.g. IEEE, SEMI, NRS) and electricity companies (e.g. EDF, Eskom). So, there are many differences among the standards which make the situation difficult to compare. Moreover, no dedicated standard exists for the customer's installation that clearly defines the limits on various PQ parameters. In addition, the number of disputes among the network operators, the customers and the equipment manufacturers regarding their respective responsibilities and the limits on various PQ parameters at a point of connection (POC) continues to increase. To achieve a harmonized PQ standard, the IEC works together with different national and regional regulatory and standardization organizations of the world. As a result of those collaboration works, important pre-standardization documents are developed that form the basis for the development of new international standards. In this chapter, first an inventory is done on various PQ standards that are available in the world. Next, based on the findings of previous chapters of this thesis, (new) emission limits on flicker and harmonics at a customer's POC are suggested. Furthermore, the average number of voltage dips is estimated and the way to use this information is discussed.

5.2 Present PQ standards

In the recent years, the 'CIGRE/CIRED- Joint Working Group C4.103 has carried out an intensive investigation to standardize various limit values of different PQ parameters. A research in the field of voltage quality is also done by EURELECTRIC (Union of the Electricity Industry) / UNIPEDE (International Union of Producers and Distributors of Electric Energy) and UIE (International Union for the Application of the Electricity). In the USA, a similar kind of research activity is carried out the 'IEEE Standards Coordinating Committee on Power Quality'. Standardization is achieved at international level by IEC and CENELEC at European level. In recent years, these international committees have decided to combine and upgrade their activities based on changes in the electricity business. The PQ standardization requires attention on mainly three aspects: emission levels from installations and equipment, immunity of equipment and the propagation of disturbances in the network. The basic aim of PQ standardization is to define limits for satisfactory performance of the network and connected equipment, to develop methods for assessing accurate performance, and assign responsibilities of the involved parties. Figure 5.1 [Mcg01] illustrates the PQ standard development activities.

The standard EN50160 gives the main characteristics of the supply voltage at a customer's terminal under normal operating conditions. It gives limit values within which a customer can expect the supply voltage being characterized at his POC. During recent years, with cooperation of various organizations and regulators, the EN50160 standard has been improved and the latest version of this standard [Std04] is published in 2010.

At the customer's POC, various electrical and electronic devices are connected. Those should operate safely and accurately. Each of the customer's equipment is characterized by their emission level and immunity level. The immunity level is the highest level of the disturbance that will not cause problems to equipment or installation. The IEC standards define also a compatibility level which is the boundary between the highest acceptable emission and the lowest acceptable immunity level in the system. The compatibility level is based on the existing disturbance level in the network. However, the disturbance level is generally different throughout the network and varies with time. The IEC standards define the supply environment, the susceptibility of equipment to adverse PQ, and the emissions from equipment (that can influence PQ) and their measurement methods. Thus, a coherent family of standards (such as the IEC 61000 series) allows for an efficient coordination of the design of the electricity network and the connected equipment.

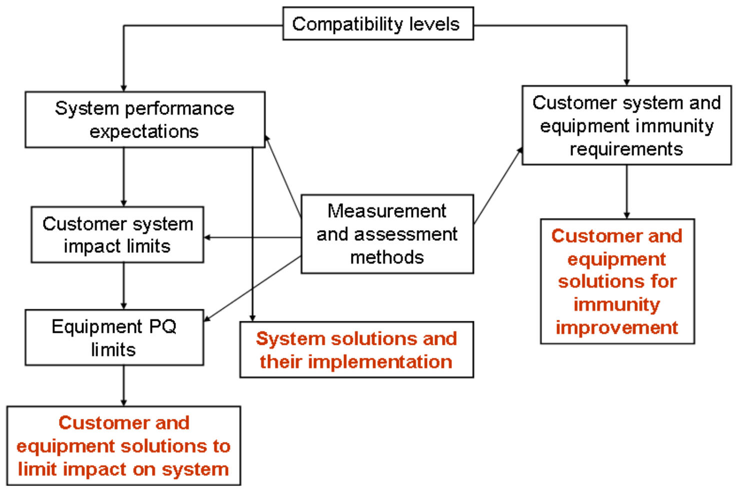


Figure 5.1. PQ standard development activities

The South African standard NRS 048-2:2007 [Nrs01] gives 'minimum standard' requirements for electricity supply in the network. It gives voltage characteristics, compatibility levels, limits and assessment methods to measure the quality of electric supply. It defines customer's rights to supply quality and conditions under which the standard is applicable. This standard also specifies limits (characteristic values) for voltage dips at different voltage levels.

5.2.1 European standard 'EN50160'

The European standard EN50160 is used as a guideline for the voltage quality in the European public electrical networks. It defines, describes and specifies the characteristics of supply voltage concerning frequency, magnitude, waveform and symmetry of the voltage. This standard is not applicable for any abnormal condition in the network such as when a fault occurs, or an emergency situation arises. The voltage characteristics given in this standard are not intended to be used for specifying requirements in equipment standards. The limits given for various voltage characteristics are often stricter than the compatibility levels specified in various IEC standards. The Council of European Energy Regulators (CEER) wanted to improve this standard in order to apply it as a 'minimum standard' by the national regulators for fulfilling voltage quality needs. A frequent criticism of the EN50160 standard was that it gives limits related to conditions that exist just for 95% of the time. In 2006, the European regulators group for electricity and gas (ERGEG) published a public consultation paper [Cer03] and the following recommendations were made to CENELEC for revising the EN50160 standard:

- Improvement of definitions and measurement rules for many voltage parameters, changing the limit of voltage variation (from 95% to 99% or 100% of the measured time).
- Enlargement of the scope to high voltage levels.
- Defining rights and duties of all the involved parties.
- Introduction of limits for voltage dip events.

Another criticism of the EN50160 standard is related to its conservative approach as this standard excludes all abnormal operating conditions. Also, as it takes 10 minutes intervals for averaging, it excludes all short-duration phenomena. In 2007, the CEER/ERGEG published a conclusion paper [Cer02] suggesting a roadmap for the revision of EN50160 and recommending that it should be applicable to all electric networks in Europe. Also, it should give ‘responsibility sharing curves’ between the network operator and customer on various PQ issues. In 2009, the final draft of 'FprEN50160' [Std02] was approved by the CENELEC members. The main modification of the new version was changing the 95% limit to 99% for voltage variations in the network. The latest edition of the EN50160 is published in 2010 [Std04]. Appendix C-1 shows the main modifications in the EN50160:2010 standard as compared to EN50160:2007 [Std03] standard.

5.2.2 The Dutch ‘Grid Code’

The Dutch Grid Code [Dte01] gives limits for different PQ parameters mostly in line with the European standard EN50160. However, in some cases, the Dutch Grid Code gives stricter boundary limits than that of the EN50160 standard. Main differences are shown in Table 5.1. The national PQ measurement results of the Dutch networks were discussed in chapter 2. It was found that there are occasional violations of the limits of the Grid Code on flicker severity level (P_{lt}) and the 5th harmonic voltage values in the Dutch network (refer Figure 2.6 and Appendix A-2). However, all measurement results for the period 2005-2008 satisfy the limits of EN50160 standard.

Table 5.1. Comparison between the Dutch Grid Code and the EN50160 standard for the MV and LV networks

PQ Parameter	Dutch Grid Code	EN50160:2010 standard
Flicker severity	Additional limit on maximum value of $P_{lt} \leq 5$ during 100% of the time	Maximum limit for P_{lt} is ≤ 1 during 95% of the time
Voltage unbalance	Additional limit on negative sequence voltage that should be smaller than 3% of the positive sequence for 100% of time	Negative sequence voltage is smaller than 2% of the positive sequence during 95% of time
Total harmonic voltage distortion	Additional limit for $THD_V \leq 12\%$ that includes harmonics up to 40^{th} during 99.9% of the time	$THD_V \leq 8\%$ for harmonics up to 40^{th} during 95% of the time
Harmonic voltage distortion	Additional limit is given for 99.9% of the time. Individual harmonic value should be smaller than 11/2 times the value given for 95% of the time	Individual harmonic limit is given for 95% of the time
Fast voltage variations	Normal condition $\leq 10\%$ U_{nom} (U_c). It is $\leq 3\%$ U_{nom} (U_c) in situations without loss of production.	As per IEC 61000-3-3 limits, relative steady state voltage change should be limited to $\leq 3.3\%$ U_{nom} (U_c).

Note: In the LV network the nominal voltage (U_{nom}) and in the MV network declared voltage (U_c) are used as reference voltage respectively.

5.2.3 IEC 61000-series of standards

The compatibility levels for low frequency related PQ disturbances are described in the IEC standards. To ensure the compatibility, all LV equipment must have immunity levels that are higher than the compatibility levels. Also the cumulative effect of emissions from different customers should not disturb the normal operation of the network. Figure 5.2 shows different IEC 61000 series of standards that are related to different PQ parameters.

The standard series of IEC 61000-2-x specify compatibility levels for low frequency related disturbances on public electric power supply. The emission condition and immunity levels of electric equipment are described in a series of IEC 61000-3-x standards and IEC 61000-4-x standards respectively. Various emission standards on different PQ parameters such as IEC 61000-3-3 [Iec01] and IEC 61000-3-11 [Iec13] for flicker; IEC 61000-3-2 [Iec05] and IEC 61000-3-12 [Iec14] for harmonics; and IEC 61000-3-13 [Iec12] for unbalance, etc. These standards give limits on individual device's emission levels for connecting them in an installation. In the last couple of years, a number of standards have been developed or revised for connection requirements of disturbing installations in the MV/HV/EHV networks; such as IEC 61000-3-6 [Iec11] standard for harmonics emission limits and IEC 61000-3-7 [Iec04] standard for flicker emissions. Another important IEC technical document is IEC/TR 61000-3-14 [Iec07] that gives the emission limits for connection of disturbing installations in the LV network. Examples of standards on immunity limits are IEC 61000-4-11 [Iec03] and IEC 61000-4-34 [Iec09] for voltage dips. The IEC 61000-4-30 [Iec08] gives testing and measurement guides on various PQ parameters.

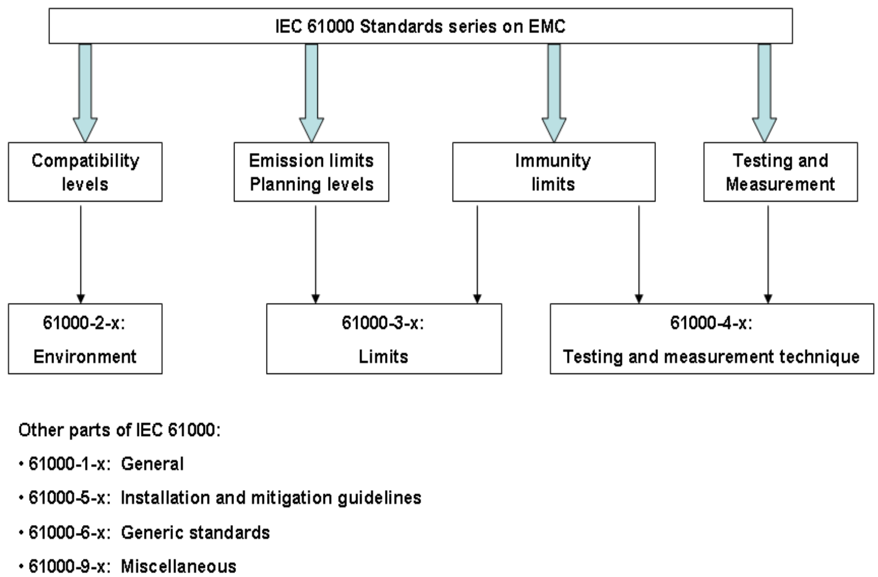


Figure 5.2. Overview of IEC 61000 standards

5.2.3.1 Planning and compatibility levels

Terms as 'planning level' and 'compatibility level' are commonly used by the IEC 61000 series standards for defining PQ disturbance levels. The relations among the planning level, compatibility level and immunity level for the entire network and an individual site are shown in Figure 1.3. The compatibility levels of various PQ parameters are given in the IEC 61000-2-2 [Iec06] for LV network and in the IEC 61000-2-12 [Iec10] for MV network. Those levels are used as reference values in the network for 95% of the locations and for 95% of the time.

5.2.3.2 Emission limits

The CIGRE/CIRED JWG C4.103 tried to update existing IEC emission standards and to set limits for disturbing installations. For steady-state disturbances, such as harmonics, flicker and unbalance, two categories of indices are distinguished: a) indices for planning purposes; b) indices for actual voltage characteristics. Indices for planning purposes can be used by a network operator to assess internal quality objectives in setting emission limits for disturbing loads and evaluating the impact of all disturbing loads in the network. The voltage characteristic indices are used to assess external quality objectives within which a customer can expect the supply voltage characteristics to remain under normal operating conditions. The level of disturbance will be depending on the network's impedance and the loading, and will vary according to the time of day, day of the week and time of the year. According to the EN50160 standard, 95% of the measured data on each PQ parameter in the network should not exceed the compatibility level. It is a statistical value and characterizes the state of the network. Three steps are recommended by the CIGRE/CIRED JWG C4.103 to assign an emission limit at a customer's POC in a consistent and comprehensive manner [Bea01].

- Adoption of a general summation law for accumulating disturbances from various sources.
- Allocation of global contributions at a given voltage level to ensure co-ordination between different parts or voltage levels of a system.
- Assignment of emission limits of an installation based on sharing of global contributions.

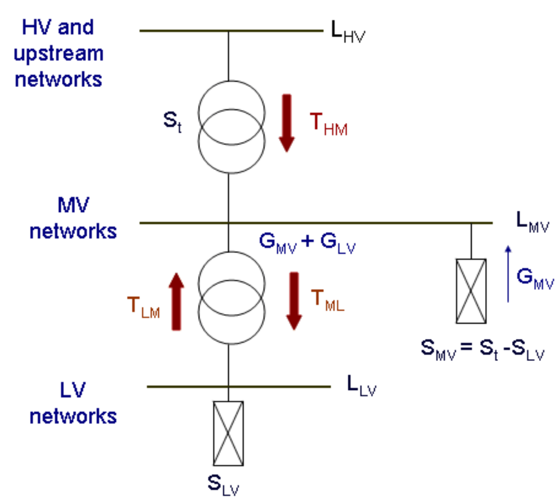


Figure 5.3. Sharing of global contributions of emission in the MV network

Figure 5.3 shows an example of the disturbance level in a MV network that is the sum of emissions from all installations and devices connected at LV, MV and HV voltage levels. Following symbols are used to define various parameters:

- L_{HV}, L_{MV} and L_{LV} represent the planning level values for the HV, MV and LV networks respectively.
- G_{MV} is the maximum global emission limit at a point anywhere in the MV network because of emission contributions of all MV installations.
- G_{LV} is the maximum global emission limit at a point anywhere in the LV network because of emission contributions of all LV installations.
- T_{HM}, T_{ML} and T_{LM} represent the transfer coefficients between the high to medium voltage, medium to low voltage and low to medium voltage levels respectively.
- S_{MV} is the combined capacity of all the MV installations.
- S_{LV} is the combined capacity of all the LV installations.
- S_t is the capacity of the HV/MV transformer that can supply the loads of all the MV and LV installations.

As stated before, the standard IEC 61000-3-6 and IEC 61000-3-7 describe the assessment methods and emission limits of harmonics and flicker respectively for the connection of disturbing installations in the MV, HV and EHV networks. The technical document IEC/TR 61000-3-14 gives these emission limits for large LV installations. All these documents give a relationship between the global emission limit and planning level values for a specific voltage level. Once the planning levels are set, the global contribution to the relevant voltage disturbances can be allocated to all MV and LV installations. Equation (5.1) shows global emission limit at a point in the MV network, ignoring the emission contributions of LV installations to the MV network.

$$G_{MV} = \sqrt[\alpha]{L_{MV}^{\alpha} - (T_{HM} \cdot L_{HV})^{\alpha}} \tag{5.1}$$

where:

- α: summation exponent/coefficient

The transfer coefficients for various PQ parameters (e.g. harmonics, flicker, etc.) in different voltage levels are described in the IEC standards, but can also be evaluated by practical measurements. Furthermore, the report 'Technical rules for assessment of network disturbances' (TR/DNO) [Bar01] also describes methods for calculating network disturbances because of disturbing loads at the LV and MV installations.

5.2.4 IEEE standards

In the United States, the IEEE and ANSI standards are commonly used. The IEEE 1159 [Iee07] contains recommended practice on monitoring PQ and categories of power system electromagnetic phenomena. The IEEE 519 [Iee01] is the standard that gives recommended practice and requirements for harmonic control in the electric power system. This standard gives limits for maximum individual harmonic voltages and the total harmonic voltage distortion (THD_V) for different voltage levels. Additionally, it also gives limits for maximum harmonic current distortion at a point of common coupling (PCC) in the voltage range of 120V to 69 kV. The IEEE 1668 [Iee05] standard is used for voltage dip; whereas IEEE P1564 [Iee02] gives recommended practice for the establishment of voltage dip indices. The standard IEEE 1453 [Iee06] gives recommended measurement guide for flicker in the network and gives various limits on flicker too. Regarding the PQ aspects, the IEEE standards mostly give identical limits and conditions as that of the applicable IEC standards. The latest version of IEEE 1459 [Iee03] standard defines the electric power quantities under sinusoidal, non-sinusoidal, balanced, or unbalanced conditions.

5.2.5 Defining optimal PQ at a POC

Voltage quality is individual for every customer and its effects / perception can be different. It is quite difficult for a network operator to prevent a voltage disturbance in the network. He can soften its impact by strengthening the network. Ideally, a network operator desires to prevent voltage quality related problems by restricting emissions from the devices and the customer's installations connected in the network. A device manufacturer wants to keep overall product cost low for the customer and prefers network modifications or local mitigation when required. On the other hand, a customer wishes low cost, high quality of service and trouble free operation of all devices connected at his installation. However, even in a very good network, PQ problems can occur because of high customer density or certain types of disturbing loads. Thus, the objectives of the three involved parties create conflicting interests regarding their responsibilities. Figure 5.4 [Pre01] represents the optimal PQ that is desired by the customers. It shows that at point A, the customer is satisfied even though he receives a lower PQ level than the basic quality offered by the network operator. At point B, the customer is not satisfied as he is offered a PQ level that is below the basic (minimum) level; while at point C the customer demands higher PQ than the basic offered level. Therefore, to satisfy the customer who is at point B, the network operator has to invest in the network to increase the offered PQ level at least to the minimum basic quality. If the customer B requires higher quality than the basic level, then the customer has to invest the rest. For the customer at point C, the network operator is providing already a higher PQ level than the minimum level. Therefore, the customer has to adjust his requirement or he has to investment more to meet his desired PQ level.

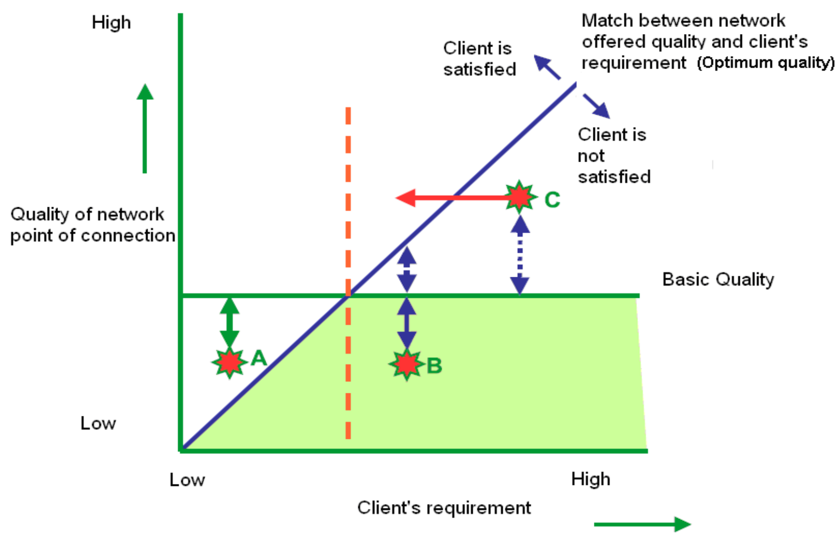


Figure 5.4. Optimal quality desired by a customer [Pre01]

Reference [Pos01] gives guiding principles for developing an optimum limit on harmonics (that further can be extended for other PQ aspects). An optimum standard should focus on minimum overall cost to the society and minimum regulatory interference. It should consider equal opportunity for all the involved parties. The limits have to be developed based on objective data such as power level, actual or expected electricity volume, usage pattern, efficiency and emission properties, etc. Further, the limits should be validated using statistical field data, and/or proven simulation model for predicting future problem. Also, the targeted application area is to be identified. Finally, the developed standard is to be implemented first to the devices that are used widely and then gradually can also be applied for other devices and installations in the network. In this research, PQ measurements are conducted at different installations of the network. Moreover, simulations are done on typical networks to find out the worst possible situation in the network. From those analyses, the actual PQ performances at the customers' installations are determined and emission limits at the POCs are estimated. Various parameters obtained from this research are compared with the limits specified in the EN50160, IEEE, IEC 61000 standards and other relevant technical documents. Further, in this thesis a proposal is made for a dedicated standard with optimal limits on various PQ parameters at a customer's POC.

5.3 Development of PQ standard for a POC

The standard EN50160 specifies the voltage quality requirements in the European network. The IEC 61000 series standards give compatibility, emission and immunity requirements mainly for devices connected to the network. The IEEE series standards are often used (mainly in the USA) as reference to specify limits for certain PQ parameters. The limit values specified in those standards often vary. That makes the situation difficult to compare relative performances of different networks. Therefore, proper evaluation is required to harmonize the limits of various PQ parameters to find an optimum balance of responsibilities of all involved parties. In the following sections various standards on flicker, harmonics and voltage dips are discussed. Optimum emission limits of flicker and harmonic emissions at a customer's POC are suggested. Besides that, the average numbers of voltage dip events in a year for HV and MV networks are estimated (mainly based on Dutch network's annual performance statistics). Various planning level values are proposed that can be helpful for network operators to design their networks in an efficient way.

5.3.1 Flicker

Regarding the flicker severity level, the standard IEC 61000-2-2 provides the compatibility level for the LV network as: short-term flicker severity (P_{st}) of 1.0 and long-term flicker severity limit (P_{lt}) of 0.8. This standard also specifies a compatibility level of 3% for individual voltage variations.

The standard EN 50160 provides restriction on rapid voltage changes in the network. In the LV network, a single rapid voltage change magnitude should not exceed 5% of the nominal voltage under normal operating conditions. However, a change up to 10% of the nominal voltage with a short duration can occur few times per day under certain circumstances. For the MV network, this value generally should not exceed 4% of the declared voltage and changes up to 6% might occur for a short duration under certain conditions. For estimating flicker severity in the network, this standard gives a requirement for long-term flicker severity (P_{lt}) for the MV and the LV networks. It states that in any period of one week the P_{lt} caused by voltage fluctuations should not exceed 1.0 for 95% of the measuring time under normal operating conditions. The standard also instructs that proper measures need to be taken in case of complaints from the customers to restrict the P_{lt} value ≤ 1.

The 'Dutch Grid Code' gives stricter restrictions on rapid voltage variations and additional requirements for the flicker severity level in the network as compared to the EN50160 standard. It allows a rapid voltage change of 3% of the nominal voltage in situations without loss of production, disconnection of heavy loads or faulted conditions. Regarding the flicker severity level, this standard gives restrictions as $P_{lt} \leq 1$ during 95% of the time and $P_{lt} \leq 5$ for 100% of the time.

The IEEE 1453 standard adopts the IEC 61000-4-15 standard for flicker and follows the compatibility level values for the LV and MV networks as given in the IEC 61000-2-2 standard. Probability data are generally used for determining compatibility levels for compliance and are based on cumulative distribution calculations. The IEEE 1453 standard suggests that if the 99% probability data is used instead of 95%, then the customer's complaints can be restricted. Thus, as a general guideline, the P_{st} and P_{lt} should not exceed the planning level values more than 1% of the time with a minimum assessment period of one week. The IEEE 1453 recommends planning level values for the MV and HV-EHV networks that are the same as the values given in IEC 61000-3-7 standard.

The standard IEC 61000-3-7 gives limits on permissible voltage changes per minute (r) based on the relative apparent power variation at the installation (refer Table 2.7). If the short-circuit power of a site is low, the emission limit is determined based on actual system characteristics. Under that situation, the transfer of emission in different voltage levels and the global share of emissions for different customers have to be analyzed in detail. The standard IEC 61000-3-7 specifies indicative value of planning levels for flicker in the MV and HV networks as shown in Table 5.2.

Table 5.2. Indicative planning level values for flicker in IEC 61000-3-7

Flicker Index	Planning levels	
	MV	HV-EHV
P_{st}	0.9	0.8
P_{lt}	0.7	0.6

The LV customer's devices connected to the public network have to meet the requirements of the standards IEC 61000-3-3 or IEC 61000-3-11. If the device current rating is lower than 16A, the standard IEC 61000-3-3 is used. Otherwise, the standard IEC 61000-3-11 is applicable for the device with current rating between 16A to 75A. In these standards, limits are mentioned for the equipment under test regarding voltage variation at its terminal. The following limits are given in IEC 61000-3-3 regarding voltage variation limits:

- P_{st} value shall not be greater than 1.0.
- P_{lt} value shall not be greater than 0.65.
- Relative voltage change shall not exceed 3.3% for more than 500 ms.
- The relative steady state voltage change shall not exceed 3.3%.

For testing a device at the manufacturer's site, a reference impedance (see section 2.4.1.1) according to the standard IEC 60725 [Iec15] is used to measure the above parameters on voltage variation. If a device is not made as per IEC 61000-3-3 or IEC 61000-3-11, the customer has to consult with the network operator about voltage variation and flicker severity requirements at his POC.

5.3.1.1 Estimation of flicker emission limits at a POC

According to the report of TR/DNO [Bar01], the calculation of the maximum relative voltage change during starting of a load in the network can be done based on the network's short-circuit data, the respective load change data and comparing them with the emission limit curve (refer equation 4.1, Figure 4.1 and Table 4.1). It was also suggested in the same report that for an installation of a single network user whose installation capacity is greater than 50kVA, the flicker emission limits have to be lower than the limits given in the IEC 61000-3-3. Thus, the P_{st} should be restricted to 0.8 and the P_{lt} to 0.5.

The standard IEC 61000-3-7 and the technical report IEC/TR 61000-3-14 describe flicker emission assessment procedure for MV and LV installations respectively. The IEC 61000-3-7 gives three-stage assessment procedures for the estimation of the flicker emission limit at a MV installation. For a small installation, its capacity is generally quite low compared to the short-circuit power at the POC. Further, if the same installation also meets the requirement of 'stage 1' (see Table 2.7) then no additional emission limit is specified for it. Otherwise, 'stage 2' is to be followed and a detailed calculation has to be done, as shown in Figure 5.3. In this procedure, the maximum global contribution of short-term and long-term flicker emissions ($G_{Pst,MV}$, $G_{Plt,MV}$) at a POC from all MV installations can be calculated and then individual emission share limits ($\Delta P_{st,MV}$, $\Delta P_{lt,MV}$) at a POC are estimated as shown in (5.2) and (5.3).

$$G_{Pst,MV} = \sqrt[\alpha_f]{L_{Pst,MV}^{\alpha_f} - T_{Pst,HM}^{\alpha_f} \cdot L_{Pst,HV}^{\alpha_f}} \tag{5.2}$$

$$\Delta P_{st,MV} = G_{Pst,MV} \cdot \sqrt[\alpha_f]{\frac{S_i}{S_t - S_{LV}}} \tag{5.3}$$

where,

- $L_{Pst,HV}$: planning level for flicker (indices P_{st} or P_{lt}) in HV network
- $L_{Pst,MV}$: planning level for flicker (indices P_{st} or P_{lt}) in MV network
- $T_{Pst,HM}$: transfer coefficient of flicker (indices P_{st} or P_{lt}) from a HV to a MV network
- S_i: agreed apparent power of customer's installation 'i' connected to the MV network
- S_t: total capacity of the considered system supplying power to all MV and LV installations
- S_{LV}: total capacity of the LV installations supplied from the considered system
- α_f: summation exponent which is taken as 3 for flicker assessment.

For the customers with low agreed power, this approach may lead to low emission limits. Therefore, to avoid this situation, a minimum emission share of a MV installation is given as $\Delta P_{st,MV}$=0.35 and $\Delta P_{lt,MV}$=0.25. Under certain circumstances, the network operator may allow a customer to have a higher emission share as per 'stage 3' estimation procedure. However, it is based on mutual agreement between a customer and a network operator. Considering the actual absorption capacity of the network, a customer may be granted with higher emission limits by the network operator on a conditional basis. The global contribution to flicker emission level ($G_{Pst.LV}$) at a LV customer's POC includes the following emissions that are generated by different flicker sources in the network:

- Pollutions coming from the customer's own installation.
- Pollutions coming from other sources present in the same LV feeder.
- Pollutions contributed by flicker sources present in other LV feeders of the network.

For a small LV installation (such as a household), all the devices connected to the installation should comply with the relevant emission limits for products defined in the IEC 61000-3-3 (for devices with current rating ≤16A) or IEC 61000-3-11 (for devices with current rating 16A<I≤75A). Also, the installation's agreed power (S_i) has to be smaller than the minimum agreed power (S_{min}) that is specified by the local network operator. If it is not the case, then a detailed assessment needs to be done as per the IEC/TR 61000-3-14. For a large LV installation, the estimation of global emission limit ($G_{Pst.LV}$) anywhere in the LV network also depends on the selection of planning level values for the MV and LV networks and their transfer coefficients. Two approaches can be used to estimate maximum flicker emission at a LV customer's installation:

- IEC approach: The planning level values for MV and LV networks and the transfer coefficients are taken as given in the standard IEC 61000-3-7. Thus, the planning level of P_{st} values for the MV and LV networks are taken as 0.9 and 1.0 respectively and the transfer coefficient between MV and LV network ($T_{Pst.ML}$) is considered 1.0.
- Realistic approach: In this approach, the compatibility level of P_{st} values for the LV network is taken as 1.0 as given in the standard IEC 61000-2-2. The MV flicker contribution (P_{st}) into the LV network is taken as 0.7, considering a pessimistic (rather high) growth of pollution level in future networks. The transfer coefficient between the MV and LV network ($T_{Pst.ML}$) is taken as 0.84, assuming that the LV network contains a significant portion of motor loads.

According to the IEC/TR 61000-3-14, the global emission limits for flicker anywhere in the LV network can be determined using (5.4) and (5.5):

$$G_{Pst,LV} = \sqrt[\alpha_f]{L_{Pst,LV}^{\alpha_f} - T_{Pst,ML}^{\alpha_f} \cdot L_{Pst,MV}^{\alpha_f}} \tag{5.4}$$

$$G_{Plt,LV} = \sqrt[\alpha_f]{L_{Plt,LV}^{\alpha_f} - T_{Plt,ML}^{\alpha_f} \cdot L_{Plt,MV}^{\alpha_f}} \tag{5.5}$$

where,

- $G_{Pst,LV}$, $G_{Plt,LV}$: the maximum acceptable global contribution to short-term/long-term flicker emission level due to all LV installations
- $L_{Pst,LV}$, $L_{Pst,LV}$: planning level values for short-term/long-term flicker severities in a LV network
- $T_{Pst,ML}$, $T_{Plt,ML}$: flicker transfer coefficient for short-term/long-term flicker severity values from the MV to the LV network

Table 5.3 shows the global emission limit at a LV customer's installation that is calculated by the IEC method and a realistic approach, using (5.4). Each individual customer’s emission limit will be a fraction of the total global emission limits $G_{Pst,LV}$ and $G_{Plt,LV}$. Individual emission limits can be calculated as described in IEC/TR 61000-3-14 and are shown in equations (5.6) and (5.7). To protect the customers with low power demands, the minimum values of $\Delta P_{st,LV}$=0.30 and $\Delta P_{lt,LV}$=0.25 are specified for a LV installation. It is also possible that under some special circumstances the customer may get higher emission limits allowance by a network operator on conditional basis (‘stage 3’).

Table 5.3. Global flicker emission limits in the LV network

Flicker level	Global emission limit due to all LV installations ($G_{Pst,LV}$)	
	IEC/TR 61000-3-14 approach	Realistic approach
P_{st}	0.65	0.95

$$\Delta P_{st,LV} = G_{Pst,LV} \cdot \sqrt[\alpha_f]{\frac{S_i}{S_{LV}}} \tag{5.6}$$

$$\Delta P_{lt,LV} = G_{Plt,LV} \cdot \sqrt[\alpha_f]{\frac{S_i}{S_{LV}}} \tag{5.7}$$

where,

- $\Delta P_{st,LV}$, $\Delta P_{lt,LV}$: the allowable short-term / long-term flicker emission limits for a customer's installation that is directly connected to the LV network
- S_i: the agreed apparent power of customer's installation 'i'
- S_{LV}: total supply capacity of the LV system (feeder) in which the considered installation is connected

Further, by using (5.6) various flicker emission limits for different current capacities can be calculated. Table 5.4 compares the maximum emission limits for different LV installations by using the IEC method and a 'realistic approach'.

Table 5.4. Analytical estimation of flicker emission limits for LV installations

Current capacity of a LV installation (Amp)	Maximum flicker emission limit ($\Delta P_{st,LV}$) as per IEC/TR 61000-3-14	Maximum flicker emission limit ($\Delta P_{st,LV}$) as per the 'realistic approach'
25	0.38	0.56
40	0.44	0.65
50	0.48	0.70
63	0.52	0.76
80	0.56	0.82

In chapter 4, the flicker emission limit at a customer's installation is calculated for a 'realistic situation' case. The same network is shown in Figure 5.5 and it is assumed that the nodes 1, 6, 9, 12 and 15 have 50A connection capacities and the nodes 5, 8, 11, 14 and 17 have 63A connection capacities.

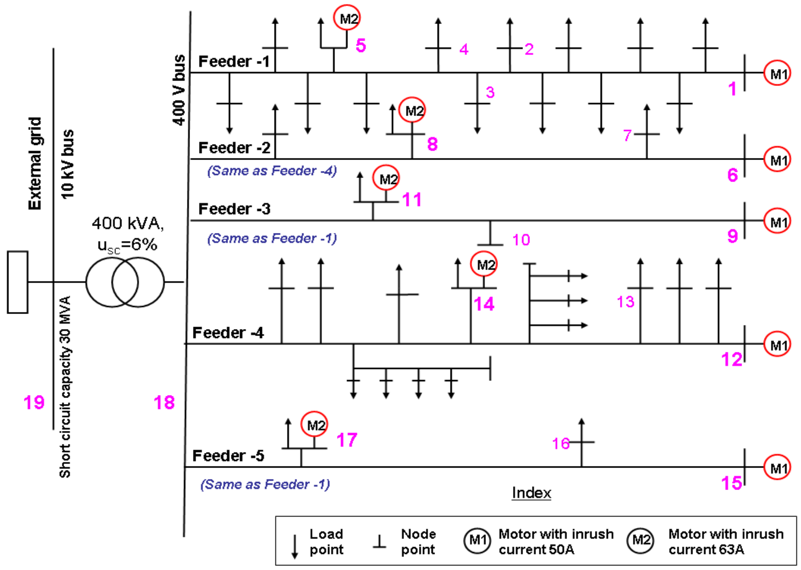


Figure 5.5. LV network used for simulation case of 'realistic situation'

First simulation is done considering that all ten LV motors (in Figure 5.5) start once during the estimation period of 10 minutes. The evaluation points are at nodes 1, 6, 5, and 8. Next, to estimate the global contribution of flicker emissions at a point, all other nine motors are started once during 10 minutes period except the motor connected at the evaluation point. Table 5.5 shows the flicker emission share of different LV installations in the simulated network.

Table 5.5. Estimation of actual flicker emission share of different installations

Evaluation point / connection capacity (A)	P_{st} value at evaluation point with all LV polluting sources (all ten motors) (P)	LV Global contribution of pollution (from nine motors) at evaluation point (G)	Emission share of the evaluation point $\Delta P_{st}=\sqrt[3]{(P^3-G^3)}$
Feeder 1			
1 (50A)	0.77	0.50	0.69
5 (63A)	0.69	0.42	0.63
Feeder 2			
6 (50A)	0.78	0.51	0.70
8 (63A)	0.70	0.44	0.64

From Table 5.5, it can be noticed that on average the emission share (ΔP_{st}) of a 50A installation is approximately 0.70 and a 63A installation is 0.64 [Bha05]. These results are bit different than the analytical calculation (see Table 5.4). The differences are mainly because of different approaches used in the simulation and in the analytical calculation. In the analytical calculation, the maximum global emission limit is used to estimate the emission limit at the POC of an installation. Therefore an installation, irrespective of its location in the LV feeder, is allowed to emit an emission as indicated in Table 5.4. However, when a large capacity installation is located at the far end of a LV feeder, the network impedance at that POC would be larger than if it is located near to the MV/LV substation. If the installation still is allowed to emit the same flicker emission, then the global emission limit (and P_{st}=1 criterion) may exceed for certain conditions. In contrast, the simulation is done considering a maximum network impedance at a POC for a specific connection capacity. The emission limits found in the simulation (see Table 5.5) can be applied to a specific capacity installation located anywhere in the LV network. From the analysis, it is estimated that a 50A installation has an emission contribution (ΔP_{st}) of approximately 0.70 whereas the emission share of a 63A installation is 0.64.

5.3.1.2 Proposed planning and compatibility level values

The IEC 61000-3-7 standard gives indicative planning level values for P_{st} and P_{lt} in the MV and HV networks, but not for the LV network (see Table 5.2). Various network operators and standardization committees around the world are working independently to find out realistic planning level values at different voltage levels. Hence, the approach and method vary significantly. Reference [Arl01] shows a list of different flicker planning level values that are used by different network operators around the world. The recent work of CIGRE/CIRED JWG C4.108 [Hal01] proposed a method to find out suitable planning level values of flicker. The planning level values (P_{st}) are estimated as 0.96 for the MV network and 1.01 for the HV network respectively which exceeds the global compatibility level of 1.0 as given in the IEC 61000-2-2 standard. The proposed values are valid for the assumption of a global emission level (of P_{st}) as 0.50 at each voltage level, and the transfer coefficients of 1.0 between the MV to LV networks, and 0.90 between the HV to MV networks.

The proposed flicker levels in this thesis should not violate the standard compatibility level criterion of P_{st}=1.0 anywhere in the network. With the advancement in new lighting technology, modern lamps are less sensitive to flicker related voltage changes. However, the voltage fluctuation (of P_{st}>1.0) can affect the performance of motors and other devices in the network [Bol01]. Hence, the compatibility level in the LV network (as per the IEC 61000-2-2) is kept unchanged and a different approach is adopted to find out flicker planning level values at other voltage levels. Various voltage disturbances (e.g. frequency of motor starts) are used in the estimation of planning level values (P_{lt}) are based on practical experiences of the Dutch network operators. The following assumptions are made in estimating the planning level (P_{st}) value in the LV network:

- MV network contributes a P_{st} value of 0.7 in to the LV network.
- Transfer coefficient from a MV to a LV network is taken as 0.84.

The global LV flicker contributions at 50A and 63A installations are shown in Table 5.5. Further, combining them with the above described MV flicker contribution, the maximum P_{st} value for a 50A installation is found 0.88 and that for a 63A installation is 0.82. These values can be taken as the indicative planning levels (P_{st}) for flicker in the simulated LV network. In practice, the network operator specifies a single common planning level value for all the customers connected to a specific voltage level (except for the customers with a special contract). Thus, P_{st}=0.90 can be taken as a realistic planning level value of flicker for the LV network.

The next step is to estimate a realistic value of P_{lt} for the LV network. A P_{lt} value is calculated on a 2 hours basis, by summing up 12 numbers of consecutive 10 minutes P_{st} values. It is assumed in the simulation that each motor is started once in every 10 minutes. A maximum of six starts in two hours is considered a reasonable choice. Following conditions are assumed for calculating a P_{lt} value:

- In every 2 hours, the number of motor starts is restricted to 6.
- Each time when a motor starts, it produces a maximum emission of P_{st}=0.9 at the POC.
- Other times the motor is in stand still condition and thus P_{st}=0.
- Based on 12 consecutive P_{st} values in two hours interval, a P_{lt} value is found approximately 0.70 (applying equation (5.8) which is same as equation (2.4)).

$$P_{lt} = \sqrt[\alpha_f]{\frac{\sum_{i=1}^{12} P_{st(i)}^{\alpha_f}}{12}} \tag{5.8}$$

Therefore, a P_{lt}=0.70 is suggested as planning level value for the LV network. Next, the planning level values for a MV network are calculated. The P_{lt} value for MV network can be determined with the similar method as that of the LV network. By considering six times of P_{st}=0.70 and six times of P_{st}=0, the planning level value of P_{lt} for the MV network is estimated as 0.55.

To propose a realistic P_{lt} value for the HV network, statistical results are utilized that are obtained from the national PQ measurements of the Dutch networks [Hes01]. The maximum value of P_{lt} in the HV network is found 0.25. Considering some margin, a P_{lt} value of 0.35 can be taken as a realistic value for the future HV network. For P_{lt} =0.35, the P_{st} value is 0.45 that can be calculated using equation (5.8). For this calculation, it is considered that six polluting loads are present in every two hours in the HV network. Table 5.6 shows the proposed planning level values at different voltage levels of the network.

Table 5.6. Proposed values of planning levels for flicker

Networks → / Indicators ↓	HV	MV	LV
P_{st}	0.45	0.70	0.90
P_{lt}	0.35	0.55	0.70

The compatibility level should be higher than the planning level as described in the IEC standards. The standard IEC 61000-2-2 provides compatibility level values for a LV network as P_{st}=1.0 and P_{lt}=0.8. These values are for 95% of the time and 95% of the measurement sites. In contrast, the EN50160 standard specifies limit values of flicker as P_{lt}=1 for 95% of the time for the data of a week (10 minutes rms value) for all sites in the networks (i.e. 100% of the locations). The EN50160 standard does not provide any limit value for P_{st}. It can be remarked here that the 95% time limit clause can be made stricter for specifying the planning and compatibility limits. As suggested in the IEEE 1453 standard, the 95% probability criterion can be changed to 99% probability limit so that some more measured data can be included for specifying the flicker severity at a site. However, the standard IEC 61000-2-2 includes 95% sites for specifying the compatibility limits. Thus, 5% of the worst-served sites are excluded from the analysis. To make the standards more harmonized, compatibility limits should be specified for 100% sites in line with the EN50160 standard. Comparing the planning level values of Table 5.6 and considering a margin between planning and compatibility levels, the following compatibility limit values for flicker are suggested in Table 5.7.

Table 5.7. Proposed values of compatibility levels for flicker

Networks → / Indicators ↓	HV	MV	LV
P_{st} (95% time, 95% sites)	0.55	0.80	1.0
P_{lt} (95% time, 95% sites)	0.40	0.60	0.80
P_{lt} (95% time, 100% sites)	0.80	0.90	1.0
P_{lt} (100% time, 100% sites)	-	-	5.0

In Table 5.7, the P_{lt} value for a LV network is taken as 1.0 for the 95% time and 100% sites situation in accordance with the limit given in the EN50160 standard. The P_{lt} value in a LV network for 100% time and 100% sites is taken 5.0 as specified in the Dutch Grid Code. For the MV and HV networks, the limits for P_{lt} values are also suggested for 95% time and 100% sites. Figure 5.6 shows graphically the various proposed values for indicative planning and compatibility levels (for 95% time and 95% sites) in different voltage levels. Presently, the EN50160 standardization committee is considering changing the 95% time limit by a stricter time clause of 99% (or 100%). In future, the IEC standards are required to be modified in the same direction to make them harmonized globally. This will help to dissolve arguments about flicker related limits among the involved parties.

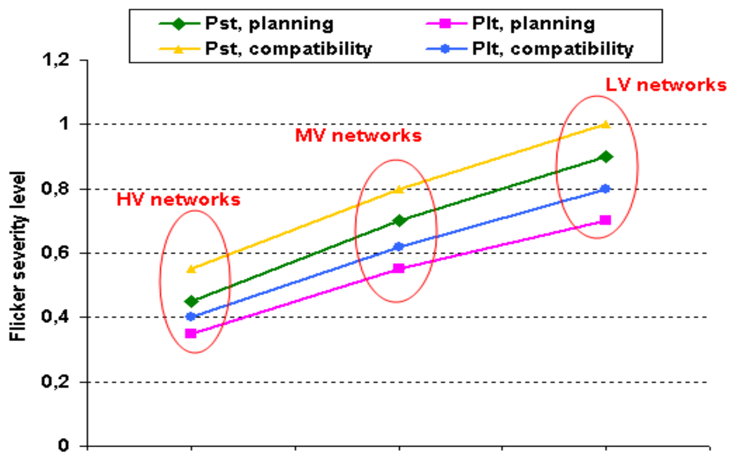


Figure 5.6. Illustration of planning and compatibility level values for flicker severities at different voltage levels (for 95% sites, 95% time)

5.3.2 Harmonics

Presently, many standards are available on harmonics that are meant for the network operators, customers and equipment manufacturers. The limiting values on a specific parameter may sometimes vary in different standards. An effective harmonic standard should be comprehensive and flexible. It should consider the dynamic and time varying nature of harmonics. Moreover, it has to be simple so that it can be applied easily at any condition. The goal of a standard is to achieve a fair distribution of the cost of compliance [Oli01]. A large share should be to the parties who are creating harmonics in the systems. On the other hand, the power system should respond reasonably to a harmonic excitation, while a sensitive device must have a certain minimum immunity to harmonic level.

5.3.2.1 Harmonic voltage limits

In the standards IEC 61000-2-2 and IEC 61000-2-12, compatibility level values are given for LV and MV networks that are related to steady-state conditions. Two types of compatibility levels are used:

- 'Long-term effect' that relates to thermal effects on network components. It arises from harmonic levels that are sustained for 10 minutes or more.
- 'Very short-term effect' (3 seconds or less) which mainly causes disturbing effects on electronic devices.

With reference to long-term effects, the compatibility level for the THD_V is 8% and that for very short-term effects is 11% in the MV and LV networks. The long-term compatibility limits for individual harmonic voltages are given in Table 5.8. The short-term individual harmonic voltages can be found by multiplying the value of Table 5.8 with a factor k_{nvs}. According to the IEC 61000-2-12 standard, the value of k_{nvs} can be calculated by equation (5.9).

$$k_{nvs} = 1.3 + \frac{0.7}{45} \cdot (n - 5) \tag{5.9}$$

Table 5.8. Standard limits on planning and compatibility levels for harmonic voltages in different voltage levels

Harmonic order (n)	Compatibility level for the LV and MV networks (%)	Indicative planning levels (%)	
		MV network	HV-EHV networks
3	5	4	2
5	6	5	2
7	5	4	2
9	1.5	1.2	1
11	3.5	3	1.5
13	3	2.5	1.5
15	0.4	0.3	0.3
$17 \leq n \leq 49$	2.27·(17/n)-0.27	1.9·(17/n)-0.2	1.2·(17/n)
21	0.3	0.2	0.2
$21 < n \leq 45$	0.2	0.2	0.2
THD_V	8	6.5	3

Note: Even harmonic limits are also mentioned in the standard but are not shown here.

Planning level values for harmonics are equal to or lower than the compatibility level values and they should allow coordination of harmonic voltages between different voltage levels. The standard IEC 61000-3-6 gives indicative values of planning levels for the MV and HV-EHV networks (refer Table 5.8). These values depend on the network's structure, characteristics and practical circumstances. No planning level value is specified for LV network. It is noticed that compatibility level limits are generally lower than the voltage limits given in the EN50160 standard (refer Appendix C-2).

The IEC 61000-3-6 gives the indicative planning level value for the total harmonic distortion in the MV network as 6.5% and that for the HV and EHV network as 3%. The global harmonic disturbance level at any point in a network is the vectorial sum of each individual disturbing source. A summation factor 'α' is used that depends on the type of disturbance, probability of its happening and degree to which varies randomly in terms of magnitude and phase. For estimating the maximum global emission limits in a LV network, the planning level of the LV network ($L_{n,LV}$) is assumed to be same as its compatibility level value. The planning level values of the HV ($L_{n,HV}$) and MV networks ($L_{n,MV}$) are taken the same as mentioned in Table 5.8. The transfer coefficients from a MV to LV network ($T_{n,ML}$) and a HV to MV network ($T_{n,HM}$) are considered to be 1.0 (which is a pessimistic estimation). They are generally less than 1.0 for high order harmonics because of damping effects of the connected loads. However, they can be higher than 1.0 too in a resonance network situation. Also, it was found that the transfer of harmonic current emission from the LV to the MV network is quite low. With a MV/LV substation transformer rating higher than 400kVA and the short-circuit power at the MV side of transformer is more than 50MVA, the value of $T_{n,LM}$ is generally very low (around 0.1-0.2) [Cob02]. Hence, the harmonic current contribution of the LV network into a MV network can be neglected. For more precise calculation, the network operator can estimate the correct values of transfer coefficients from PQ measurements in the network. Table 5.9 shows the maximum global emission limits of the harmonic voltages anywhere in a MV and LV network and are calculated by using equations (5.10) and (5.11) respectively.

$$G_{n,MV} = \sqrt[\alpha]{L_{n,MV}^{\alpha} - (T_{n,HM} \cdot L_{n,HV})^{\alpha}} \tag{5.10}$$

$$G_{n,LV} = \sqrt[\alpha]{L_{n,LV}^{\alpha} - (T_{n,ML} \cdot L_{n,MV})^{\alpha}} \tag{5.11}$$

where,

- $G_{n,MV}$: maximum harmonic voltage allowance to all MV installations in the network, which is determined by subtracting contributions of all LV installations
- $G_{n,LV}$: maximum global contribution of local installations to the n^{th} harmonic voltage anywhere in the LV network

- $L_{n,HV}$, $L_{n,MV}$, $L_{n,LV}$: planning level values for HV, MV and LV networks respectively
- $T_{n,HM}$: transfer coefficient from the HV to MV networks
- $T_{n,ML}$: transfer coefficient from the MV to LV networks

Table 5.9. Estimation of maximum acceptable global emissions of harmonic voltages in the MV and LV networks

Harmonic order (n)	Summation factor 'α'	Maximum emission contributions of all MV installations ($G_{n,MV}$ in % of U_c)	Maximum emission contributions of all LV installations ($G_{n,LV}$ in % of U_{nom})
3	1.2	2.5	1.5
5	1.4	4.0	2.1
7	1.4	2.8	2.0
*9**	*1.4*	*0.4*	*0.6*
11	2.0	2.6	1.8
13	2.0	2.0	1.7
*15**	*2.0*	*0.0*	*0.3*
17	2.0	1.2	1.1
19	2.0	1.0	1.0
*21**	*2.0*	*0.0*	*0.2*
23	2.0	0.8	0.7
25	2.0	0.7	0.7

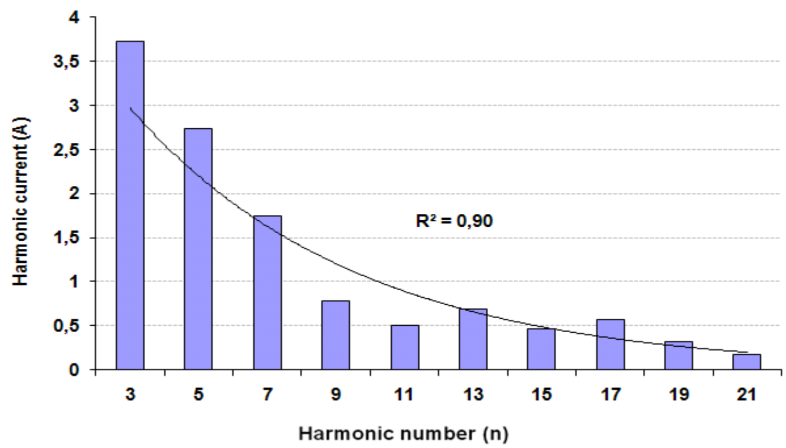
* New planning level values are recommended for 'triple n' harmonics in Table 5.10, therefore other global emission limits are found for them in Figure 5.10.

As shown in Table 5.9, the value of 'α' is considered 1.2 for 3rd harmonic component in comparison to 1.0 given in the IEC 61000-3-6 standard. This allows the maximum emission contributions for 3rd harmonic voltage in the MV and LV networks relatively higher than that with α as 1.0. Laboratory measurement with various devices showed that the phase angles of 3rd harmonic current component for the measured devices are significantly out of phase to each other (see Figure 4.13). This also justifies to choose a value of $\alpha>1$. Moreover, the IEC/TR 61000-3-14 also suggests to consider a value of $\alpha>1$ for the MV network and also for large LV installations where the phase diversity among the devices are expected to be higher than a small household installation.

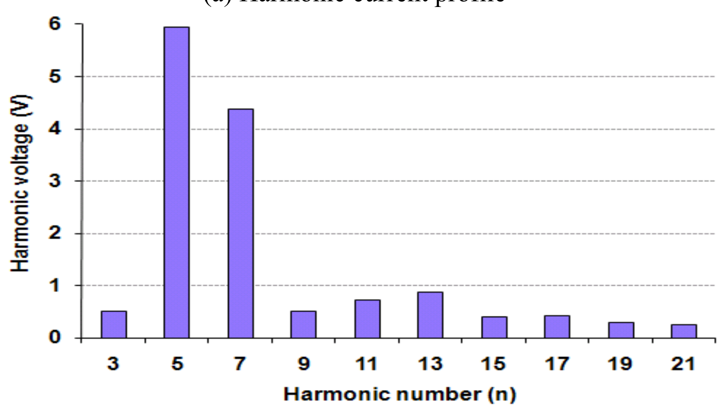
From Table 5.9, it can be noticed that the global emission contribution calculated for the 9th, 15th and 21st harmonics in the MV network is zero or very low. In the IEC 61000-3-6 standard, the planning level values for the 9th, 15th and 21st harmonics are specified quite low in comparison to other order harmonics (see Table 5.8). Therefore, the calculated values for the global emission of them are lower as compared to other order harmonics.

5.3.2.2 Proposal for harmonic voltage planning and compatibility levels

In Figure 5.7, the 99.9% probability values of harmonic currents and voltages (up to 21st orders) are measured at a LV busbar that is located close to a LV substation. The harmonic current profile shows an exponential characteristic with a gradual decreasing value for higher order harmonics. The 5th and 7th harmonic voltages are found the highest, but they are within the EN50160 standard limits. The other order harmonic voltages are quite low and are almost of the same magnitudes.



(a) Harmonic current profile

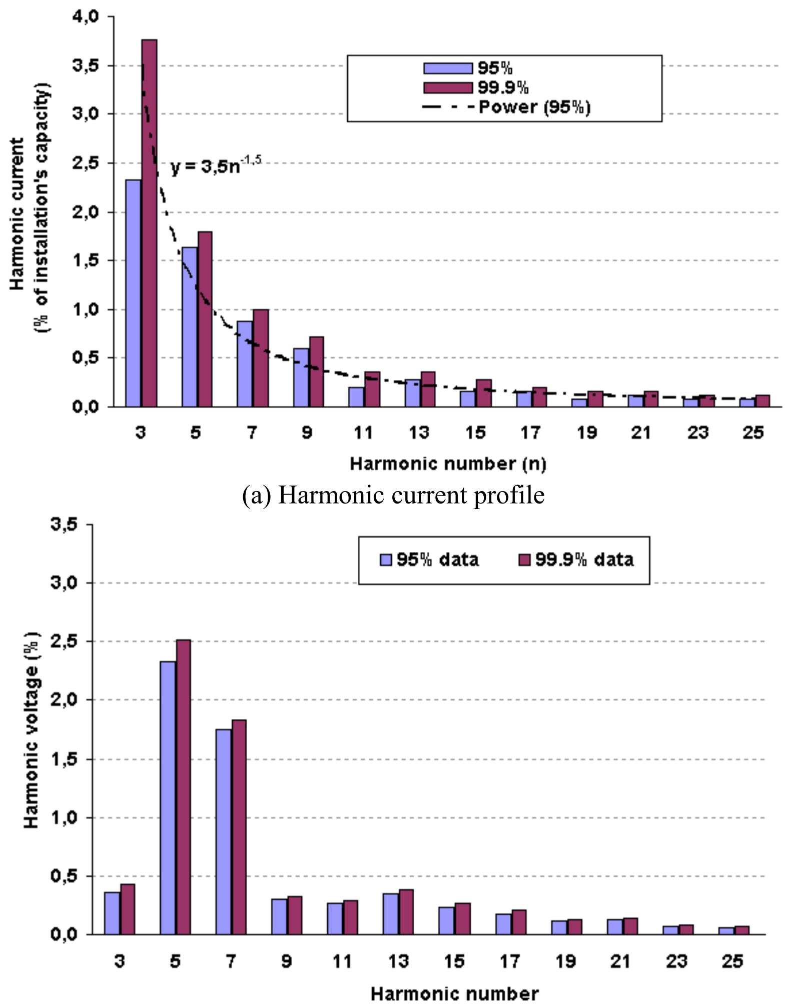


(b) Harmonic voltage profile

Figure 5.7. Harmonic profiles (per phase) at a LV busbar close to a substation

In Figure 5.8, the harmonic current and voltage profiles are shown that are measured at a POC located at the end of a LV feeder. The 95% and 99.9% probability values (based on weekly measured data) of the harmonic spectrums are plotted. The harmonic current profile at the measuring location shows an exponential decaying characteristic. From Figure 5.8, it can be noticed that the relative value of the harmonic current (I_n) with respect to the installation's current carrying capacity has an inverse relationship with the harmonic order (n). The presence of harmonic currents increases losses in the network components (as described in section 3.2.2 of this thesis), but the higher order harmonic currents are quite small in magnitude.

The 'triple n' harmonic currents may flow through the neutral conductors and the delta connected windings of the transformers of a three-phase balanced system, and can cause significant losses, increased heating and further early aging/failure of the components. However, the unbalanced currents in three-phase system and in a single-phase system, the 'triple n' harmonic currents will have similar impacts as the 'non-triple n' harmonics.



(a) Harmonic current profile

(b) Harmonic voltage profile

Figure 5.8. Harmonic profiles measured at a POC located at the end of a LV feeder

For a LV network, the harmonic impedance generally increases linearly with higher order harmonics (see Figure 5.11). The harmonic voltage which is a combination of the harmonic current and impedance will have an exponentially decreasing value for higher order harmonics. As discussed before, the IEC 61000-3-6 standard specifies very low values for the 9^{th}, 15^{th}, 21^{st} order harmonic voltages while the limits for the 13^{th}, 17^{th}, 19^{th}, 23^{rd}, and 25^{th} order harmonic voltages were given relatively higher than the 'triple n' harmonics. Measurements on the Dutch networks have shown that all harmonic voltages from the 9^{th} up to the 25^{th} order are within the same range of values.

The ‘triple n’ harmonic voltage limits of the EN50160 standard are also quite small (refer Appendix C-2). Those limit values were developed during the early years of 1990 and were based on field measurements. In the last two decades, many power electronics based controls, distributed generators and large numbers of single-phase electronic devices are integrated in the power system, resulting in a slow but steady increase of ‘triple n’ harmonics in the network. Recent field measurements in different networks in the world show a growing trend of ‘triple n’ harmonic voltages in the grid [Iss01], [Cee01]. Reference [Kan01] describes a recent field measurement that was conducted for MV and LV networks in Korea. It is indicated in the analysis that more than 10% of the measured data for the 9^{th}, 15^{th} harmonic voltages in the Korean LV network exceeded the IEC 61000-3-6 standard limits. Also, some of the measured data for the 3^{rd}, 9^{th}, 15^{th} and 21^{st} harmonic voltages in the MV network exceeded the IEC standard limit values. Hence, it is proposed to modify the planning level limit values for the 9^{th}, 15^{th}, 21^{st} order harmonic voltages in the MV and LV networks. These modifications will provide a provision of 'triple n' harmonic currents emission possibility from the MV and LV installations. After considering a reasonable margin between various limits for different order harmonics, new planning levels for the 9^{th}, 15^{th}, 21^{st} order harmonic voltages are proposed in Table 5.10. In this proposal, the planning level value in the HV network is kept unchanged.

Table 5.10. Proposed limits for 9^{th}, 15^{th} and 21^{st} order harmonics

Harmonic number	New planning levels (%)		New global emission limits for voltage (%)	
	LV	MV	LV	MV
9	2.0	1.5	0.9	0.8
15	1.0	0.7	0.7	0.6
21	0.8	0.6	0.5	0.5

In Figure 5.9, the planning level values in different voltage levels are plotted. The proposed new planning level values would change the global emission limits of the MV and LV networks (shown in Table 5.9). Presently, the standard gives the same limit values (compatibility level) for a specific order harmonic in the MV and LV networks (see Table 5.8). Hence, if the specific order harmonic voltage reaches the maximum value in the MV level, theoretically there will be no more emission allowed for that harmonic order in the LV network (because of almost 1:1 transfer of harmonic voltage from the MV to LV network). This makes the standard inflexible and ineffective. Therefore, new global emission level values for the 9th, 15th and 21st harmonic voltages in the MV and LV networks are proposed. The various global emission harmonic voltages are plotted in Figure 5.10.

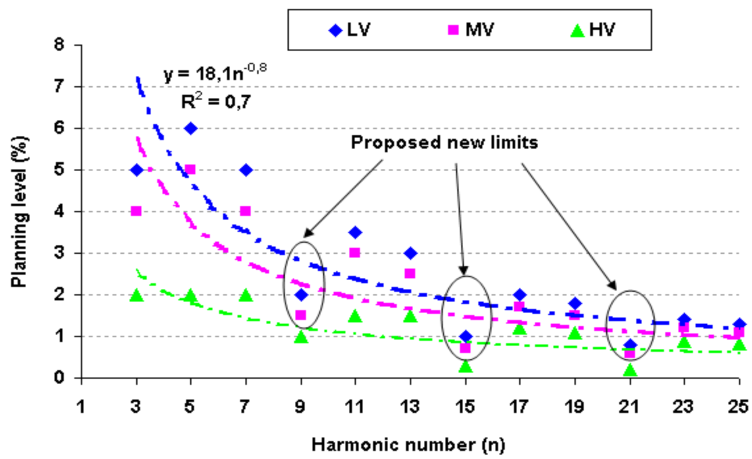


Figure 5.9. Planning level values of harmonic voltages atdifferent voltage levels

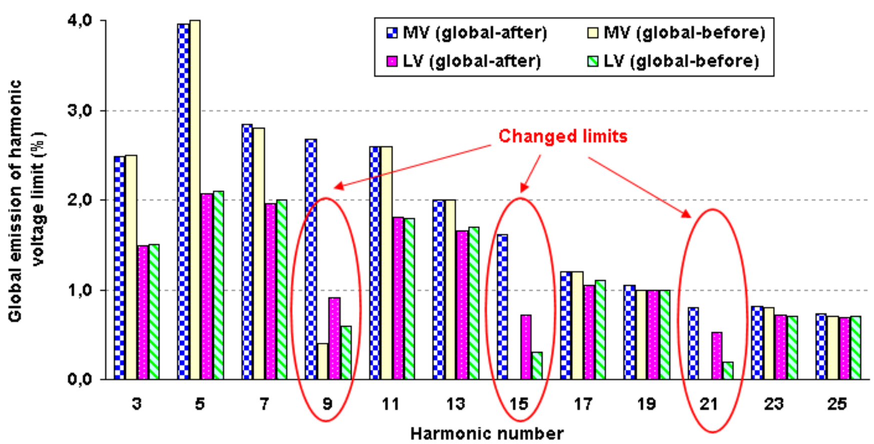


Figure 5.10. Global harmonic voltage emission limits in MV and LV networks

Thus, the MV and LV installations are allotted with reasonably some share of global emission for 'triple n' harmonic voltages as compared to the previous limit values. A similar methodology can also be applied for other order harmonics at different voltage levels.

5.3.2.3 Proposal for harmonic current limit at a small LV installation

For a small installation (such as household), each device connected to the network should individually fulfil the harmonic current requirements of the respective equipment standards IEC 61000-3-2 or IEC 61000-3-12. Also, the total demand at the POC should be lower than the installation’s connection (current) capacity. The harmonic load flow analysis discussed in chapter 4 is done to find out harmonic current emissions at a household terminal (with a three-phase 25A connection, equivalent to 17.3kVA). The minimum short-circuit power at a POC in the simulated network is found approximately 1.2MVA. Therefore, the ratio of the installation’s agreed capacity and the minimum short-circuit power is 0.014, which is below the limit of 0.1 as per IEC/TR 61000-3-14, ‘stage 1’ requirement. Hence, for the simulated LV network, the harmonic current emission limits at a POC can be taken as per ‘stage 1’ requirement, as shown in Table 5.11.

Table 5.11. Harmonic current emission limits at a small LV installation

Applicable standard / report	Harmonic current emission limit (%) relative to the size of customer’s installation for different harmonic order (n)						
	3	5	7	9	11	13	>13
IEC/TR 61000-3-14	4	5	5	1	3	3	(500/ n^2)

Figure 5.11 shows harmonic impedance characteristics of the main LV busbar and a POC which is located at the far end of the LV feeder of the simulated network. The capacitive component of network impedance (due to LV loads and LV cables) in the simulated network is quite low as compared to its inductive component. Therefore, no resonance network situation is found in the simulation. In the ‘Theme-2’ of the KTI project [Hes02], a simulation was done with many inverters and capacitive loads connected at different household terminals in a typical LV Dutch network. It was found that parallel capacitances of appliances in combination with the capacitances of the Electro Magnetic interference (EMI) filters of the PV inverters can result in a significant capacitance at the POC of a household. This capacitance together with the impedances of the network components can induce resonances (even below the 25th order harmonics) in the LV network and can increase harmonic distortion levels. Thus, resonances in a range lower than the 25th harmonic may become more common in the near future.

If such a resonance situation occurs in the network, measures should be taken to control it. In the same research, an ancillary service is proposed that minimizes the resonance peaks and shifts the possible resonances to higher frequency range (more than three times than the previously observed value).

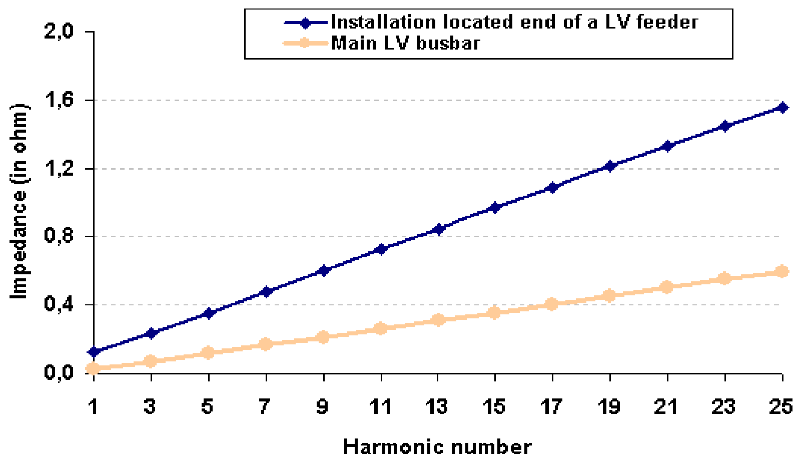
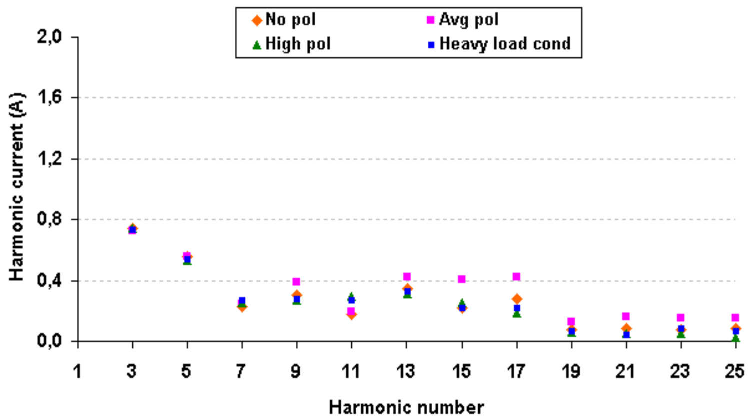


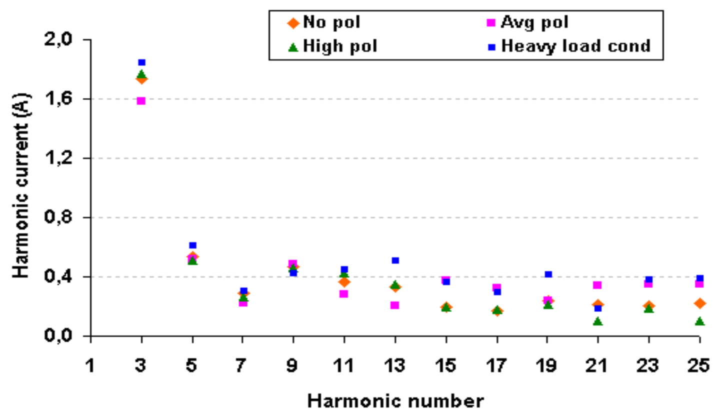
Figure 5.11. Harmonic impedances of the simulated LV network model

Figure 5.12 shows the harmonic currents at the high and low load demand households' terminals. The simulations are done for 'case 4' network situation (with average loading of 40A at the beginning of a LV feeder). Three network conditions are assumed: no MV background distortion, average distortion and high MV background distortion (as described in section 4.3.3). Also, a high load condition (with loading of 70A at the beginning of a LV feeder) is considered in the simulation for comparison.

Comparing the limits of various standards (see Appendix C-3) and Figure 5.12, it can be seen that the limits given in IEC/TR 61000-3-14 ('stage 1') are more applicable for the considered simulation case. However, in the simulation for high load demand houses, the 3rd harmonic current is quite high, exceeding the above limit. It is because of the operation of vacuum cleaner (VC) that produces high 3rd harmonic currents in comparison to other devices (refer Figure 4.13). It is used only a few minutes per day (intermediate operation) in a typical household. Therefore, the values specified in the IEC/TR 61000-3-14 (stage 1) can be considered as limiting values (for 95% measurement time) for a typical household installation. The harmonic current emission (95%, 99.9% and 100% probability data) at a typical Dutch household's POC is shown in Table 5.12 (also see Figure 4.24). The values are found comparable with the IEC/TR 61000-3-14 (stage 1) recommended values. Moreover, the 95% probability values match with the simulation results of a low load demand household too, shown in Figure 5.12 (a).



(a) Low load demand household



(b) High load demand household

Figure 5.12. Simulation results of harmonic currents in different installations

Table 5.12. Harmonic current emissions measured at a 25A LV installation

Current at a POC (A)	3	5	7	9	11	13	15	17	19	21	23	25
95% data	0.58	0.41	0.22	0.15	0.05	0.07	0.04	0.04	0.02	0.03	0.02	0.02
99.9% data	0.94	0.45	0.25	0.18	0.09	0.09	0.07	0.05	0.04	0.04	0.03	0.03
100% data	1.3	0.54	0.26	0.20	0.09	0.11	0.09	0.08	0.07	0.06	0.05	0.05

5.3.2.4 Proposal for harmonic current limits at a large LV installation

The harmonic current emission limits at a large LV installation can be calculated as per ‘stage 2’recommendation of the IEC/TR 61000-3-14 report and are given by (5.12).

$$E_{Ini} = \frac{U_{nom}^2}{S_i} \cdot G_{n,LV} \cdot \sqrt[\alpha]{\frac{S_i}{S_{LV}}} \cdot min\left(\frac{K_{nB}}{Z_{nB}}; \frac{1}{Z_{ni}}\right) \tag{5.12}$$

where,

- $G_{n,LV}$: maximum global contribution of local installations to the n^{th} harmonic voltage anywhere in the LV network
- E_{Ini}: harmonic current emission limit of order ‘n’ for the installation 'i' connected to the LV network (in ‘%’ of the installation capacity current)
- Z_{nB}: harmonic impedance for n^{th} order harmonic at a LV busbar (in Ω)
- Z_{ni}: harmonic impedance for n^{th} order at the i^{th} customer's POC (in Ω)
- K_{nB}: reduction factor at harmonic order ‘n’. Typical value is 0.20 for triple ‘n’ harmonics; and 0.65 for non-triple ‘n’ harmonics in an underground LV network
- U_{nom}: nominal phase to phase voltage of the LV network (in V)
- S_i: agreed apparent power of the installation ‘i’ (in VA)
- S_{LV}: total supply capacity of the considered LV network (in VA)

Equation (5.12) shows that harmonic current emission limit is dependent on the installation's current carrying capacity, harmonic impedance at the POC and harmonic impedance of the substation's main busbar. Therefore, an installation with a lower value of connection current capacity (for example 25A compared to a 80A installation) is permitted to emit a higher percentage of harmonic currents when the network impedances at POC for both the cases are considered the same. Hence, reasonable harmonic currents limits for the LV installations have to be estimated. The harmonic current emission limits for 50A and 63A connections are estimated considering a maximum impedance condition. A 50A installation can have a maximum network impedance of 0.261 Ω and a 63A installation has 0.207 Ω at the fundamental frequency (to fulfil the flicker severity limit of P_{st}=1). A harmonic simulation is done for the modelled LV network considering those maximum impedances at different installations. Figure 5.13 shows the harmonic currents emission limits at different LV installations. These values are calculated based on this harmonic simulation result and further using equations (5.11) and (5.12). As expected, with the maximum impedance condition at a POC, the harmonic current emissions at 50A and 63A installations for a specific order harmonic are about the same. Therefore, the values shown in Figure 5.13 can be considered as the maximum harmonic current emission limits for a LV customer.

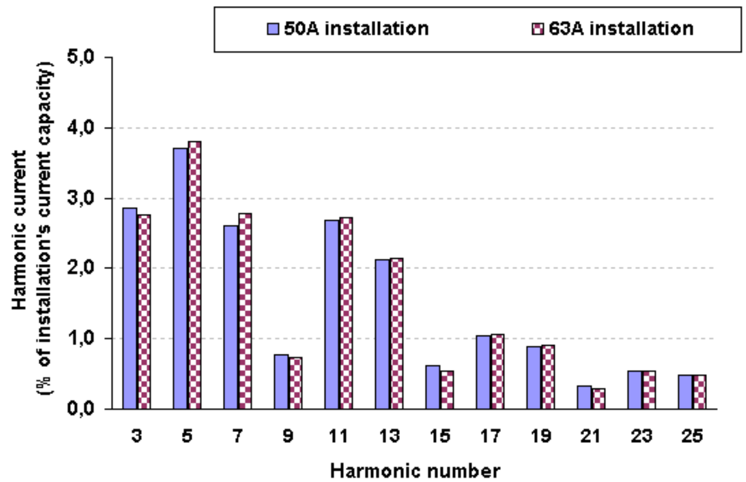


Figure 5.13. Proposed harmonic current emission limits for LV installations

With the previous limits of 'triple n' harmonic voltages, the 9th, 15th and 21st order harmonic current limits would be either very small or zero. In contrast, with the new proposed planning level values, the LV installations are allowed to emit a certain percentage of 'triple n' harmonic currents. It can also be observed that even with a neutral conductor, the 'triple n' harmonic currents will be comparable to the other consecutive harmonic order current. The proposed harmonic current emission limit values are again tabulated in Table 5.13. With those limits, the maximum harmonic current distortion (THD_I value) at a LV customer's POC will be 7% of its connection capacity. However, a network operator may allow a customer more emission limit when the impedance at a POC is smaller than the maximum value. However, it should be based on mutual agreement between them. For general purpose, the proposed limits can be taken as maximum emission limits at a POC.

Table 5.13. Harmonic current emission limits at a LV installation

Harmonic number	3	5	7	9	11	13	15	17	19	21	23	25
Current as % of POC's capacity	2.8	3.7	2.6	0.7	2.7	2.1	0.6	1.0	0.9	0.3	0.5	0.4

Note: the emission limits for triple 'n' harmonics are relatively less because of low values for the reduction factor (K_{nB}), shown in equation (5.12).

In this thesis, main attention is given to estimate the harmonic current emission limit for a LV installation. Therefore, the limit values are proposed for LV installations. The harmonic current estimation procedure for a MV installation is described in Appendix C-3.

5.3.3 Voltage dips

Many industrial process devices are very sensitive to voltage dips at their installations. When a critical device in a process is affected by a voltage dip, it can cause complete interruption of the process. The standards IEEE 1668 and IEEE P1547 and the industry standards such as SEMI F42, CBEMA, ITIC, etc. are used by the industrial customers for defining industrial devices' immunities against voltage dips and for evaluating the economic impacts of a voltage dip event on the operation of their process devices. Different immunity classes are also specified in the IEC 61000-4-11 and IEC 61000-4-34 standards. The CIGRE/CIRED JWG C4.110 [Cir01] proposed immunity classes for equipment against balanced and unbalanced voltage dips (refer section 4.4.3 of this thesis). Table 5.14 shows the proposed voltage dip classification table of the EN50160 standard in which each cell is identified similar to the product class definition for immunity tests given in the IEC 61000-4-11 and IEC 61000-4-34 standards. The following holds for Table 5.14:

- Areas covered by cells 'A1+A2+B1+B2' are illustrative for equipment tested as 'class 2' (yellow shaded area) of the product standards.
- Areas covered by 'A1+A2+A3+A4+B1+B2+C1' are valid for equipment tested as 'class 3' (yellow plus green shaded areas) of the product standards. This class of devices has a higher immunity level than that of 'class 2' devices.

Table 5.14. Integrating voltage dip product classification with the FprEN50160

Range of residual voltage U (in % of U_{nom})	Duration 't' (ms)		
	$10<t\leq200$	$200<t\leq500$	$500<t\leq5000$
$90>U\geq80$	A1	A2	A3+A4
$80>U\geq70$	B1	B2	B3+B4
$70>U\geq40$	C1	C2	C3+C4
$40>U\geq0$	D1	D2	D3+D4

The classification of voltage dip events is very useful and important from a regulatory view point mainly for two reasons. Firstly, it provides a basis for evaluating the network's voltage dip performance level. Secondly, it sets a performance target limit regarding voltage quality issues in the network. Thus, it hypothetically gives a responsibility sharing border between the network operator and the customer/equipment manufacturer.

The IEC/TR 61000-2-8 report gives statistical measurement results on voltage dips and short interruptions in different countries of the world. It was concluded that the frequency and probability of occurrences of voltage dip at any voltage level are highly unpredictable (both in time and place). It varies depending on the type of network and on the point of observation. The technical report IEC/TR 61000-2-8 also describes some reference rules to measure voltage dip events. According to this standard, dips that involve more than one phase should be designated as a single event if they overlap in time. In general, the standard IEC 61000-4-30 describes the testing and measurement techniques for PQ measurement methods. In this standard, the detection and evaluation of a voltage dip (with reference to the nominal supply voltage) is described. It also introduces the 'flagging concept' to avoid counting single event more than once in different PQ parameters. Therefore, whenever an event occurs (such as a voltage dip) in the network, it will flag the time of occurrence of the event and will continue the flagging state until the event is cleared.

The standard NRS 048-2:2007 specifies minimum performance levels for voltage dips in South Africa. The characterisation of voltage dips is made to differentiate the responsibilities of customers and to protect their installations against less severe (and more frequent) voltage dips. This standard defines rectangular regions in the dip duration table and gives the number of dip incidents falling in to each region. However, the main disadvantage of specifying dip limits is that it does not take into account the specific condition that can vary largely from site to site and in time (seasons and years). Furthermore, if the voltage dip limits (in the standard or by the network operator) are set higher than the existing performance level, then more dips would be allowed to occur at the customers' POC. It means that the quality of the electric supply will be lower than the existing level and the customers perhaps will not accept it. On the other hand, when the existing PQ performance of the network is below the standard limits, the network operator is obliged to improve its performance level. In contrast, there is no direct incentive for the network operator to improve the existing performance level of the network to a higher level than the standard. In some cases, it is also possible that the cost of network improvement is too high because of unfavourable (geographical) conditions and the customers connected to the network are satisfied with the existing performance level. Hence, standardising on voltage dip limiting numbers is a complicated issue and requires a lot of analysis to establish it for voltage quality management purpose.

5.3.3.1 Voltage dip limits as per NRS 048-2 standard

The standard NRS 048-2:2007 defines the voltage dip table as shown in Table 5.15.

Table 5.15. Voltage dip table based on NRS 048-2:2007

<table>
<tr><th rowspan="2">Range of residual voltage U (%)</th><th colspan="3">Duration</th></tr>
<tr><th>20 <t≤ 150 (ms)</th><th>150 <t≤ 600 (ms)</th><th>0.6 <t≤ 3 (s)</th></tr>
<tr><td>90 > U ≥ 85</td><td rowspan="3"></td><td rowspan="2">Y</td><td></td></tr>
<tr><td>85 > U ≥ 80</td><td rowspan="3">Z1</td></tr>
<tr><td>80 > U ≥ 70</td><td rowspan="3">S</td></tr>
<tr><td>70 > U ≥ 60</td><td>X1</td></tr>
<tr><td>60 > U ≥ 40</td><td>X2</td><td rowspan="2">Z2</td></tr>
<tr><td>40 > U ≥ 0</td><td colspan="2">T</td></tr>
</table>

In Table 5.15, the ‘Y area’ (shown in orange) indicates voltage dips that are expected to occur more frequently in the HV and MV networks and a customer should protect his installation against these dip events. The ‘X area’ (X1 and X2) reflects normal HV protection clearance time. Hence, many dip events are expected to occur in this area. The customers with sensitive devices should try to protect their installations against at least X1 type dips. The ‘T type’ dips are not expected to occur frequently. The dips of ‘S type’ can happen in the network only when impedance protection schemes are used or voltage recovery is delayed. ‘Z type’ dips are not very common in HV networks (and if occurs, indicates problematic protection operation). However, this type of dip occurs quite frequently in the MV networks.

The South African standard (also called ‘ESKOM’ standard) gives the characteristic values about the occurrence of maximum numbers of voltage dips in a year for each dip category of Table 5.15. It indicates characteristic numbers of voltage dips for 50th and 95th percentile of the measured sites in different voltage levels as shown in Table 5.16 [Nrs01].

Table 5.16. Characteristic number of dips for 50th percentile and (95th percentile) of sites based on measured data in South Africa (NRS-048-2 Edition 2& 3)

Network voltage range (U_{nom})	Number of voltage dips per year					
	Dip window category					
	X1	X2	T	S	Z1	Z2
6.6kV to ≤ 44kV (note)	13 (85)	12 (210)	10 (115)	13 (400)	11 (450)	10 (450)
6.6kV to ≤ 44kV	7 (20)	7 (30)	7 (110)	6 (30)	3 (20)	4 (45)
> 44kV to ≤ 220kV	13 (35)	10 (35)	5 (25)	7 (40)	4 (40)	2 (10)
220kV to ≤ 765kV	8 (30)	9 (30)	3 (20)	2 (20)	1 (10)	1 (5)

Note: Extensively overhead networks

5.3.3.2 Voltage dip events in Dutch networks

In the Netherlands continuous PQ measurement is done only in the high and extra high voltage networks. Presently, the Dutch network operators are working together to establish typical numbers of voltage dip events in their networks based on historical data. Table 5.17 shows the maximum number of dips recorded at a measuring site in the HV network during 2005-2009 [Lui01], [Hes01], [Hes03], [Boe01]. The number shown in each cell for each year represents the maximum amount of dips registered at one of the measuring sites. The maximum number of events indicated in the cells had (probably) occurred in different measuring sites. For a worst case scenario, if it is considered that all those maximum number of events occurred at one particular site, then the number of maximum voltage dips would be 52. However, such a situation seldom occurs in reality. The other numbers shown within the brackets of each cell in Table 5.17 indicate the average number of voltage dips recorded at all measurement sites (e.g. 20 measurement locations in HV network of the Netherlands). Figure 5.14 shows the average number of dips (including all categories) during 2005-2009 that have occurred at 20 measurement locations in HV network of the Netherlands. In 2005, many voltage dips were registered because of extreme weather condition (on 25th -26th

November) in that year. If these two days are excluded, then the average amount of voltage dips would be 6.2 for 2005 [Lui01].

Table 5.17. Maximum (average) number of voltage dips recorded at a site (all sites) in the Dutch HV network

Residual voltage U (in % of U_{nom})	Year	Duration 't' (ms)				
		10<t≤20	20<t≤100	100<t≤ 500	500<t≤ 2500	2500<t≤ 5000
90>U≥70	2005	3	24	5	1	-
	2006	4 (0.4)	9 (1.8)	2 (0.7)	0	-
	2007	0 (0)	19 (4)	7 (1.7)	2 (0.2)	0 (0)
	2008	1 (0.1)	11 (4.1)	12 (1.9)	1 (0.1)	1 (0.1)
	2009	1 (0.1)	30 (4.9)	5 (1.1)	3 (0.3)	0 (0)
70>U≥40	2005	0	9	2	1	-
	2006	3 (0.3)	10 (1.4)	2 (0.2)	2 (0.2)	-
	2007	0 (0)	2 (0.4)	5 (0.5)	1 (0.1)	0
	2008	0 (0)	3 (0.5)	2 (0.2)	0 (0)	0 (0)
	2009	0 (0)	3 (0.8)	3 (0.3)	0 (0)	0 (0)
40>U≥1	2005	0	6	7	1	-
	2006	0 (0)	8 (0.8)	9 (0.6)	3 (0.2)	-
	2007	0 (0)	7 (0.9)	5 (0.5)	0 (0)	4 (0.2)
	2008	0 (0)	7 (0.5)	1 (0.3)	0 (0)	0 (0)
	2009	0 (0)	12 (1.1)	7 (0.5)	1 (0.1)	0 (0)

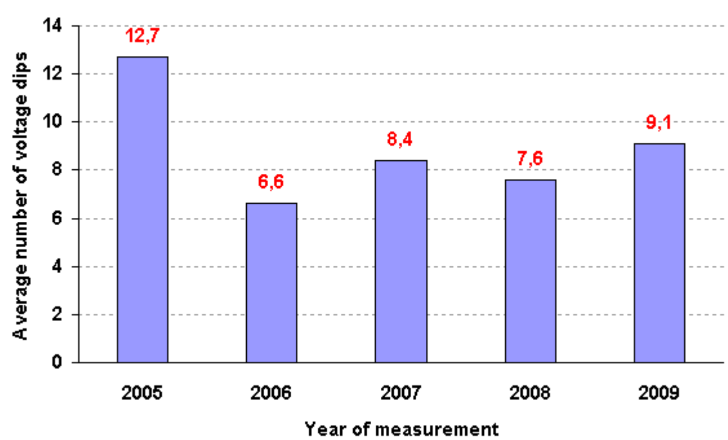


Figure 5.14. Voltage dips (average) recorded in the Dutch HV networks

For estimating the average voltage dip profile, the year 2005 is ignored as no reliable data on average values were found for that year. Based on the four years (2006-2009) measurement records, the average number of voltage dips at a HV site is found approximately 8 in a year. Next, simulations are done on a typical MV network to find out the yearly voltage dip profile due to various fault events in the MV network. From the network's national reliability report of the Netherlands [Com01], it is found that the failure rate of a MV feeder is 0.0243/km of cable/year and that for a MV terminal is 0.012/connection/year. Also, it is assumed that in the MV network 50% faults are of single-phase, 25% are of two-phase and 25% are of three-phase faults [see chapter 4]. Further, it is assumed that all faults occurring in the HV network are propagating to the MV network. Therefore, the yearly voltage dip profile at a MV customer's POC is calculated by combining the contribution of the HV and MV networks and is shown in Table 5.18. It is estimated that there are on average approximately 11 voltage dip events in a year at a MV customer's POC and 3 events fall in the danger zone that is outside the shaded areas of Table 5.18 (e.g. excluding the areas covered by green and yellow cells). The detailed calculation is given in Appendix C-4.

Table 5.18. Average number of dips estimated at a MV customer's POC

Residual voltage U (in % of U_{nom})	Duration (ms)			
	10<t≤20	20<t≤100	100<t≤ 500	500<t≤ 5000
90>U≥80	0.075	1.85	0.75	1.64
80>U≥70	0.075	1.85	0.74	0.49
70>U≥60	0.025	0.26	0.18	0.31
60>U≥50	0.025	0.26	0.13	0.23
50>U≥40	0.025	0.26	0.11	0.11
40>U≥30	0	0.21	0.14	0.04
30>U≥20	0	0.21	0.13	0.04
20>U≥10	0	0.21	0.12	0.04
U<10	0	0.21	0.13	0.04
Total	*0.23*	*5.30*	*2.43*	*2.92*

In chapter 4, the expected number of voltage dips in a year for the MV network was calculated based on the voltage dip statistics of the year 2008 for Dutch HV networks (refer Table 2.3). The average number of voltage dip events in a MV network was found as 10.6/year and among them 2.1 events could cause process interruptions (when the installation's immunity requirements are same as that of the SEMI graph). Table 5.18 also shows the average number of voltage dip events in the MV network which is estimated based on the four years voltage dip statistics of the Dutch HV network. Hence, the result based on only year 2008 data and the result obtained with four years voltage dip statistics are comparable. Therefore, both the network operators and the customers connected can use Table 5.18 as reference data for the expected voltage dip events in a year for a typical Dutch MV network.

For estimating the maximum occurrence of voltage dip events at a MV site, all the measurements for five years (2005-2009) are utilized. Those are then combined with MV network's simulation results to obtain annual voltage dip profile at a MV customer's POC (refer Table 5.19). As per this statistics, it can be seen that yearly a maximum of 57 dips can occur at a MV customer's POC and approximately 22 of them might lead to process outage when the installation is designed for 'class 3' immunity requirements. The chance of occurrence of this situation is however quite low. By comparing Table 5.18 and Table 5.19, it can be seen that there are significant differences in the voltage dip numbers in the MV network when the statistics are based on the maximum number and average number of voltage dip events in the networks.

Table 5.19. Maximum number of dips estimated at a MV customer's POC

Residual voltage U (in % of U_{nom})	Duration (ms)			
	10<t≤20	20<t≤100	100<t≤ 500	500<t≤ 5000
90>U≥80	0.9	9.3	3.2	2.4
80>U≥70	0.9	9.3	3.2	1.2
70>U≥60	0.2	1.8	1.0	0.6
60>U≥50	0.2	1.8	1.0	0.5
50>U≥40	0.2	1.8	0.9	0.4
40>U≥30	0.0	2.0	1.5	0.6
30>U≥20	0.0	2.0	1.5	0.6
20>U≥10	0.0	2.0	1.5	0.6
U<10	0.0	2.0	1.5	0.6
Total	*2.4*	*32.0*	*15.1*	*7.3*

Figure 5.15 shows the probability of occurrence of voltage dip events (based on discrete numbers) at a MV customer's POC. This is plotted using the 'Poisson's distribution' function, with the assumptions that the occurrence of events is random and the consecutive events are independent of each other. The 'Poisson's distribution' is a discrete distribution function and calculates the probability of a number of events occurring in a fixed period of time when the average rate of events (e.g. average number of voltage dips/year) is known. When a POC in the MV network registers an average 11 dips/ year, then for 95% of the situations the number of voltage dips at that site will be limited to 16 with the maximum probability value 22 dips/year.

Further, to estimate for one of the worst situations in the network, it is considered that each of the MV customers faces yearly 22 voltage dips. Using the ‘Poisson’s distribution’ function again, it can be found that the number of voltage dips at a MV customer’s POC will be restricted to 30 for 95% of the time in a year (see Figure 5.15). In the field measurement in Dutch networks, it was found that most of the MV sites experience less than 15 voltage dips in a year at the POCs. With the above information, the annual voltage dips numbers at an average MV site in the Netherlands should be limited to 15 (which can be treated as ‘planning level value’). When the number at a MV site reaches 30 dips in a year, it will be considered as an alarming situation for the network operator (thus can be treated as ‘compatibility level value’).

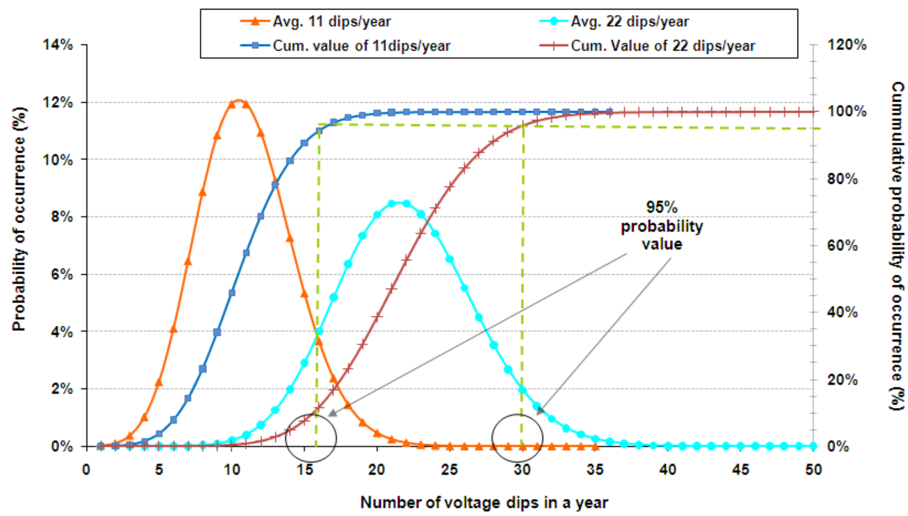


Figure 5.15. Probability distribution and cumulative function of annual occurrence of voltage dips at a MV installation

5.3.3.3 Voltage dip limits in other countries

In the USA, a power quality contract is made between a customer and a network operator. As per this contract, voltage dip is calculated based on the 'quantifying sag' concept [Dug01]. A voltage dip is referred to as 'quantifying sag' when the rms value of any of the three phase voltages is lower than 75% of the nominal voltage. The minimum duration of voltage dip has not yet been defined in this concept. It includes all disturbances, except the voltage dips associated with protection system operation and dips occurring on unloaded lines. Thus, the 'sag score' is calculated as shown in (5.13), where U_A, U_B, U_C are the voltages of the three different phases in per unit. The greater the value of 'sag score' index, the more severe the disturbance. Moreover, the concept of 'sag score target' is part of the PQ contract. This index is determined for the customers who can record voltage dip events at their installations. The sag scores of the measurement points are compared to the value agreed in the PQ contract. The mutual financial commitments are determined at the end of each year depending on the actual sag score compared to the target value.

$$Sag\ Score = 1-(U_A+U_B+U_C)/3 \tag{5.13}$$

In the 4th benchmarking report of CEER [Cee01], yearly voltage dip profiles for some countries in Europe are also published. The UNIPEDE DISDIP [Iec02] measurement campaign was conducted for a period of three years mainly in the LV network of nine European countries. Total 85 measurement sites were surveyed under different climates and network configuration. Table 5.20 shows the 95th percentile data of the survey results of underground networks.

Table 5.20. UNIPEDE survey for underground networks (95th percentile value)

Residual voltage U (as % of reference voltage)	Duration (t)					
	10≤t<100 ms	100≤t<500 ms	0.5≤t<1 s	1≤t<3 s	3≤t<20 s	20≤t<60 s
90>U≥70	23	19	3	1	0	0
70>U≥40	5	19	1	0	0	0
40>U≥0	1	8	1	0	0	0

In France, the idea of individual PQ contract (also called 'Emerald contract') is introduced in which an agreement is signed between a (HV) customer and a network operator (e.g. EDF). The threshold value adopted for voltage dip in the contract is generally for dip depth greater than 30% with duration longer than 600 ms [Han01]. Voltage dips that occur successively in times shorter than 100ms are considered as a single disturbance. Such a PQ contract indicates the maximum number of short interruptions that may occur in a year (such as maximum 5 in a year for a customer connected to a voltage level higher than 50kV). When a customer requests (negotiates) for better power supply quality, the network operator may guarantee to provide that only when he can assure himself that it is technically and financially feasible.

In Norway, PQ measurement is done in different voltage levels. The voltage dip results for the period 1992-2001 were published in reference [Kjl01]. It was found that the number of voltage dips has varied considerably over the years of measurements. On an average, the numbers of voltage dips in the distribution network and high voltage network are 63 and 16 respectively in a year. Majority of the HV and MV networks in Norway are overhead lines. The dips generated in HV network are to a large extent transferred to the distribution network. As a result, the customers in the distribution network faced around 25% of the voltage dips that are contributed by the HV network. In the recent years, an additional norm is set in Norway for an installation to restrict rapid voltage variations (and related voltage dip numbers) to a maximum of 12 on a day [Cee01].

Reference [Del01] published voltage dip data (recorded over a three-month period) at a MV customer's installation in the Italian network and is shown in Table 5.21. It can be seen that during the measurement period 29 voltage dip events might have caused interruptions at the customer's POC when the installation is immune for ‘class 3’ type environment.

Table 5.21. Voltage dips recorded in MV network in Italy

Range of residual voltage U (in % of U_{nom})	Duration 't' (ms)		
	$10<t\leq200$	$200<t\leq500$	$500<t\leq5000$
$90>U\geq80$	12	9	0
$80>U\geq70$	14	9	0
$70>U\geq40$	12	10	0
$40>U\geq5$	13	4	0
$5>U$	2	0	0

From the discussion of this section, it can be remarked that setting up a unique maximum limit on each type of dip category is very difficult. Also, it will not be valid for different types of networks in various countries. However, the information on an approximate number of voltage dips of each category (and on different voltage levels) would be useful for the customer and the equipment manufacturer to design (voltage dip immunity performance) an installation / a device more efficiently.

5.4 Summary and conclusions

This chapter presents an overview of various standards on PQ in the world. The definitions of PQ parameters, measurement methods and protocols, limiting values and other related issues presented observable differences among available international standards. Therefore, various organizations related to electricity business and regulators in different countries are working on harmonizing those available standards.

In this chapter, the standards and technical international documents related to flicker and harmonics are discussed and emission limits at a POC are proposed. For voltage dips, a dip-duration table is made for the HV and MV networks. Also, the average number of voltage dips in the network is estimated. Moreover, various limits on PQ parameters at a POC are proposed. Based on those limits, PQ related responsibilities for various involved parties in the network are defined in chapter 6.

Flicker emission estimation method is described in the IEC 61000-3-7 standard for MV networks. In this research, an alternative approach for flicker emission estimation is proposed and compared with the IEC standard. The value of the maximum global emission anywhere in the LV network is calculated and the flicker emission limits at different installations (with their connection capacities) are estimated based on the approach proposed by the IEC/TR 61000-3-14. Based on those limits, the planning and compatibility level values at different voltage levels are determined. In defining those values, some assumptions are made regarding the frequency of operations of the disturbing loads in various networks and the value of expected level of background flicker emission in the MV network. In this analysis, the compatibility level of the short-term flicker severity in the LV network is taken as 1.0, as suggested in the IEC 61000-2-2 standard. Also, it is argued that introducing 99% and 100% probability limits (both in time and space) for compatibility levels can be useful to restrict flicker related complaints in the network. The maximum flicker emission limits proposed in this research can be helpful for designing future networks.

Various harmonic related standards such as IEC 61000-3-6, IEC/TR 61000-3-14 and IEEE 519, and the technical report (TR/DNO) made by the distribution network operators of four European countries are discussed. It was found from the analysis that the value of the summation law exponent 'α' for 3rd harmonic component should be modified for reaching more accurate estimation. It is proposed to change 'α' value from 1.0 to 1.2 for 3rd harmonic component. Also, the triple 'n' harmonic voltage limits given in the EN50160 standard and the compatibility/planning levels given in the IEC standards are considered quite low as compared to the consecutive non-triple 'n' harmonics. Field measurements revealed that the 9th, 15th and 21st order harmonics have similar ranges of values when compared with their nearest non-triple 'n' order harmonics. Therefore, new planning level limits are proposed for the 9th, 15th and 21st order harmonics. Presently, the standard gives same compatibility limits for the LV and MV networks. So, if the value a certain order harmonic in the MV network reaches its maximum limit, then virtually no extra emission is allowed in the LV network for that particular order harmonic. Hence, the standard should specify a reasonable margin between the values of each order harmonic at different voltage levels, considering their practical applicability.

Further, the values of harmonic current emission limits for different harmonic orders at the LV installations are proposed. Those estimations are done based on the maximum impedance condition (at fundamental frequency for limiting flicker severity P_{st}=1) at a POC. It is expected that the proposed values of harmonic current emission limits will be helpful for the network operators to facilitate new connections in the network. They should also compare the maximum value of impedance for each harmonic order with the actual impedance values at a POC while allowing a large installation to connect in a network. If the actual impedance at a POC is found much lower than the maximum allowable limit, the network operator may assign higher value of harmonic current emission at the POC.

The latest version of the EN50160:2010 standard gives a voltage dip classification table (for various voltage magnitude and duration ranges). The voltage dip profile for the Dutch networks is determined based on the four years voltage dip measurement data of the HV network. The average value of voltage dip events in a year is estimated as 8 at a site in the HV networks. On the other hand, an average MV customer can expect annually around 11 voltage dips at his POC with a maximum of 22 dips in a year. It is noticed that the worst-served (MV) site in the Netherlands can have maximum 57 voltage dips/ year. Thus, from the analysis and field measurements, it is estimated that the annual number of voltage dips at an average site should be restricted to 15 (which can be taken as 'planning level value'); whereas it will be an alarming situation when this number exceeds 30 ('compatibility level value') in the MV networks of the Netherlands. Assigning uniform limiting values (compatibility numbers) for voltage dips is complicated as it largely depends on the voltage level, network type and its topology. Nevertheless, the proposed method for estimating the number of voltage dip events shall be useful for the customers as guidelines to design their installations more efficiently.

Chapter 6

PQ responsibility sharing at a POC

6.1 Introduction

The sharing of power quality (PQ) related responsibilities among customers, network operators and device manufacturers is not very clearly defined in the existing standards. In chapter 5, optimal limits on flicker severity and harmonic current emissions for a customer at a point of connection (POC) are proposed. The proposals were mainly based on field measurements, network simulations and comparing the limits of various national and international standards and reports. Assigning PQ emission limits at a POC is helpful for the customers to know their rights and responsibilities in the network. On the other hand, network operators have to provide a good operating condition in the network and should supply a voltage that fulfils the quality requirements described in the EN50160 standard or any other relevant standard. Also, they should provide a network impedance at a customer's POC that is lower than the maximum impedance limit as proposed (Table 2.5) at fundamental frequency for a specific connection capacity.

The devices used by customers are commonly designed and tested mainly for clean sinusoidal voltage conditions according to the present product standard's requirements. However, in practice, a network voltage is always distorted. Presently, a device manufacturer is not obliged to provide (or declare) a device's harmonic current emission behaviour under different distorted supply voltage conditions. When many polluting devices are connected to the network, they can produce significant current emissions which can distort the network voltage further. Moreover, the harmonic current emission of a device largely depends on magnitude and phase angle of the supply voltage which is also influenced by the background distortion level of the network. It is observed that the presence of different types of devices at a customer's installation generally reduces the total harmonic current distortion (THD_I) at a POC (mainly because of attenuation and diversity effects). In spite of that, under certain conditions the harmonic currents at a POC for specific order harmonics can be large, exceeding the emission limits suggested in chapter 5.

For the voltage dip immunity requirements, the standard IEC 61000-4-11 gives some combinations of voltage magnitudes and respective durations for testing of a device. However, it does not specify any further requirement for a device such as the immunity of a device for different combination of residual voltage magnitude and duration of voltage dips in the network. Hence, it is necessary to improve the product standards for voltage dip specification to make it more compatible with the changing network situation. In chapter 5, the average number of voltage dips occurring at a MV customer's POC in the Netherlands is estimated. Information on annual occurrence of voltage dip numbers is useful for a customer to protect his installation in an efficient way against different types of voltage dips.

Discussion is also going on about PQ responsibility sharing of the network operator, the customer and the device manufacturer at a POC. In this chapter, decision making flow charts are developed to find out PQ related (such as flicker, harmonics and voltage dips) responsibilities of the above three parties in the power system. Additionally, some (practical industrial) case studies are discussed that can illustrate the responsibility of each of the involved parties at a POC. Finally, PQ regulation activities that are presently under development in different countries of the world are discussed.

6.2 Responsibilities on flicker and harmonics

It is discussed in chapter 3 that an inadequate PQ can cause techno-economical inconveniences to the customers and in some situations to the network operators too. Many mitigation measures are available to solve PQ problems. However, before implementing a mitigation measure, it is important to know the source of the problem and examine the effects of the measure. Figure 6.1 shows a systematic approach to decide flicker and harmonics related responsibility of the involved parties at a POC.

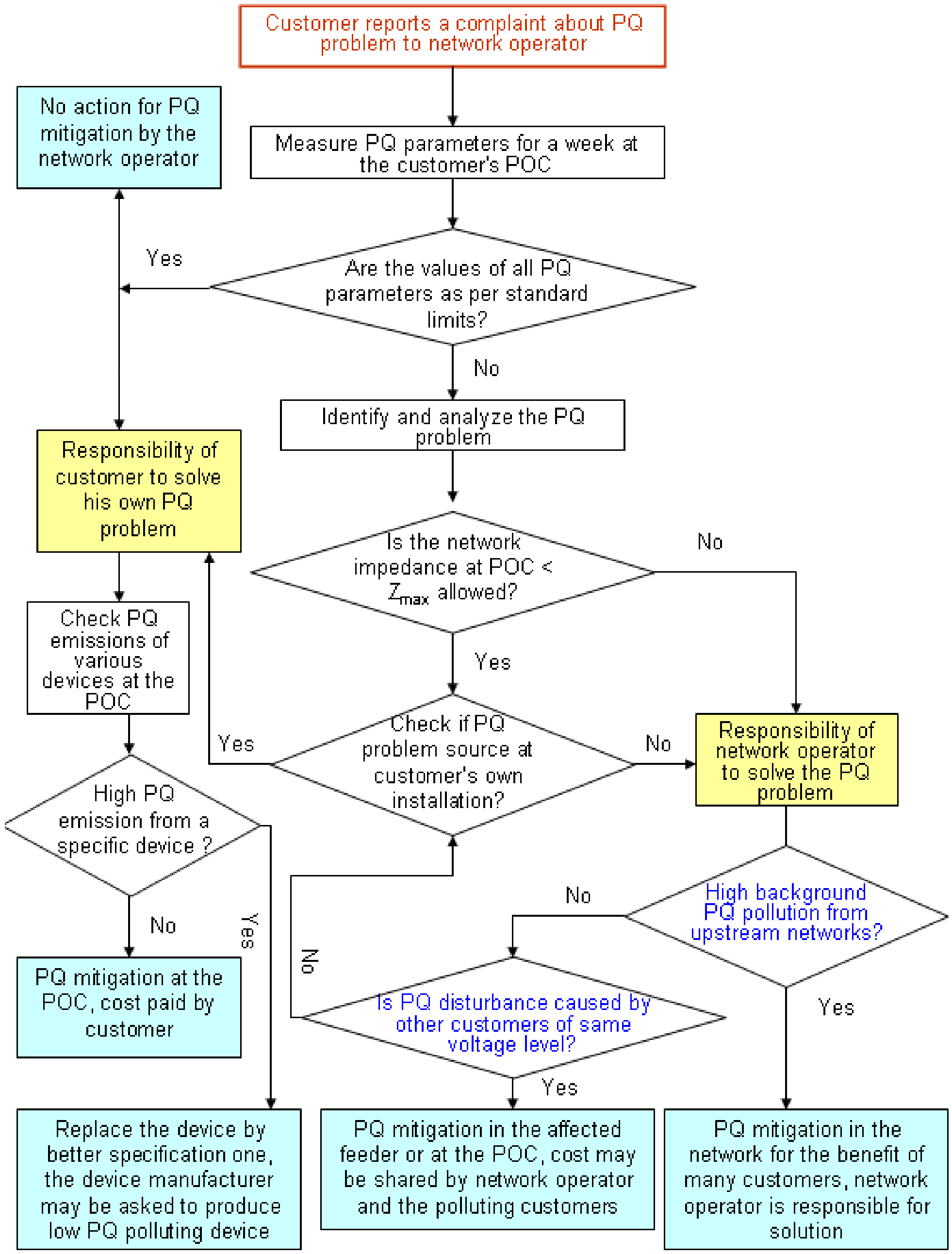


Figure 6.1. Flow-chart to define flicker and harmonics responsibilities at a POC

When a customer complains about flicker or harmonics at his installation, the network operator should first find out the source of the PQ problem at the POC. However, identifying the problem sources can be quite difficult as harmonic currents originated in an installation and the harmonic currents in the network can influence mutually (because of cross-interferences and aggregation effects). Therefore, it is often difficult to distinguish the harmonic current contributions of different customers in the network. In contrast, it is relatively easy to identify flicker (problem) sources in the network as no such cross-interference occurs among the flicker generating sources. After analysing the problem, the network operator may ask the customer either to install a mitigation device at the POC, or to pay for the solution if the problem is caused by the customer's own device(s). On contrary, if the network impedance at a POC is found higher than the maximum impedance allowed for the customer's connection type (see Table 2.5), the network operator will be responsible to solve all kinds of supply voltage related problems.

Depending on the severity of a problem, the network operator will provide mitigation measure at the complaining customer's POC, or in a feeder or elsewhere in the network to fulfil the needs of a large group of customers. Sometimes, it can also happen that PQ disturbances originate at higher voltage levels and propagate to lower voltage networks and affect the customers there. For such a situation, the network operator should again be responsible to solve the problem or he should take action against the customers who cause that problem in the network. It can also be the case that the network impedances in a specific neighbourhood are lower than the maximum limit and the customers still suffer supply voltage related inconveniences. For such a situation, the problem source is probably located locally. Then, the network operator should monitor the neighbourhood by performing decentralised measurements at several locations to find out the problem source. Depending on the situation, the PQ solution cost can be paid by a customer or a group of customers or a part of the cost can be shared by the network operator too. If it is found that inadequate PQ in the system is caused by certain type of device(s), then replacing it by another device with better specification will be the most efficient choice.

6.2.1 Role of network operator

As shown in Figure 6.1, a network operator has an important role regarding flicker and harmonic issues in the network. In many cases flicker is a local problem and is commonly caused by the operations of customers' time varying (large) loads. Lighting devices (such as incandescent lamps) are quite sensitive to voltage variations and cause light flicker. When a customer reports flicker problems, the network operator should first measure the flicker severity at that installation by conducting a PQ measurement for some time. If the measurement result also confirms high flicker severity, the next step is to locate any suspected flicker generating source within the installation. If no problematic flicker source is found there, then the network operator will be responsible to investigate further to find out the reason of the problem.

It can also happen that network impedances in the LV network are quite high and many customers of that neighbourhood frequently complain about flicker problem. Then, the network operator should measure the PQ parameters at multiple locations in the network to locate flicker generating sources. Sometimes, high flicker severity is generated in the upstream networks and propagates to the LV customers' terminals. Thus, a high background flicker level can have a high impact to the LV customers too (see Figure 4.5). It was also discussed in chapter 5 that the network operator can allow high emission level to a particular customer (based on a special contract). While approving such a connection, the network operator should check flicker severities at different voltage levels to confirm that those values are within the standard limits.

Regarding harmonics, each order harmonic voltage value in the network should be within the limits of EN50160 standard. This standard gives THD_V limit as 8% for the MV and LV networks. While designing a network, the network operator should follow the planning level values specified in the standard. In the standard, the limits for 'triple n' harmonics are specified quite low in comparison to 'non-triple n' harmonics (refer Table 5.8). From the analysis, it was concluded that the limits for 'triple n' harmonics should be changed to a higher value to make them comparable with the other order harmonics. Thus, new values for the harmonic voltage planning levels were proposed in Figure 5.9 which provides the network operators with some additional allowance for the 'triple n' harmonic values. Additionally, the network operator may check the frequency response of network's impedance (at different voltage levels) to find out probable resonance points in the system. Those points have to be shifted to avoid large increase of harmonic voltages/currents in the network. The impedance of a LV network is generally inductive, but when many capacitor loads are switched in resonance conditions can occur. Therefore, in the future network design, a network operator will need to specify a limit on capacitances at a customer's POC too.

6.2.2 Role of device manufacturer

The customer's devices that draw large inrush currents often cause flicker (and dips) at the same installation and/or at the neighbour's premises. The devices that require frequent switching in a specified period of time should carefully be designed to restrict voltage variations because of their starting events. When a device is installed at a customer's installation, it is required to check the actual network impedance at the POC. Generally, when a device manufacturer supplies a device, he specifies the reference impedance based on which the device is designed. If the information of actual impedance at a POC is known, the allowable value of inrush current can be calculated by using equation (6.1). When, network impedance at a POC is lower than the reference impedance, theoretically higher inrush currents are allowed. However, the network operator can specify a maximum limit value for inrush currents equal to the connection capacity of the installation to avoid (flicker emission related) discrimination among different customers in the network. Moreover, the flicker severity (P_{st}) ≤1 at a POC should also be met.

$$I_{new,in} = \frac{Z_{ref}}{Z_s} * I_{inrush} \tag{6.1}$$

where,

- $I_{new,\,in}$: adjusted new value of inrush current
- I_{inrush}: inrush current of device (provided by manufacturer)
- Z_{ref}: reference network impedance
- Z_s: network impedance measured at the POC

At present, a device manufacturer tests his device for harmonics mainly under a sinusoidal voltage condition. Laboratory measurements show that if the supply voltage is distorted with harmonics, a device draws different harmonic currents than at a normal sinusoidal voltage situation (see Appendix A-4). Therefore, a device manufacturer should design the device in such a way so that it can operate even under different supply voltage distortion conditions. The average background harmonic distortion in the European networks (such as described in section 4.3.3 of this thesis) can be taken as reference supply voltage distortion condition for testing devices. Hence, it is recommended that a device manufacturer should provide the maximum harmonic current emission value for each order harmonic (as shown in Figure 6.2) in device specification when he sells it in the market. It was also noticed that the harmonic current emission levels of various devices in an installation vary significantly. For example, a vacuum cleaner (VC) produces a larger value of 3rd harmonic current than other commonly used household devices. Under certain situations, the harmonic current emission level of a VC exceeds the standard limits of IEC 61000-3-2 [Iec05]. For such type of (special) devices, the device manufacturer can also provide phase angle information in the specification for each order harmonic current (when required by a customer). This information can be very useful for the customer to design the installation more efficiently. However, all those above additional information will increase the cost of a device as it has to be tested additionally for other voltage conditions too. Figure 6.2

illustrates that different devices have different harmonic current emission characteristics. The device manufacturer should test each device for different supply voltage conditions and should specify the device's maximum value of harmonic current emission at various order harmonics. Those maximum values should be mentioned in the device specification too.

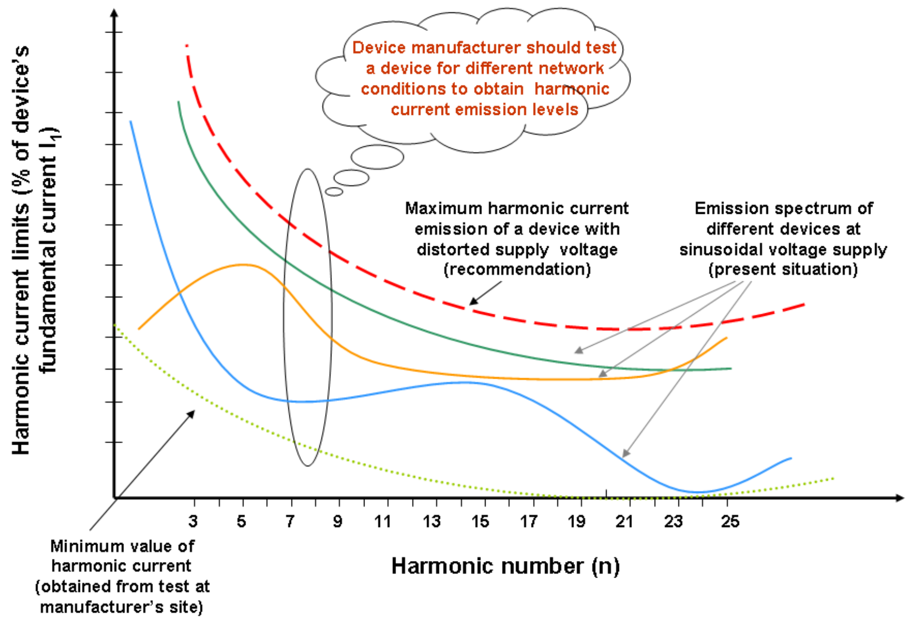


Figure 6.2. Proposal for modifying a device's specification for harmonics

6.2.3 Role of customers

The customers who use incandescent lamps generally observe light flicker more frequently than the customer having modern lighting devices (such as energy saving lamps). At present, the network operators get many complaints from the customers about flicker. In future, with large scale integration of energy saving lamps and LED lamps flicker related complaints will reduce. In many countries, governments already started to take action to stop the use of incandescent lamps.

The customer also should restrict the inrush current demand and frequency of starts of his disturbing loads to limit voltage variation at a POC as per the standard requirements. Flicker emission limits for various LV installations are proposed in Table 5.4. When a customer follows these limits, it is expected that flicker severity can be kept below the compatibility level values. To meet the standard limit for voltage variations at a POC, a customer can also restrict the inrush current demand of his devices by implementing another starting methodology such as soft-starter.

Alternatively, he can also use a mitigation measure to limit flicker emission at the POC.

Flicker issues are relatively easy to handle as it is more directly visible. In contrast, harmonics related responsibilities are quite complicated as a device's harmonic current emission can largely be influenced by distortions generated by other customers or background distortion in the network. With a variety of devices connected in the installation, the harmonic current at a POC can vary significantly. Also, it is a quite dynamic and time variant and is difficult to predict. It was found that the harmonic current emission limit for households can be set as per the limit of 'stage 1' of IEC/TR 61000-3-14 report (see chapter 5). For industrial customers, there can be significant harmonic current emissions because of the operation of many non-linear devices. These can cause inconveniences to the customer himself too. When this is the case, the customer should restrict the harmonic current emission in his installation by applying suitable mitigation measure at his own cost. For large LV installations, harmonic current emission limits are suggested in Table 5.13. The customer should follow these proposed limits to restrict his installation's harmonic current contribution into the network. Moreover, when the network operator can identify the major harmonic/flicker sources in the network (by conducting regular decentralised monitoring), he can also oblige the customer to take remedial measure.

6.2.4 Practical case study on flicker

It is noticed that when the long-term flicker severity (P_{lt}) is more than 1.0 in the network, the customers are generally susceptible to flicker related inconveniences. However, even with a low P_{lt} value (P_{lt}<1), some customers complain about light flicker; whereas high flicker severity (P_{lt}>1) can also be unnoticed by the customers [Hal01]. The network operators are obliged to maintain P_{lt} compatibility level lower than 1.0 in the network as per the standard IEC 61000-2-2 [Iec06]. Flicker problems are originated mainly by the operation of medium and large industries that use time varying loads in their process operations. It can cause large voltage variations in the network and hence flicker in the customer's installations. A case study at a 'car shredder' industry is discussed here that was producing high flicker severity and poor power factor at the installation, exceeding the contractual requirements [Lup01].

6.2.4.1 Description of the case

A car shredder industry has a variable load demand. In this example case, the industry is supplied by a dedicated transformer (4500kVA, 20kV/6kV) from the 20kV public distribution network as shown in Figure 6.3.

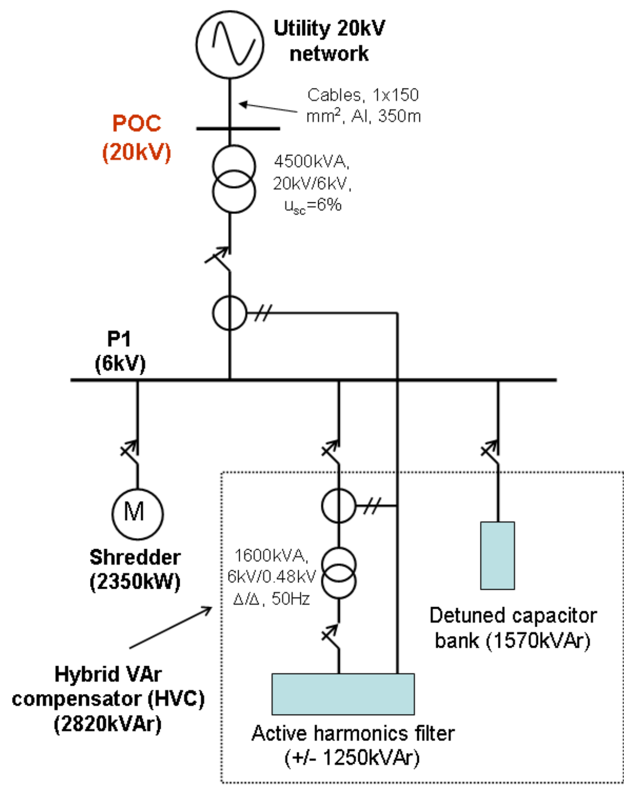


Figure 6.3. Single-line diagram of 'car shredder' installation and mitigation device

The metal shredder has hammers fixed on the periphery of the cylinder called a 'rotor'. The rotor is moved by an asynchronous motor with rating 6kV, 2350kW. When cars are brought into the shredder, the hammers strike and shred steel. This causes pulsating torque. Therefore, the asynchronous motor draws varying power and changes the total apparent power demand of the installation. To estimate the voltage drops at the 6kV busbar (P1) of Figure 6.3 because of the operation of the shredder motor, first the equivalent impedance (Z) is to be estimated. The impedance is a combination of resistance (R) and reactance (X) of the equivalent network shown in Figure 6.3. Total impedance (Z) at P1 (6kV busbar) is = R + jX = 0.0372 + j 0.8217 Ω. The short-circuit power at P1 is found as 40MVA approximately and that at the POC is 95MVA. The shredder manufacturer provided three overload situations and their frequency of occurrences in the installation, as shown in Table 6.1.

Table 6.1. Shredder power operation characteristics

Operational modes	P (kW)	Q (kVAr)	S (kVA)	Power factor	Frequency of operation (per minute)
Normal	2350	1332	2701	0.87	
Overload-1	2350	1820	2972	0.79	10 to 20
Overload-2	2350	3787	4457	0.53	1
Overload-3	2350	2962	3781	0.62	2

As can be seen from Table 6.1, the apparent power demand of the shredder motor varies between 2701kVA to a maximum of 4457kVA due to its various modes of operation. These load changes in the installation cause voltage drop at the P1 (6kV busbar) and the POC (20kV busbar) that can be calculated using equation (6.2).

$$d_{max} = \frac{\Delta S_i}{S_{sc}} \cdot cos(\theta_k - \alpha_i) \qquad (6.2)$$

where,

- ΔS_i: apparent power demand change during an operation
- S_{sc}: short-circuit power at POC
- θ_k : impedance angle calculated at POC from the network study
- α_i : phase angle of load during normal operation

This causes the voltage drops to vary from 3.2% to 8.9% at the 6kV busbar. Under such an operating condition, the maximum value of P_{lt} recorded at P1 was around 1.5 with a 95% value of 0.63. The voltage drops at the POC (20kV busbar) for various operating conditions vary in the range of 1.5% to 4.0%. As per the contract signed between the customer and the network operator, the following requirements were agreed for limiting flicker emission contribution into the 20kV network (at the POC):

- A short-term flicker emission contribution of ΔP_{st}=0.35
- A long-term flicker emission contribution of ΔP_{lt}=0.25

The network operator's objective is to guarantee a $P_{lt} \leq 1.0$ in the network. To limit the desired emission level at the POC, the maximum voltage drop should be limited to 0.95%. Therefore, additional capacitive reactive power is required to compensate for the inductive reactive power demand of the installation. Therefore, the customer installed a dynamic hybrid compensation system of 2820kVAr at P1 that consists of a fixed detuned capacitor bank rated 1570kVAr and an active harmonic filter (AHF) of rating +/-1250kVAr. It results in a full compensation of the reactive power demand of 1332kVAr during normal operation. The remaining amount of reactive power of the hybrid Var compensator (HVC) unit is 1488kVAr (=2820kVAr-1332kVAr) that can further be used to provide the reactive power demand of the shredder motor during overload operation.

Thus, by installing HVC at the customer's installation, the voltage drop at P1 (6kV busbar) during normal load is found 0.2% only. Also, the average power factor is improved to 0.993 and the 95% value of P_{lt} is found 0.40 (with a maximum value of 0.46) at P1 (6kV busbar). The presence of a transformer at the installation's entrance limits the transfer of flicker severity from P1 (6kV side) to the POC (20kV side). The flicker transfer coefficient from 6kV to 20kV side is approximately 0.31. Therefore, the 95% value of P_{lt} at the 20kV side is 0.12 (with a maximum value of 0.14). This value is well below the contractual agreement of 0.25. Hence, by implementing a mitigation method in the installation, the customer could avoid the cost of penalty that is imposed by the network operator regarding flicker emission requirements at the POC.

6.2.4.2 Remark on the flicker case study

The customer of the 'car shredder' case has a contractual agreement with the local network operator regarding the flicker emission limit at the POC. Before the implementation of a PQ mitigation method in the installation, it was reported that the customer was paying power factor penalty. The customer wanted to increase his production capacity for which the installation required an increased amount of apparent power. This caused larger voltage drops than before and increased flicker emission level at the POC. In this case, the customer should be responsible to solve for the PQ problem occurring at his installation. The network operator advised the customer to use a dedicated power line to feed the expanded facility. However, that requires more investment and time. Considering the constraints, the customer chose to install a PQ mitigation device (HVC in this case) to solve the flicker problem and to meet the installation's required reactive power demand.

The HVC system has improved the PQ performance level at the POC. It supplies the reactive power demand of the loads connected to the installation. Furthermore, the power factor at the POC is improved and the customer saves penalty cost. A 'cost-benefit' analysis for the customer can be done when the investment for the PQ mitigation device, the penalty costs and energy costs are known. In most of the cases, the customers themselves invest on a PQ mitigation measure at their installations to fulfil the contractual agreements with the network operator and to avoid penalties. Thus, the customer is mostly responsible to solve the flicker problem at the installation. On the other hand, the network operator should guarantee a minimum level of short-circuit power at a MV customer's POC. In Italy, the regulators have already imposed such a limit in their national standard [All01]. However, not in many countries of the world yet have such a requirement. In this case, the ratio of the installation's maximum power demand and short-circuit power is <0.1 (=4457kVA/45MVA). The maximum number of motor starts per minute is limited to 20 (see Table 6.1) that meets the connection rule requirements of the IEC 61000-3-7 [Iec04] standard (refer section 2.4.2).

For the considered case, the network operator had strict flicker emission limits for the installation and the customer agreed to meet the requirements. When such a PQ contract is applied between a customer and the network operator, or the standard specifies flicker emission limits at a POC, it is relatively straight- forward to define responsibility of the involved parties regarding a specific PQ issue. Hence, the optimal (or minimum) PQ criteria at a POC should clearly be defined by the (inter)national regulators to avoid arguing between the customer and the network operator.

6.2.5 Practical case study on harmonics

The customer's non-linear loads produce harmonic currents that can cause inconveniences to the customers as well as the network operator. In this section, first a case study is discussed for an industrial customer who has non-linear loads that cause harmonics in the installation. Also, two mitigation measures are discussed that can solve the harmonics problem of the considered installation. In the second part of this section, a technical estimation is done for a network operator to find out various impacts of harmonics to the network components.

6.2.5.1 Description of case

A case study on harmonics was conducted at a low voltage (LV) installation of a 'laminate floor panels' manufacturing industry [Sch01]. This industry has many AC variable frequency drives (without reactor) and thyristor-controlled devices at the installation. It was connected to the MV network of the utility grid through a MV/LV transformer as shown in Figure 6.4.

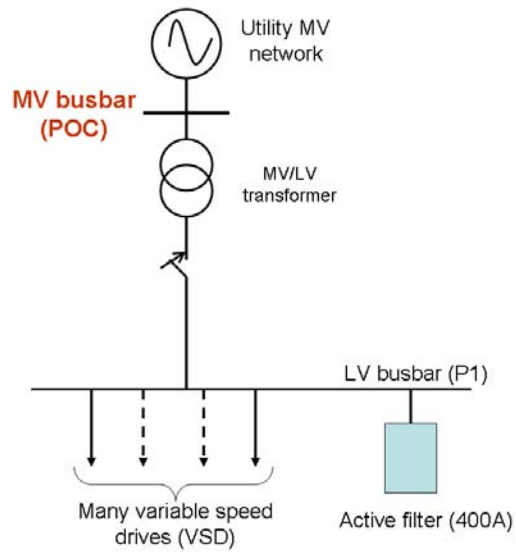


Figure 6.4. Simplified single-line of 'laminate floor' manufacturer's installation

Total non-linear load at the considered POC is about 66% of the customer's transformer load. This load causes a harmonic current distortion at the POC and sometimes causes failure to the production facility too (for example, sudden tripping of a breaker). The harmonic currents also produce extra heating of the components such as cables and motors. This heat causes temperature rise that eventually decreases the useful life of the affected components by premature aging. Moreover, an increase of the 3rd harmonic voltage level was recorded in the MV busbar (see Figure 6.5). A total harmonic voltage distortion (THD_V) at the LV busbar (P1) was recorded of 5.4% and the total current harmonic distortion (THD_I) was 22% as shown in Figure 6.6. It was suspected that the harmonics at the installation were causing the tripping of protection devices. The unplanned tripping was causing significant production hour loss, raw material damage, and extra labour at the installation. Furthermore, harmonic currents were causing additional energy losses in the components of the installation. Hence, the customer wanted to mitigate the harmonics related problem at the installation. Two options are possible:

- Installation of an active filter.
- Insert reactors with the drives.

In this case study, it was noticed that implementation of a reactor with the drives reduced the harmonic current and harmonic voltage level at the installation to some extent. However, it still accounts for some amount of energy losses.

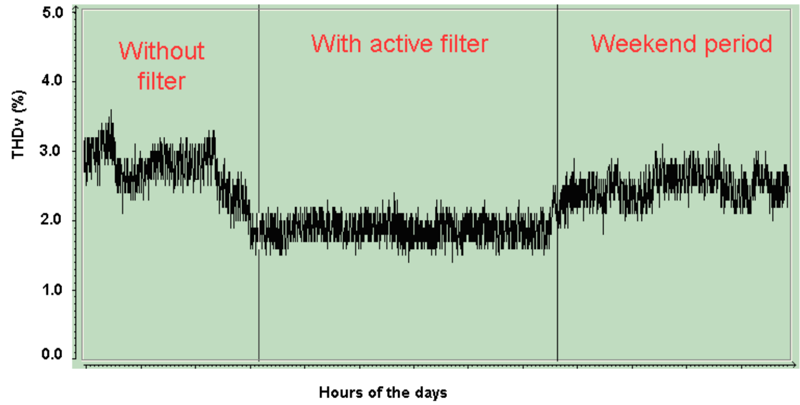


Figure 6.5. 3rd harmonic voltage distortion recorded (at POC) in the MV network

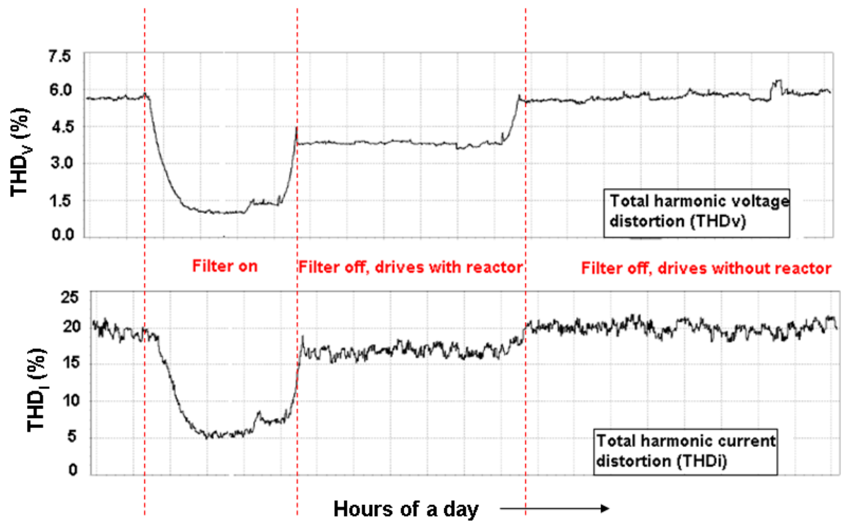


Figure 6.6. Harmonics distortions at the LV busbar (P1) with and without series reactor and the active filter

By implementing an active filter of 400A capacity in the installation, it was found that the THD_V as well as the THD_I values improved significantly. The new value of THD_V was recorded 2.5% and that of the THD_I was 5.8% at the LV busbar as shown in Figure 6.6. In chapter 5, maximum limits for harmonic currents at a LV installation are proposed (see Figure 5.13) with a maximum THD_I value of 7%. For the considered case, the full harmonic current spectrum is not available; however, the THD_I is found 5.8% which is below the maximum limit of 7% (as suggested in this thesis). The 3rd harmonic voltage level in the MV network is improved from 2.8% earlier to less than 2% afterwards. It is found that there is some saving in the electricity usage (monthly energy bill) after the implementation of active filter at the installation. Moreover, the production hour losses are minimized as unwanted interruptions because of a protective device tripping could be avoided. Therefore, for the same working (labour) hours more production of laminate floor panel is possible. Thus, the company's yearly profit is increased and the investment for active filter is paid back within a couple of years time [Sch01]. Further, it was observed that the supply transformer is less loaded and becomes less warm after the implementation of active filter at the POC.

6.2.5.2 Remark on the harmonics case study

In the above case of the 'laminate floor' manufacturer, it was found from the measurement that the THD_V at the POC was below the limit of EN50160 standard. However, the values of some specific order harmonic voltages (such as the 3^{rd} and 5^{th} harmonics) were quite high. The customer was also facing harmonics related energy losses as well as production hour losses due to sudden tripping of protective devices at the POC. In this case, the operation of installation's non-linear devices is causing several inconveniences to the customer (and probably to neighbouring customers too). Thus, to avoid production loss, the customer decided to install an active filter at his installation. This mitigation device reduced the harmonic currents and also the unwanted tripping of protective devices was avoided. Therefore, the customer could save money as the installation's monthly electricity bill was reduced and could get extra income because of more production hours. In this case, the customer invested for the PQ mitigation measure at the installation. Reference [Sch01] showed that the implementation of the active filter is cost-effective for the considered installation and has a short pay-back time.

6.2.5.3 Impacts of harmonics on network components

The simulation results of 'case 4' from chapter 4 (refer section 4.3.5.4 of this thesis) are utilized here to estimate the technical losses in cables and transformer due to the harmonic currents in the network. Table 6.2 shows a summary of the simulation results for the harmonic load flow in different LV feeders of the network. The harmonics related non-fundamental active power loss was found 1.8kW in the three phases of the simulated LV network. It is noticed that the MV/LV transformer supplies an extra amount of 1.15kVA apparent power in each phase because of harmonic loads in the network. This is approximately 2.5% of the total load supplied by the transformer, whereas the total non-fundamental active power loss is 1.3% of the total demand. The simulation is repeated considering no background harmonic pollution from the MV network. Under such a condition, the extra apparent power demand in LV network is around 1.9% of the total load supplied by the transformer. The transformer under consideration is operating at a much lower load condition than its nominal value.

Table 6.2. Simulation results for estimating LV feeder losses and extra loads

Description of LV feeder	THD_I at the beginning of LV feeder	Loading per phase in the simulated LV feeder		
		Normal load flow results (kW/kVAr)	Harmonic load flow results (kW/kVAr)	Increase in power demand because of harmonics (kW/kVAr)
Feeder with high and low load demand houses	15%	9.67kW 1.37kVAr	9.84kW 1.58kVAr	0.17kW 0.2kVAr
Feeder with PV inverter + average load, and low load demand houses	49%	4.55kW 4.80kVAr	4.56kW 4.94kVAr	0.01kW 0.14kVAr
Feeder with PV inverter + average load, and high load demand houses	28%	8.26kW 3.75kVAr	8.36kW 3.95kVAr	0.10kW 0.20kVAr

Note: Simulation results are for high MV background distortion condition.

The above analysis is done for an (average) evening load condition in a typical LV feeder in the Netherlands. In a real network, loads are dynamic and time variant. It was observed from the field measurements that total current of a typical Dutch LV feeder varies between 20A to 60A on a day. Moreover, the current demand also varies significantly between a summer day and a winter day. Therefore, harmonics related losses vary too throughout the year depending on the season and time of the day. In chapter 3, a field survey was referred about a test LV network in the Netherlands [Hod01]. This test network supplies electricity to a holiday park. The total harmonic losses were estimated 0.06% of the total load demand in a year. As people stay in this area only during holiday periods, harmonic losses found are relatively low compared to a typical household neighbourhood. Although the harmonics related active power losses are relatively low in the network, the apparent power demand due to harmonics was found not negligible. Therefore, the network components have to carry that extra power flow when harmonics are present in the network.

6.3 Responsibilities on voltage dips

A voltage dip event at a customer's POC often incurs large financial losses for an industrial customer. Many voltage dips are originated in the network and are hard to eliminate completely because of natural events. Reducing the number of voltage dips by improving the network leads to a huge amount of investment for a network operator. On the other hand, a process owner ideally does not want any voltage dip related process interruption at his installation. Hence, he needs to know the numbers and types of voltage dips per year that can probably occur at his POC. Incorporating high immune process devices can improve the process performance against voltage dips, but it requires a large investment for the customer. Alternatively, PQ mitigation measures can be applied to prevent voltage dip related inconveniences at an installation. As it can be quite costly, it requires coordinated actions to reach an optimum decision about the investment (see Figure 6.7).

As mentioned above, information on voltage dip numbers in the network is very important for customers. The South African standard specifies the characteristic number of voltage dips at different voltage levels of the networks. However, those numbers will not be valid (optimum) for other networks in different countries of the world. It is found that the numbers of voltage dips in the Dutch HV and MV networks are relatively low (see Figure 5.14 and Table 5.18) in comparison to the South African networks (see Table 5.16). In France, the number of short interruptions in a year at a POC is negotiated based on a PQ contract between a network operator and an individual customer. The threshold values adapted in such a contract are: dip duration longer than 600ms and dip depth greater than 30% respectively are not acceptable.

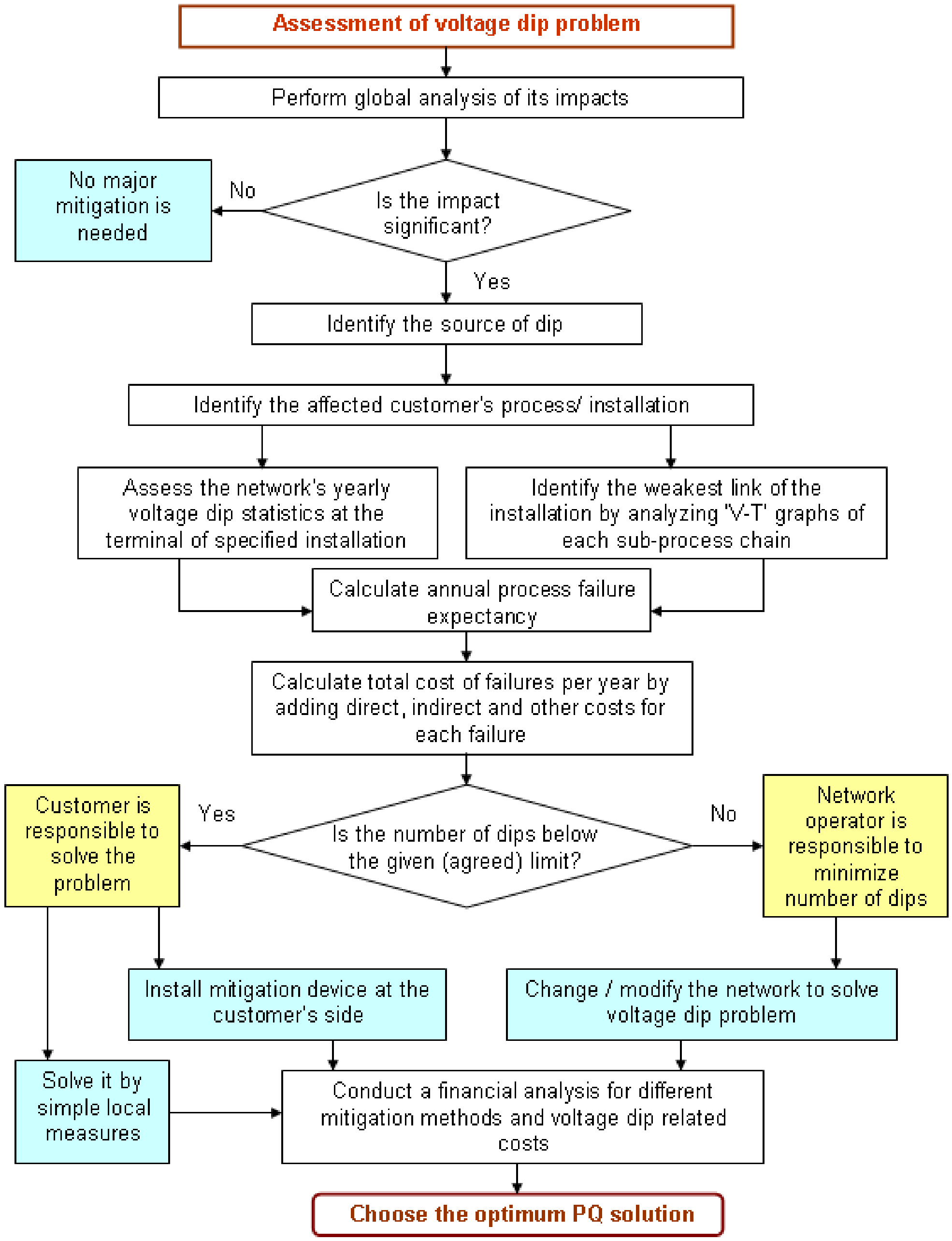


Figure 6.7. Decision making flow chart for voltage dip mitigation at a POC

In Sweden, a proposal is made to limit the voltage dip numbers and to share the responsibility between the network operator and the customer at a POC as illustrated in Figure 6.8 [Bol03]. However, no limit value for the responsibility sharing area (border) is yet specified in the proposal. A small area is identified in the voltage dip chart where no dips are allowed. However, it is hardly possible for a network operator to guarantee that there would be no voltage dip in that region (area shown below the green line of Figure 6.8).

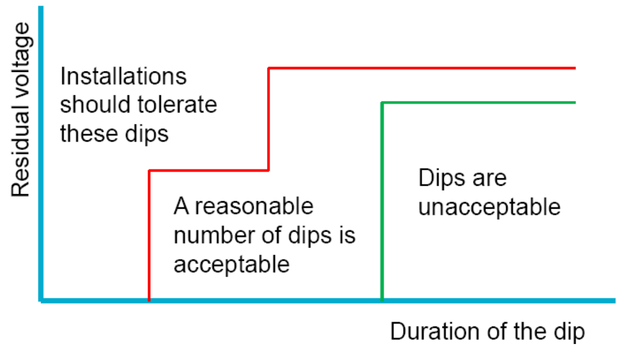


Figure 6.8. Proposal to limit voltage dips at a customer's POC in Sweden

6.3.1 Role of network operators

Voltage dips can not be eliminated completely from the networks mainly because of various natural phenomena. However, based on historical data, a network operator should be able to provide an approximate value for the expected number of voltage dip events at a POC when customer asks about it. He should also give information to the customer about the reason of a voltage dip and the probability of getting another one in the network directly after that. This information can be helpful for a customer to make a (critical) decision such as, restarting of a process. In chapter 5, a voltage dip-duration table is made for the Dutch MV network, and the average and maximum number of events that are expected in each cell of the dip-duration table are specified. Those numbers can be used as a reference value for a MV customer. From the same analysis, it was estimated that a MV customer in the Netherlands can expect an average of around 11 dips in a year at his POC. However, it was found that a customer's POC can face a maximum of 57 dips in a year among which approximately 22 dips can cause process outage when the installation is designed for 'class 3' immunity requirements. It was found that the chance of occurrence of such a situation is quite rare. The 95% probability value of the number of voltage dips at a POC in Dutch MV network is found as 16 in a year, when the yearly average is 11. For an annual average of 22 dips, the 95% probability value of the voltage dip number is estimated as 30 at a MV customer's POC in the Netherlands. By keeping some margin, the planning level value can be set as 15 and the compatibility level value as 30 for the MV networks in the Netherlands.

Presently, it is still a discussion point among the international regulators whether voltage dip limit numbers should be given for different voltage levels and also for different types of dips separately. Nevertheless, some countries have already started to adopt the classification methodology as given in the EN50160 [Std04] standard and publish the voltage dip statistical data for their networks. A national level regulation can be enforced to assign a reference value for each of the cells of the voltage classification table of EN50160 standard.

6.3.2 Role of equipment manufacturer

A device manufacturer should be able to establish a device that fulfils immunity requirements as per the IEC standard and/or a tailor-made device as per the customer's special need (for increased cost). Figure 6.9 gives a proposal to define the voltage dip related responsibilities of the three involved parties: the network operator, the customer and the device manufacturer.

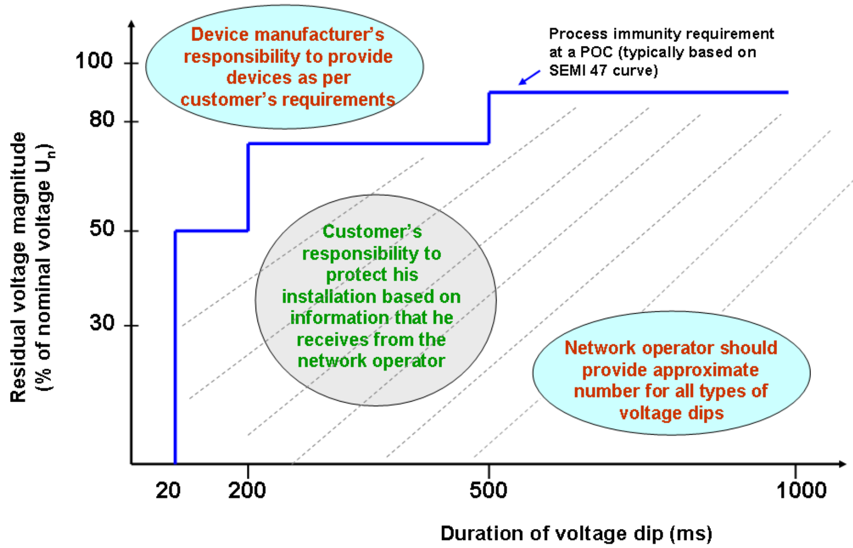


Figure 6.9. Illustration of responsibility borders for different involved parties regarding voltage dips in the network

Figure 6.9 shows that a customer should define his process's typical immunity level based on the voltage-time ('V-T') performance of each process device. The network operator, on the other hand, should provide the customer with the expected number of all types of voltage dips at the POC. It will be very useful for a customer if the network operator can provide approximate number of dips in each cell of the voltage dip-duration table. The device manufacturer should make a device according to the standard immunity requirements such as SEMI 47 curve, ITIC graph, IEC 61000-4-11, etc. and should clearly mention this information in the device specification too. To implement a better regulation in the electricity business, the equipment's performance standard (such as the voltage-time immunity characteristic) should be integrated with the voltage quality requirements of the network, as shown in Table 5.14. Such a coordinated approach in standards would be useful for all involved parties in the network who are concerned about voltage dip related problems.

6.3.3 Role of customers

Based on the information on voltage dip numbers provided by the network operator, a customer should make a calculative guess (based on his experience) about the number of process failure (chances) in a year at his installation. A customer's process failure can be affected by various factors (refer section 4.4.3). Therefore, he should estimate the uncertainty region where the process may survive or fail depending on certain circumstances. If the customer wants to avoid voltage dip related inconveniences, he should install an appropriate mitigation measure at his installation. Reference [Ajo01] suggests that short and shallow dips are generally quite common (and frequent) in the networks and are difficult to avoid. For those cases, it is also responsibility of a vulnerable customer to take appropriate measure in protecting the installation. In Figure 6.10, various possible mitigation measures for voltage dips, their relative costs-benefits and the parties mainly responsible for the investment are illustrated.

The network side solutions are generally very costly, but it can benefit many customers. In contrast, an individual (vulnerable) customer's solution to mitigate voltage dips at his installation may be cost effective from the system point of view. Improving of a device's voltage immunity characteristic generally requires signification investments for a device manufacturer as he has to modify the process layout and testing devices. However, if this is to be done for a specific customer, the relative benefit will be small from a societal perspective. When many customers in a neighbourhood desire to improve the voltage dip performance at their installations, they can invest on a mitigation measure in consultation with the network operator. In that case, the cost can be shared among the benefitted customers (and the network operator).

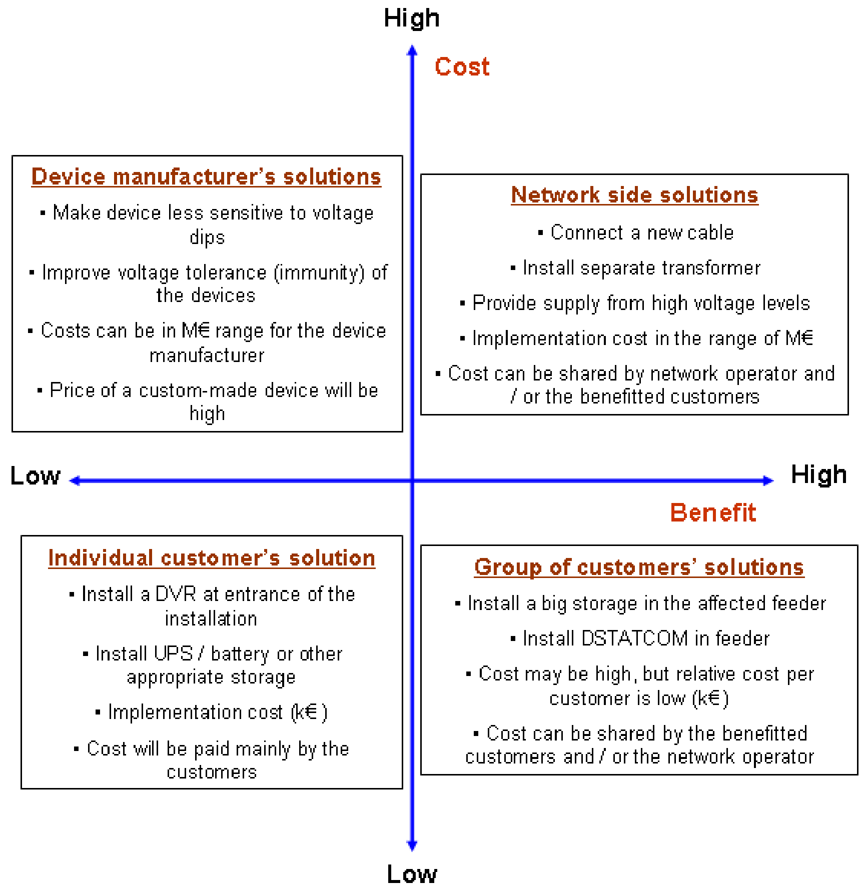


Figure 6.10. Voltage dip mitigation options and responsibility of involved parties

If a customer wants to protect his installation against all voltage dips, he can install high immunity devices that are less sensitive to voltage dips. When a customer knows about the critical time of his process, he can invest for a suitable mitigation measure to minimize the impacts of voltage dips at his POC. Alternatively, a customer can sign a mutual contract with the network operator to restrict voltage dip numbers at his POC. With such a contract, if the network operator fails to meet the agreed commitment, he will be responsible to pay for the solution. Most of the cases, a customer himself invests for a mitigation measure at his POC to immune his installation against a voltage dip problem.

6.3.4 Practical case study on voltage dips

A voltage dip case is analysed for an ‘automobile’ manufacturing industry [Lum01]. This industry was connected by two MV feeders (cables) to the 36 kV voltage level in the network. During the period of 2000-2005, voltage dips were recorded at that installation (refer Figure 4.31). Out of which the customer had suffered process-interruptions for 17 times during the five years period. The total financial losses were registered to be €924,000. It means that every year on average approximately 3 process interruptions occurred at the customer's installation, resulting in average monetary loss of around €54,000 for each voltage dip related interruption/year. Presently, there is no limiting number specified in the EN50160 standard or most of the national grid codes regarding yearly voltage dip events at a POC. The customer mostly is not aware of the frequency of voltage dips that he can expect at his installation in a year. However, if a dip event occurs and when his installation is sensitive to that voltage dip, there would be significant financial costs involved. Hence, he needs to take preventive actions to avoid inconveniences due to voltage dips leading to a process interruption. A cost-benefit analysis can be done for the customer to select the optimum PQ mitigation device at his installation.

6.3.4.1 Description of the case study

The main departments of this industry that suffer significantly because of voltage dips are the metal operation, spray coating and assembly. In the spray coating department, the main devices that are vulnerable to voltage dips are various programmable logic controllers (PLC) and several large fans. The fans can be interrupted for 20 seconds without causing significant problems. However, some voltage dips can cause interruptions for longer periods and lead to financial losses. In the assembly, during a standard production schedule a car leaves this department in every 65 seconds ('typical time'). In case of a production delay of one typical time, the assembly loses €1800. It is estimated that on average one process interruption causes production loss of 20 cars leading to a financial loss of €36,000 in the assembly. Figure 6.11 shows the schematic view of the main process operational chain of the considered ‘automobile’ industry along with its detailed assembly process layout.

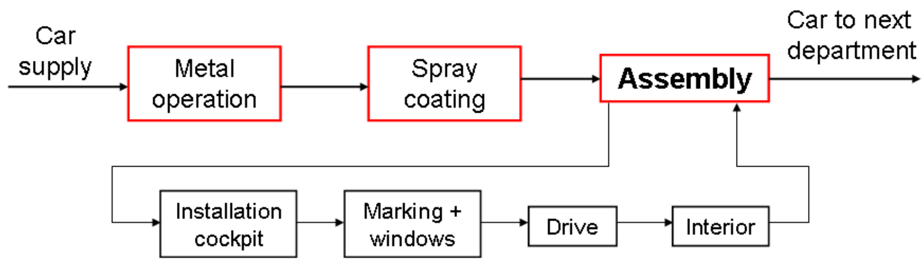


Figure 6.11. Schematic of main departments and the detailed assembly process

Figure 6.12 illustrates the records of the financial losses because of three-phase voltage dips occurred at the automobile customer's POC (see Figure 4.31) during a measurement period of two years (2003-2005) [Lum01].

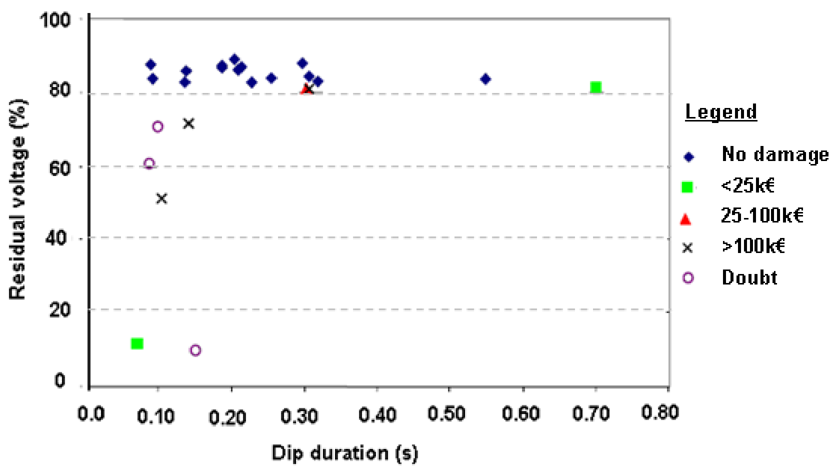


Figure 6.12. Voltage dips and production losses during the period of 2003-2005

The considered customer lost approximately one million euro during the observation period, with an average of €54,000 per interruption. From Figure 6.12, it can be noticed that the customer has suffered financial losses at least for six times during the observation period because of production losses at his installation. To minimise voltage dip related financial losses, various mitigation (immunisation) options can be adopted as shown in Figure 6.13. A modification in the network such as creating a separate high capacity cable for the customer can influence the number and type of voltage dips at the POC. However, such a mitigation measure in the network is a quite expensive investment and the network operator will not be willing to pay for it easily. In most of the cases, the customer needs to implement a mitigation method in his installation at his own expenses. If the network operator provides the customer with the statistics of voltage dips and an approximate number of occurrences of voltage dips at the POC, the customer can accordingly take action to tackle voltage dip problems at the installation.

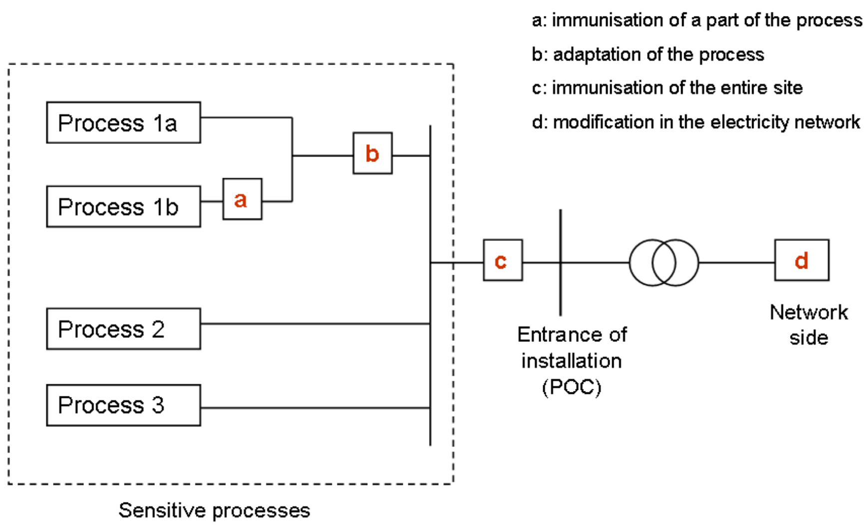


Figure 6.13. Various mitigation measures against voltage dips at a POC

It is also possible to immune the entire site or the whole process chain (at the locations 'c' of Figure 6.13) against various types of voltage dips, but this measure requires significant investments. In contrast, adapting immunisation for a part of process-chain or a sub-process (at the location 'a' or 'b' of Figure 6.13) will be more cost-effective and less time-consuming solution. While analysing this case, it was observed that 'drive' sub-process of the assembly (in Figure 6.11) is the bottleneck for restarting the process after a voltage dip event leading to process interruption. The restarting cost of this process accounts for a significant percentage of the total financial losses related to the voltage dips. Therefore, main attention was paid to this sub-process to immune it against the voltage dips.

A sensitive sub-process can be protected against all voltage dips by using an uninterrupted power supply (UPS) or a flywheel. It was found from the analysis that installing UPS is the most cost-effective option in comparison to flywheel. Another option can be to protect the sensitive process against the most frequently occurring dip events only. Installing a dynamic voltage restorer (DVR) can provide voltage support (typically up to 30% of the nominal voltage, for one second) during a voltage dip event. Thus, almost 2/3 of all interruptions due to voltage dips can be avoided by installing DVR in the 'assembly' process (see Figure 6.14). It was estimated that the investment for a DVR is almost half of the UPS system at the installation. A cost-benefit analysis was done for the customer to select the most cost-effective and optimum solution. It was found that installing DVR for the whole assembly chain is the economically optimum. It gives the lowest pay-back period of 1.4 years and a positive net present value (NPV) when the minimum lifetime of the installation is five years [Lum01]. It can be seen from Figure 6.12 that no financial damage occurs at the installation when the residual voltage is more than 82% of the nominal voltage. Therefore, the installation is immune to voltage dips up to a residual voltage 82% of the nominal value. With the DVR installed, it can provide voltage support of another 30% of the nominal voltage. Thus, the installation will be immune to voltage dip with a residual voltage of 52% of the nominal value or more, as shown in Figure 6.14.

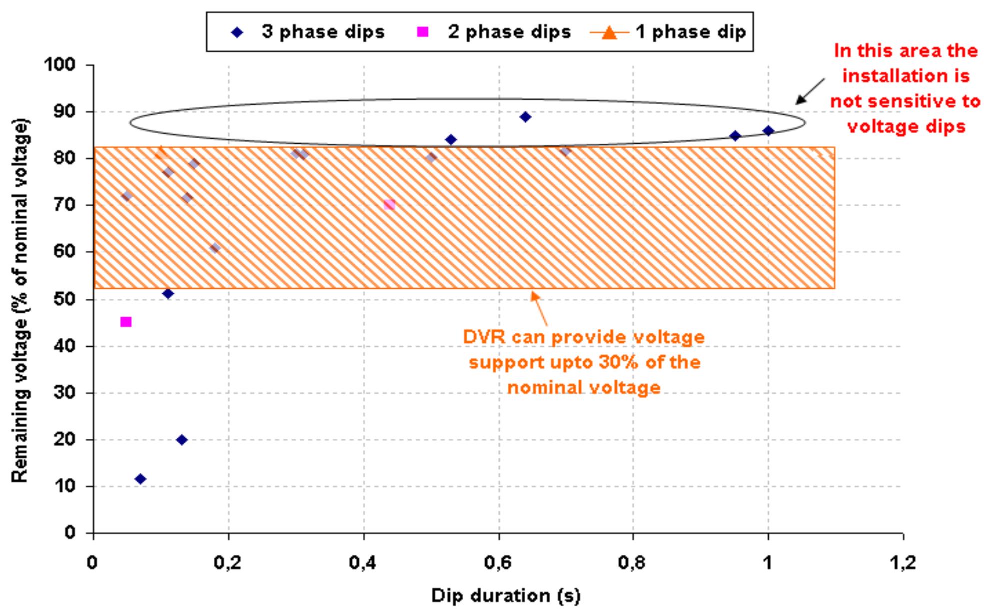


Figure 6.14. Installation protected by a DVR against voltage dips

6.3.4.2 Remark on the voltage dip case study

In the present standards, almost no limit is given regarding the number of voltage dip events at a customer's POC. Therefore, the network operator is not directly responsible to restrict the number of voltage dips in the network. Also, it is often difficult for the network operator to guarantee a minimum number of voltage dips at a POC as they can be caused by natural events too. Presently the customers with sensitive processes take mitigation measures by themselves to minimize voltage dip related inconveniences at their installations. In the majority of the cases, the customers implement a PQ mitigation device or improve immunities of their installation's sensitive devices against voltage dips. The customer of the considered case has adapted an economically optimum mitigation method (DVR) at his installation to minimise the number of voltage dips causing process interruption. Regulation on the maximum number of voltage dips (of various magnitudes and durations) at a POC could be introduced in the future electricity business to minimize the financial losses of the customers. Moreover, the costs of mitigations can also be shared based on the mutual agreements between the customer and the network operator.

6.4 PQ regulation

With the deregulation in the electricity business, the network operators are under pressure to provide a good quality electric supply at a low price. Price and quality are complementary terms but together they define the value of the electricity service that the customers obtain from the network. Power quality regulation is a complex issue because of its multi-dimensional nature and inherent difficulties of its measurements. It can be effectively applied in the electricity business by introducing regular monitoring, defining optimum PQ limits at a POC and implementing incentive schemes for the network operators.

When a customer demands to receive a better power quality than the normal supplied quality, a special agreement called ‘power quality contract’ (PQ contract) can be introduced between the customer and the network operator. Thus, the customer can obtain his desired quality of electric supply by paying an extra tariff for it. In this case, the network operator gets higher revenues for providing a higher quality of supply. On the contrary, if the supplied PQ of the electricity is below than the agreed value, the customer gets compensation from the network operator. Thus, a premium power quality market can be introduced in the present electricity business to provide an electric supply to the customers according to their individual's desire. This also requires regulatory involvement. In France, such type of PQ contract between a network operator and a customer is already in use for restricting the number of voltage dips at a POC.

Reference [Del01] suggests introducing incentives for the network operators to reduce voltage dip numbers in the networks, whenever possible. From the regulatory point of view, the network operator should be given an incentive for providing the customers with an optimal PQ of the supply. If this is the case, the net benefits from a societal point of view will be the maximum [Ajo01]. From 2005, the national regulators in the Netherlands started a scheme for the distribution network operators (DNO) by setting a yearly target for interruption time and frequency of interruptions in the network. If a DNO fails this target, the revenue will be reduced while it will be increased when DNO performs better than the target [Dte01]. This type of incentive scheme can also be introduced for controlling voltage quality targets in the network. However, there are some disadvantages too with an incentive scheme:

- Difficulty to acquire exact data for the customer's cost because of inadequate quality and the method of interpretation.
- Problem to collect sufficient and high quality data of the (field) measurement based on which incentive value is decided.

PQ meters should be installed at every important location in the network. Furthermore, the measurement method and representation of the available data should be made unique globally. In Finland, a quality incentive scheme is introduced. In Norway, the incentive for supply quality improvement is quite high, whereas there is no upper limit of the penalty for failing to achieve the target. The interruption time is used as a target factor in Norway and hence, there is an incentive to reduce it. It is pointed out in the regulation that PQ shall be a part of the network contract between the network operator and the customers. Such a contract is also an important tool to restrict distortions and emissions from the customers so that the PQ requirements at supply terminals can be met [Sel01].

In Great Britain, there is also an upper limit for the continuity of supply. By doing so, the regulator sets a balance between quality improvements and sufficient income for the companies. The quality of service regulation through incentive scheme is applied in Great Britain. It is done through customer surveys. However, the regulators there face some practical problems because of lack of reliable measurement data [Ofg01]. When the PQ is already good enough (fulfils the requirements of the EN50160 standard) the incentive scheme will not be much effective. This control mechanism will be more useful if it is applied locally for important improvements such as:

- Confirming the standard limits for various PQ parameters (e.g. voltage variation) at several locations in the network for 100% of time.
- Restricting the number of voltage dips at a POC.

Therefore, it is difficult to introduce an incentive scheme on a global basis for flicker and harmonics. It is because these disturbances are time-varying and can originate in a certain location but can propagate and cause inconveniences to other parts of the network. If the network operator performs regular (decentralised) monitoring at several locations of a network, then he can identify the problem sources. The PQ regulation needs for the electricity network are still under development. In different countries of the world, some PQ regulation schemes have been introduced in the recent years. Therefore, it is expected that the feedback of those schemes from different countries will help the international regulators to develop a socio-economic optimum PQ regulation in the future.

In this thesis, limits on various PQ aspects are proposed at a POC. Also, the responsibilities (and rights) on various PQ issues are defined for the network operators, the customers and the device manufacturers. The findings of this research will be useful to implement PQ regulation in the present electricity infrastructure in a more efficient way.

6.5 Summary and conclusions

In this chapter, the various responsibilities on power quality issues are defined for a network operator, the customer and a device manufacturer. The network operator should be mainly responsible to provide open and clear information about PQ performance of the supplied electricity to the customers (public). They should also provide a good electric supply that confirms the voltage quality requirements of the standard. With the introduction of power quality monitoring through out the grid, the network operator will be able to locate the source of problem sites more conveniently. Therefore, it will be possible to identify the involved party who is responsible for a specific PQ problem in the network. By introducing appropriate regulations, the regulators encourage the network operators to provide a good quality electric supply to the customers. Also, they provide the network operators with certain amount of authority too. For example, a network operator can oblige a customer to install a mitigation measure at his POC when the PQ problem source is found at the customer's premise. Various practical field studies showed that in most of the cases, a customer invests for a mitigation measure at the installation to avoid/minimize PQ disturbances at the POC.

In this thesis, various emission limits (on flicker and harmonic current) for a customer are proposed. Also, the planning and compatibility limit values for the voltage dips in the Dutch MV network are proposed as 15 and 30 respectively. Those limits can be used by a customer as guidelines for designing his installation. Thus, the customers will be more aware of their rights as well as their obligations. On the other hand, the device manufacturers should provide more information about a device's emission behaviour for different supply voltage conditions (in the device specification when requested by a customer). Additionally, a product's immunity standard (for a voltage dip performance for instance) should be synchronised with the network's standard for their easy interpretation to all the involved parties in the network.

In future, there will be large implementation of sustainable energy sources for the electricity production, while more sophisticated and intelligent supervisory and control techniques will be integrated in the transmission and distribution networks. With many decentralized generations in the network (for example photovoltaic panels, wind turbines), some PQ issues such as over-voltage, unbalance and harmonics can increase significantly. Thus, in the future network, PQ regulation is to be applied more appropriately to minimize the disagreements among network operators, customers and device manufacturers.

Chapter 7

Conclusions, thesis contribution, and future work

7.1 Main conclusions

At present, many standards are in use with respect to Power Quality (PQ), but they are not very well harmonized in terms of definitions about various PQ parameters, measurement methods, limiting values and other related issues. In this research, PQ field measurements and simulations are done with focus on the Dutch MV and LV networks and the results are compared with the available standard limits. This thesis proposed more inclusive requirements for various PQ parameters. Also, the responsibilities of customers, network operators, and device manufacturers at a point of connection (POC) are better defined.

PQ problems such as voltage dips and harmonics can have significant techno-economic impacts to the customers and the network operators, while other PQ aspects like flicker are mainly annoying for the customer. Estimating the financial losses of a customer because of inadequate PQ is quite complex as it includes the estimation of various direct (immediately visible) and indirect (long-term) cost components. The network operators can face additional energy losses, abnormal tripping, overloading and premature failure of the network components because of PQ disturbances in the network. However, at present no appropriate PQ standard is available that defines the responsibility of the involved parties. As a result, various PQ related disagreements are increasing in the electricity business.

In this thesis, flicker, harmonics and voltage dips related PQ issues are investigated. The main conclusions are as follows:

Flicker

- Flicker severity (P_{st} value) at a customer's POC depends on inrush current demands of customer's load, its frequency of starts, the network's short-circuit power, and the background flicker level (P_{st} and P_{lt}). It also depends on the location of the flicker source and the impedance at the observation point.
- The planning and compatibility level values at different voltage levels are examined and appropriate values are proposed. The planning level P_{lt} values at the HV, MV and LV networks are proposed as 0.35, 0.55 and 0.70 respectively. On the other hand, the compatibility level P_{lt} values at the HV, MV and LV networks are proposed as 0.40, 0.60 and 0.80 respectively.
- Introducing 99% and 100% probability limits (in both time and space) for specifying compatibility levels are useful to restrict flicker related complaints in the network.
- The limits on maximum flicker emission at a POC can be utilized in designing future networks especially in relation to the maximum grid impedances in the network.

Harmonics

- The harmonic current in a network highly depends on the emission characteristics of the connected devices, their mutual phase angles and the background distortion level. Information on the harmonic current emission spectrum (harmonic fingerprint) of a device under different supply voltage conditions is very useful for analyzing its impact and can further be extended for evaluating 'time-varying' harmonics behaviour in the network. Maximum values of various harmonic current emissions at LV installations are proposed.
- It was observed in the simulations and field measurements that some specific order harmonic voltages exceeded the EN50160 standard's limit values, while the total harmonic voltage distortion (THD_V) was found mostly within the standard limit of 8%.
- New planning level limits are proposed for the 'triple n' harmonic voltages at the MV and LV networks. The 9^{th}, 15^{th} and 21^{st} order harmonics at the LV network are proposed as 2.0%, 1.0% and 0.8% respectively; whereas these are 1.5%, 0.7% and 0.6% respectively at

the MV network. Also, new global emission limits for harmonic voltages are suggested for the MV and LV networks, based on the proposed planning level values.
- The proposed values of the harmonic voltage and harmonic current limits will be helpful for the network operators to facilitate new connections in the network.

Voltage dip
- The average voltage dip profile of Dutch HV networks is estimated based on the five-year voltage dip measurement records. Those data are combined with the network components' fault statistics to estimate voltage dip profile of a MV network. Also, the appropriate numbers of events in each cell of the voltage dip classification table of the EN50160 standard are estimated.
- The annual number of process failures (at a customer's POC) is calculated based on the process's immunity graph and the network's annual voltage dip profiles. In a typical MV network in the Netherlands, a customer can expect approximately 11 voltage dips in a year at his POC. However, he will suffer around 3 process interruptions in a year when the installation is protected with the immunity 'class 3' requirements.
- From the analysis, the average and maximum values of voltage dip events in a year are estimated as 11 and 22 respectively at a customer's POC in the MV network. The planning and compatibility level values for voltage dips in MV networks (of the Netherlands) are proposed as 15 and 30 in a year respectively. These values will give the network operators an insight to the quality of the existing network.
- Assigning a unique compatibility value for voltage dips is complex as it is largely dependent on voltage level, network type and its topology.

From the practical case studies, it was noticed that the customer is commonly responsible for the originated PQ disturbance at his installation and should invest for a suitable mitigation measure. Sometimes, there exists a specific contractual agreement regarding PQ issues between a customer and a network operator. The decision on responsibility sharing of various PQ issues is very complex and is mostly case specific. Based on the limits proposed in this thesis for different PQ parameters, the decision making procedures are proposed for defining PQ related responsibilities among the involved parties at a POC.

7.2 Thesis contributions

In this thesis, first an overview is made on various PQ aspects and their technical and financial impacts to various involved parties in different countries of the world. It was decided to focus in this thesis on flicker, harmonics and voltage dips which were found to be the most important PQ issues in the present electricity environment. It was also observed that the existing standards on PQ (in use in different countries) are not harmonized. Moreover, the customers are not sufficiently aware of their rights and responsibilities regarding various PQ issues at the point of connection. The main contributions of this thesis are described below.

7.2.1 Guidelines for optimal PQ requirements at a POC

Emission limits are set for flicker severity and harmonic currents at a customer's POC. Also, the average, maximum numbers of voltage dips in a year at a MV customer's POC are estimated. All this information is helpful for a customer to understand his rights and responsibilities at the connection point.

A flicker emission share for different LV installations is proposed. Further, the planning level and compatibility level values for flicker at different voltage levels are proposed. Also, some additional indicators are proposed such as 95% and 100% limits both in time and space for specifying various P_{st} and P_{lt} values at a point of observation in the network.

New planning level values for 'triple n' harmonic voltages are suggested for MV and LV networks. A higher value is proposed for the harmonic summation coefficient 'α' for the 3rd order harmonic as sufficient diversity in phase angles are observed among various harmonic loads at the POC. Moreover, the harmonic current emission limits at different LV installations are proposed.

The average numbers of voltage dip events in the HV and MV networks of the Netherlands are estimated. Furthermore, planning and compatibility level values for voltage dips in a MV network are proposed.

7.2.2 Defining PQ responsibilities at a POC

A decision making procedure is proposed to define PQ responsibilities of the network operator, the customer and the device manufacturer. PQ regulation can be applied more intensively when responsibilities are defined clearly in the standards.

The network impedance at a POC is found a very important parameter in deciding the responsibility of the involved parties. Therefore, limit values for the network impedance should be introduced in the regulation. It is the responsibility of the network operator to follow those impedance values while providing connections to the customers. Furthermore, voltage dip related responsibility sharing at a POC is introduced. A network operator should provide information about the expected number and the characteristics (such as depth and duration) of voltage dips in a year at the POC, when asked by the customer. Alternatively, a PQ contract can be introduced between a customer and a network operator based on their mutual agreements.

Various emission limits for flicker and harmonics are proposed in this thesis. The customer should follow those limits while purchasing devices from the market and designing his installation. Also, based on the voltage dip data provided by the network operator, the customer should take preventive actions and design his installation according to the immunity requirements. Hence, the customer needs to be aware of his rights and responsibilities and should have full understanding about the emission and immunity requirements at the POC.

While manufacturing a device, a device manufacturer should test it for various voltage conditions (including distorted supply voltage conditions). He should specify the emission behaviour (such as for harmonics) and the maximum emission limits of the device in the specification (or when asked by a customer). For voltage dip immunity, the device manufacturer should follow the applicable standard requirements (for balanced and/or unbalanced dips) and should mention the various voltage and time duration for which the device was tested in the device's specification. He should also provide a 'voltage-time' tolerance graph for the manufactured device. Introducing such type of extra tests/requirements may increase the cost of the device, but this can help the customer to understand the device's characteristic more clearly.

7.3 Future work

In this thesis, guidelines are proposed for flicker, harmonics and voltage dips at a POC. The IEC standardization committee can use the findings of this thesis that give analysis results of typical networks in the Netherlands. Further, a generic standard on PQ can be developed after comparing other measurements and analysis of different networks in the world. Also, the proposals done in this thesis can be used by the regulators for performing further work in the direction of the development of PQ regulation schemes. The research is also needed to identify various PQ related problems that might arise because of the large implementation of various decentralized generations using renewable energy sources.

More research is needed for the new lighting technologies (such as CFL or LED lamp) and their impacts to flicker. These new lamp types are generally less sensitive to voltage variations (and flicker) than the incandescent lamps. However, it is suspected that such new types of lamps when improved to produce similar visual sensation as of normal day-light can also have some sensitivities to voltage variations. Also, there is a doubt among the users (as well as the researchers) about the illumination quality of new lamp types.

Further research is needed to identify the harmonic characteristics of different devices. Harmonic current spectrums of different devices/typical installations can be extended to analyse the time varying harmonic behaviour of the network. With the implementation of smart meters and decentralized power quality monitoring in the network, the (large) harmonics producing installations can be identified efficiently. If they violate their assigned emission limits, the harmonic producing customers can be penalised. Furthermore, research is needed about the viability of harmonics related penalty schemes in the electricity business.

Research is necessary to justify if the PQ measurement interval is required to change from 10 minutes to a shorter interval (such as 1 minute). This will increase the volume and complexity of measured data and their handling procedures. Also, investigation is necessary to check the effectiveness of introducing additional indices to specify a PQ parameter (for example, planning and compatibility level limits for 99%/100% time and 99%/100% sites).

More research should be done to distinguish the impacts of different types of dips to the various parties in the network (such as impacts on process devices for industrial customers). The network operator should specify the number for each type of dips at different voltage levels separately. Therefore, an intensive research is needed to assign an appropriate number to each cell of the dip-duration table. This will give a clear understanding of the voltage dip profiles in the network.

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APPENDICES A-C

Appendix A-1

Harmonic related power consumption in the network

There are two terms describing harmonic power: a) harmonic distortion power (D_H expressed in 'VAr') and b) harmonic apparent power (S_H expressed in 'VA'). These are calculated from the network's fundamental apparent power (S_1) and non-fundamental apparent power (S_N). There are two non-active components of power produced by the harmonics in the network:

- Voltage distortion power (D_V in 'VAr')
- Current distortion power (D_I in 'VAr')

Table 1. Various fundamental and non-fundamental power terms as defined in the IEEE 1459 standard

Quantity or indicator	Combined	Fundamental power	Non-fundamental power
Apparent	S (VA)	S_1 (VA)	S_N, S_H (VA)
Active	P (W)	P_1 (W)	P_H (W)
Non-active	N (VAr)	Q_1 (VAr)	D_I D_V D_H (VAr)
Line utilization	PF = P/S	$PF_1 = P_1/S_1$	-
Harmonic pollution	-	-	S_N/S_1

The total apparent power (S in 'VA') in the network is the combination of fundamental (S_1) and non-fundamental (S_N) power components, as shown in equation (1). In equation (2), the voltage and current components are given. Equations (3), (4) and (5) give expressions for various terms related to harmonic power in the network.

$$S^2 = S_1^2 + S_N^2 = (U \cdot I)^2 = (U_1 \cdot I_1)^2 + (U_H \cdot I_1)^2 + (U_1 \cdot I_H)^2 + (U_H \cdot I_H)^2 \quad (1)$$

$$U^2 = U_1^2 + U_H^2 = U_1^2 + U_0^2 + \sum_{n \neq 1} U_n^2 \; ; \quad I^2 = I_1^2 + I_H^2 = I_1^2 + I_0^2 + \sum_{n \neq 1} I_n^2 \quad (2)$$

$$S_N^2 = D_I^2 + D_V^2 + S_H^2 \; ; \qquad S_N \cong S_1 \cdot \sqrt{(THD_I)^2 + (THD_V)^2} \quad (3)$$

$$S_H = U_H \cdot I_H \; ; \qquad S_H = S_1 \cdot THD_I \cdot THD_V \quad (4)$$

$$D_I = U_1 \cdot I_H = S_1 \cdot THD_I; \qquad D_V = U_H \cdot I_1 = S_1 \cdot THD_V \tag{5}$$

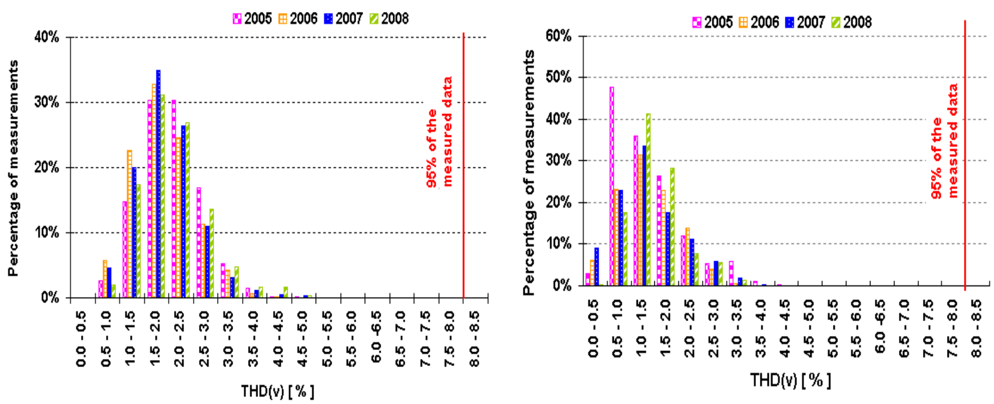
where,

- U: Rms value of the voltage
- U_1: Voltage component at fundamental frequency
- U_0: Direct voltage component
- U_H: Summation of all harmonic voltage components
- U_n: Harmonic voltage component at harmonic number ‘n’
- I : Rms value of the current
- I_1: Current component at fundamental frequency
- I_0: Direct current component
- I_H: Summation of all harmonic current components
- I_n: Harmonic current component at harmonic number ‘n’
- THD_I : Total harmonic current distortion
- THD_V : Total harmonic voltage distortion

Appendix A-2

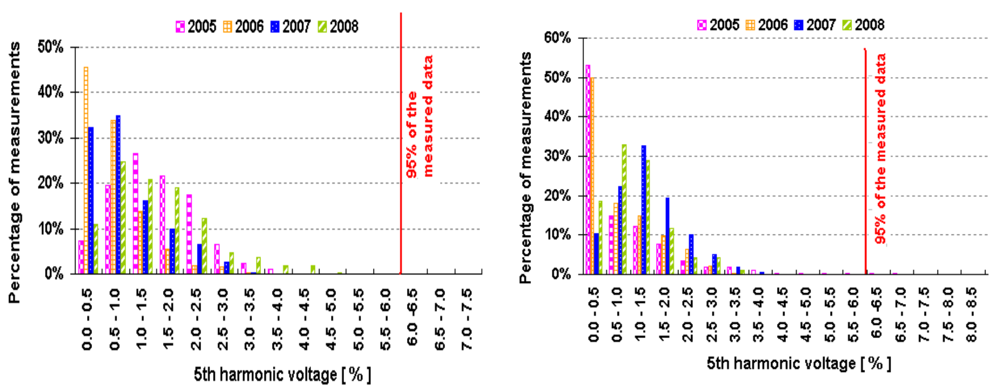
Summary of national PQM results

Various PQ measurement results (during the years 2005-2008) of the Dutch LV and MV networks are shown in Figures 1 to Figure 3.



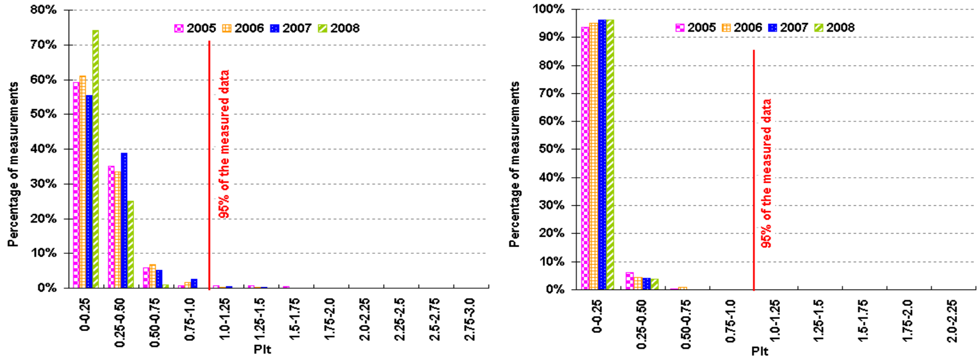
(a) LV network (b) MV network

Figure 1. THD_V trends (2005-2008) in the LV and MV networks in the Netherlands



(a) LV network (b) MV network

Figure 2. 5th harmonic voltage trend (2005-2008) in the LV and MV networks in the Netherlands



(a) LV network (b) MV network

Figure 3. P_{lt} trend (2005-2008) in the LV and MV networks in the Netherlands

Voltage dips are recorded at 20 locations in the HV networks in the Netherlands on a yearly basis. From year to year statistics can slightly change. The explanation of various values of Table 2 is as follows: dips with duration of 0.02s to 0.1s and depth of 10% - 30% are occurring 82 times in a year at 20 locations. Therefore, an average number of 4.1 dips are occurring at each location. Moreover, the highest number of dips recorded at a site is 11.

Table 2. Number of voltage dip events in the Dutch HV networks in 2008 [Hes01]

Voltage dip depth (%)	Duration (seconds)										Voltage dip depth (%)
	0,01 tot 0,02		0,02 tot 0,1		0,10 tot 0,5		0,5 tot 2,5		2,5 tot 5,0		
10%	**0.1**	1	**4.1**	11	**1.9**	12	**0.1**	1	**0.1**	1	10%
	1	1	82	20	38	11	1	1	1	1	20%
30%	0.0	0	**0.5**	3	**0.2**	2	0.0	0	0.0	0	
	0	0	10	5	4	2	0	0	0	0	50%
60%	0.0	0	**0.5**	7	**0.3**	1	0.0	0	0.0	0	
	0	0	9	3	5	5	0	0	0	0	
99%											99%

Appendix A-3

Description of a typical MV feeding structure in the Netherlands

In the Netherlands, two types of networks are found. The old networks are in operation for more than 40 years and the modern networks of 5-10 years old. The modern network is designed with higher cross-section cables with better specification and has relatively lower grid impedances compared to the old networks. A typical modern MV substation in the Netherlands has the following features:

- Average short-circuit power at the MV substation is 300 MVA.
- 15 outgoing MV feeders in average; and a MV feeder can have 15-25 transforming substations (of 10/0.4 kV type) to feed different customers.
- From the analysis of various networks, it is found that around 75% of the total MV/LV transforming substations feed to the household and small commercial customers and other 25% of them feed to large commercial and industrial customers.
- Most of the distribution transformers have a typical rating of 400kVA that supply to the household customers; small commercial customers (maximum demand of 50kVA) or the combination of both.
- When the LV supply is fed to multiple large commercial or small industrial customers of load demand 160kVA or more, a transformer of 630kVA rating is used. If a customer's load demand is 200kVA or more, then the customer should have his own cables and transformers.
- The average length of a MV feeder is 12km, and the average distance between two consecutive MV nodes is taken as 1.2km.
- Transformers (400kVA) that feed to household / small commercial customers are loaded by 40-50% of their nameplate rating (typical Dutch scenario found from the statistics of the network operators).
- Transformers (630kVA) that feed to large commercial or industries are loaded by 65-70% of their capacity.

The MV feeder configuration and its various load points are shown in Figure 4.

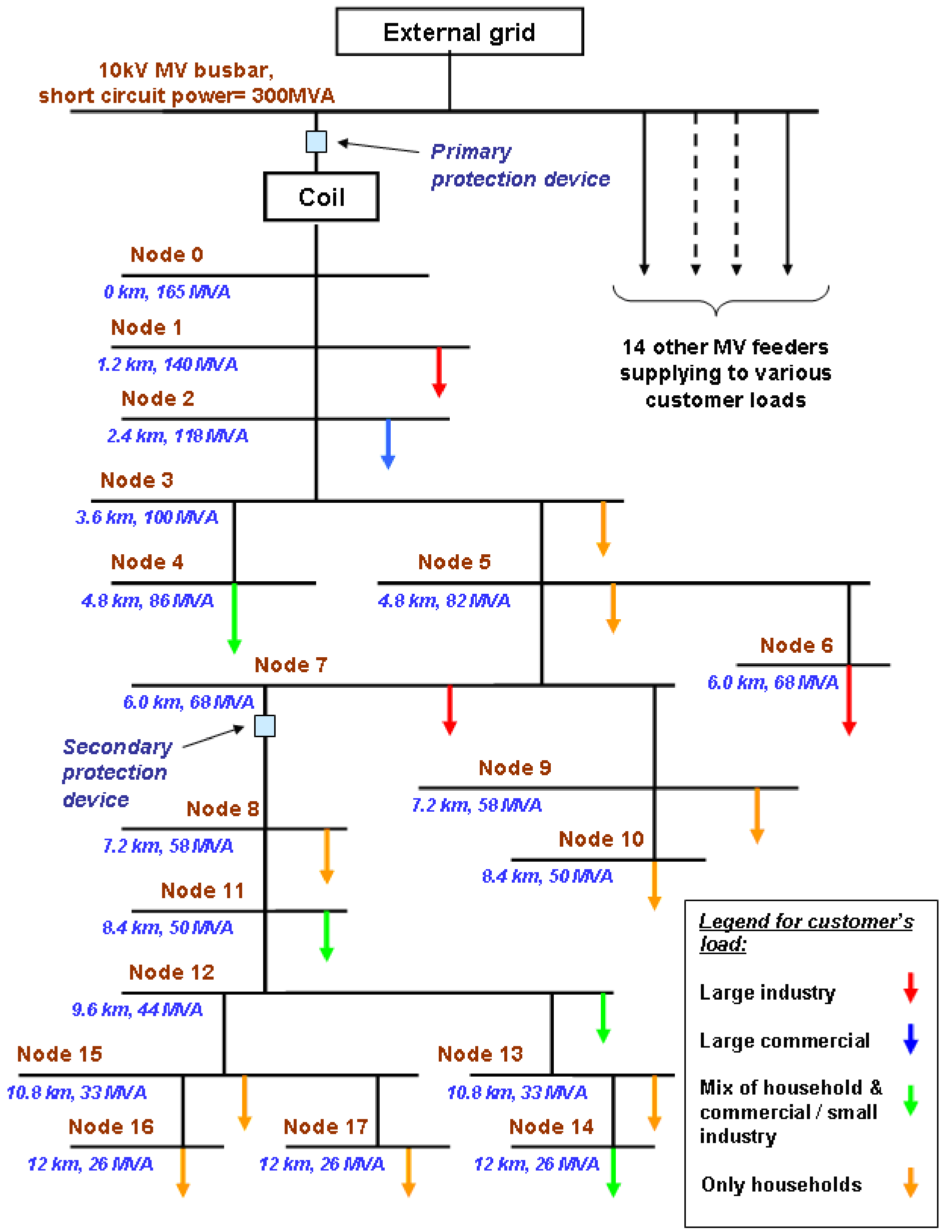


Figure 4. Typical configuration of a MV network in the Netherlands

Appendix A-4

Devices used for harmonic fingerprint measurements

In the PQ lab of TU/Eindhoven, some household devices (listed in Table 3) are measured to find out their harmonic fingerprints. From those measurements, the characteristics of the devices and also their harmonic current behaviours can be found out for different supply voltage conditions.

Table 3. Technical details of devices (measured by PQ meter in the laboratory)

Device in operation	Made of	Cosφ	DPF	I_{rms} (A)	I_1 (A)	THD I (%) w.r.t I_{rms}	Remarks
Compact fluorescent lamp (CFL)	Philips	0.555	0.903	0.092	0.058	67.4	All are of 11W lamps. 6 nos. of Philips lamps and 4 nos. Osram lamps were used in measurement.
	Osram	0.633	0.897	0.087	0.062	71.7	
Refrigerator	Whirlpool	0.596	0.593	0.751	0.727	9.9	Type: ARC 5754/2, Energy consumption 2700kWh/year
LCD TV	Philips	0.758	0.994	0.775	0.599	64.4	81cm LCD TV, Power consumption 130W
PC + Monitor (PC-1)	Retailer (Aragorn)+Dell	0.486	0.975	0.881	0.427	82.4	Laboratory measurement shows that it has large harmonic currents of all orders. As it is an assembled one, it is difficult to say which one is causing this problem.
PC + Monitor (PC-2)	Aragorn (Assembled)	0.755	0.998	0.641	0.486	61.9	It gives reasonable amount of harmonic currents as a standard PC assembly.
Inverter	SMA, America	0.998	0.999	3.678	3.676	2.98	Model: Sunny Boy
Vacuum cleaner (VC) (Low & high power stand respectively)	Princess	0.558	0.695	3.375	2.771	59.9	Low power stand (half of maximum power) produces high harmonic currents
		0.975	0.990	4.540	4.477	17.4	High power stand (at maximum power condition) produces lesser harmonic currents than at low power stand

Appendix B-1

Voltage drop estimation method

For calculation of the relative voltage change (d), an approximate equation can be used. It takes into account the longitudinal component (ΔU_{Long}) of the complex voltage drop and ignores the perpendicular voltage drop (ΔU_{Perp}). The error that occurs due to this approximation is shown in Figure 5, which can be disregarded in general [Bar01].

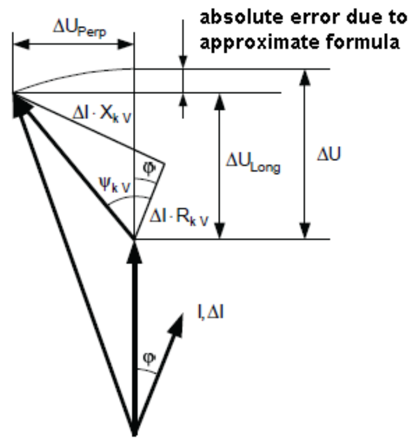


Figure 5. Vectorical representation to calculate voltage drops

The absolute voltage change (ΔU) at a POC (named 'V') can be calculated as shown in equation (6) for symmetrical load change:

$$\begin{aligned}\Delta U &\approx \Delta U_{Long} = \Delta I \cdot (R_{kV} \cdot \cos\Phi + X_{kV} \cdot \sin\Phi) \\ &= \Delta I_{Active} \cdot R_{kV} + \Delta I_{Reactive} \cdot X_{kV} = \frac{\Delta P_A}{U_V} \cdot R_{kV} + \frac{\Delta Q_A}{U_V} \cdot X_{kV}\end{aligned} \quad (6)$$

The relative voltage change (d) can be calculated by equation (7) as follows:

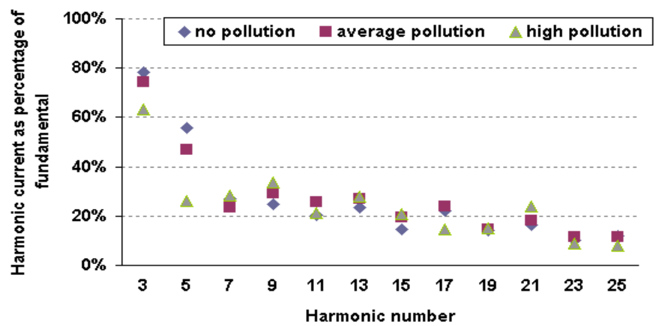
$$\begin{aligned}d &= \frac{\Delta U}{U_V} = \frac{\Delta P_A}{S_{kV}} \cdot \cos\Psi_{kV} + \frac{\Delta Q_A}{S_{kV}} \cdot \sin\Psi_{kV} \\ &= \frac{\Delta S_A}{S_{kV}} \cdot (\cos\Psi_{kV} \cdot \cos\Phi + \sin\Psi_{kV} \cdot \sin\Phi) = \frac{\Delta S_A}{S_{kV}} \cdot \cos(\Psi_{kV} - \Phi)\end{aligned} \quad (7)$$

where, U_V= phase to phase voltage at the considered POC, ΔS_A= load change (apparent power change) in kVA, S_{kV}= short-circuit power at the POC in kVA, Ψ_{kV} = network's impedance angle (in º), φ = the angle of load change (in º), ΔP_A= active power change in kW, ΔQ_A= reactive power change in kVAr, X_{kV}= network reactance at the POC in Ω, R_{kV}= network resistance at the POC in Ω.

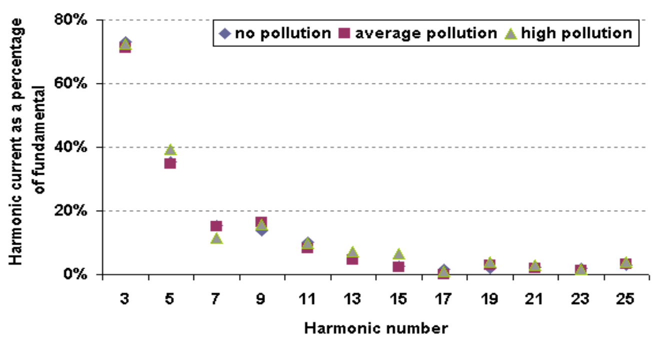
Appendix B-2

Harmonic current emission of devices found in laboratory measurements under different supply voltage conditions

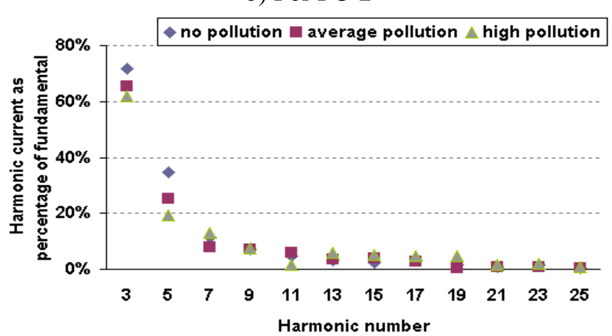
Some household devices are tested in the laboratory for two typical distorted supply voltage conditions: a) average distortion with THD_V of 3.2% and b) high distortion with THD_V of 6%. A detailed description of background distortion conditions is given in chapter 4. Figure 6 shows that with a distorted supply, devices emit different harmonic currents than at a sinusoidal voltage condition.



a) For CFL



b) For PC-2



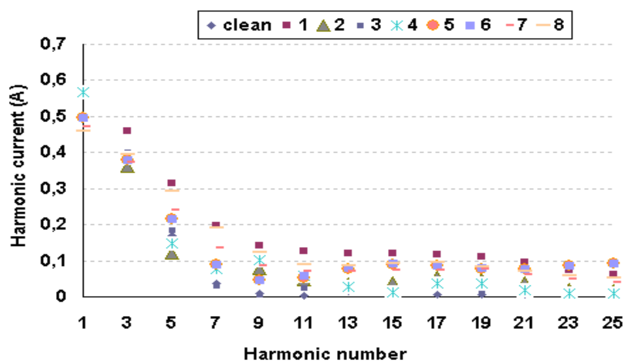
c) For TV

Figure 6. Harmonic current emissions for different devices under distorted supply voltages

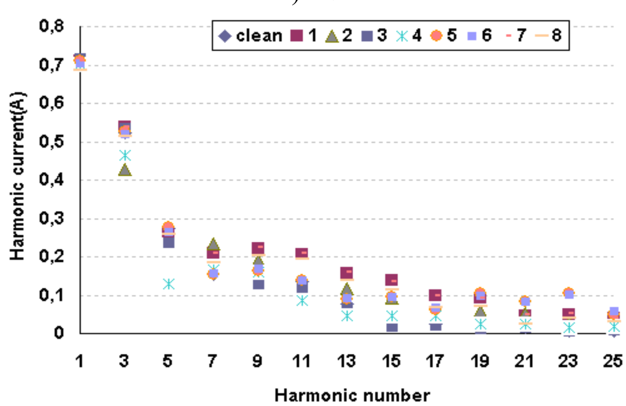
Another test was done with eight different supply voltage conditions that are applied at the device's terminal. Harmonic current emissions are noted for each condition and are shown in Figure 7.

Table 4. Supply voltage conditions for testing of device's harmonics spectrum

Distortion	Supply voltage condition							
(magnitude/ phase angle)	1	2	3	4	5	6	7	8
3rd	4 / 0°	4 / 90°	5 / 0°	5/ 120°	-	-	3 / 0°	3/ 150°
5th	5 / 0°	5/ 120°	6/ 0°	6/ 90°	-	-	3 / 0°	3/ 30°
7th	1 / 0°	1/ 30°	5/ 0°	5/ 30°	-	-	-	-
9th	1 / 0°	1/ 90°	1.5/ 0°	1.5/ 60°	-	-	1 / 0°	1/ 60°
17th	1 / 0°	1 / 120°	-	-	2 / 0°	2 / 60°	1 / 0°	1/ 90°
21st	0.5/0°	0.5/60°	-	-	0.5/0°	0.5/90°	0.5/0°	0.5/120°
25th	-	-	-	-	1.5/0°	1.5/30°	-	-
THD (%)	6.6	6.6	9.4	9.4	2.5	2.5	4.5	4.5



a) TV



b) PC

Figure 7. Harmonic current emissions for devices under distorted supply voltages

Appendix C-1

Comparison of the new and old versions of EN50160 standard

Table 5. Comparison of the last two versions of EN50160 standard

Parameters applicable for LV, MV supply	EN 50160:2007	EN50160:2010
PQ measurement method	Not mentioned	As per standard EN 61000-4-30
Sharing of complaint management and PQ mitigation cost	Not mentioned	Outside scope of EN50160
PQ parameter definitions	Some were ambiguous	Made clearer than previous definitions
Rapid voltage change definitions for LV network	For normal operating condition, it should not exceed 5% of U_{nom}, but a change up to 10% of U_{nom} with a short duration can occur	Follow the standard IEC 61000-3-3
Rapid voltage change definition for MV network	For normal operating condition, it should not exceed 4% of U_c, but a change up to 6% of U_c with a short duration can occur	Refer standard EN 61000-2-2 for single rapid voltage change and IEC 61000-3-7 for flicker
Supply voltage variations - requirements	For special customers, the voltage was allowed to be outside the range of U_{nom}+10% / -15%.	Should not exceed ±10% of U_{nom} under normal operating conditions (excluding interruption periods). For special customers, voltage variation should not exceed +10% / -15% of U_{nom}.
Supply voltage variations – test method	Under normal operating conditions, during each period of one week 95% of the 10 min mean rms values of supply voltage shall be within the range of U_{nom} + 10%	Under normal operating conditions, during each period of one week 99% of the 10 min mean rms values of supply voltage shall be within the range of U_{nom} ± 10%
Voltage dip / swell measurement and detection	Not included	Added (EN 61000-4-30 standard for measurement method is applicable)
Voltage dip and swell evaluations and classifications	Not included	Added
Short and long interruptions of the supply voltage	-	Partly modified
Temporary power frequency over-voltages	-	Some indicative values are included
Transient over-voltages between live conductors and earth	-	Some indicative values are included

Note: The new version of EN50160 standard is extended for the HV networks too. 'U_{nom}' should be read as 'U_c ' for the MV networks.

Appendix C-2

Harmonic voltage limits as per EN50160 standard

The European Standard EN50160 gives restriction on harmonic voltage values in the network. Under normal operating conditions, during each period of one week 95% of the 10 minutes mean rms values of each individual harmonic voltage shall be less than or equal to the values mentioned in Table 6. They are calculated with respect to the fundamental voltage component. The values mentioned within brackets of Table 6 are applicable for HV networks, whereas the other values are for MV and LV networks. In a HV network, no limit is yet mentioned for the 17^{th}, 19^{th}, 23^{rd} and 25^{th} order harmonics in the EN50160 standard. It was found that generally none of the networks in Europe largely exceeds those harmonic voltage limiting values [Bol01].

Table 6. Harmonic voltage limits in the EN50160 standard for LV, MV, and (HV) networks

Odd harmonics				Even harmonics	
Not multiples of 3		Multiples of 3			
Harmonic order (n)	Relative voltage U_n %	Harmonic order (n)	Relative voltage U_n %	Harmonic order (n)	Relative voltage U_n %
5	6 (5)	3	5 (3)	2	2 (1.9)
7	5 (4)	9	1.5 (1.3)	4	1 (1)
11	3.5 (3)	15	0.5 (0.5)	6…24	0.5 (0.5)
13	3 (2.5)	21	0.5 (0.5)		
17	2 (-)				
19, 23, 25	1.5 (-)				

The EN50160 standard also gives restriction on the total harmonic voltage distortion (THD_V) of the supply voltage (including all harmonics up to order 40) that should be less than or equal to 8% for 95% of the measurement time. The Dutch Grid Code gives an additional requirement as $THD_V \leq 12\%$ for 99.9% of the measurement time. It also specifies additional limits for individual harmonic voltages as indicated in Table 5.1 of chapter 5.

Table 6 shows that the limits for triple ‘n’ harmonic voltages are quite low as compared to non-triple ‘n’ harmonic voltages (except for 3^{rd} harmonic component).

Appendix C-3

Harmonic current limits of devices and installations

Device standards

For an individual device, it has to meet harmonic current requirements of the IEC 61000-3-2 standard as shown in Table 7 when the device's current rating is less than 16A.

Table7: Harmonic current limits on 'class A' devices as per IEC 61000-3-2

Harmonic order (n)	Maximum permissible harmonic current (A)
Odd harmonics	
3	2.30
5	1.14
7	0.77
9	0.40
11	0.33
13	0.21
$15 \leq n \leq 39$	0.15*(15/n)
Even harmonics	
2	1.08
4	0.43
6	0.30
$8 \leq n \leq 40$	0.23*(8/n)

If a device has current rating more than 16A but less than 75A, the standard IEC 61000-3-12 is applicable. According to this standard, a device is characterized by its short-circuit ratio (R_{sce}). For a single-phase device, R_{sce} is defined as the ratio of the short-circuit power (S_{sc}) of the network where the device is connected to the three times the rated apparent power (S_{equ}) of the device as shown in equation (8).

$$R_{sce} = \frac{S_{sc}}{(3 \cdot S_{equ})} \tag{8}$$

Similarly, for a balanced three-phase device R_{sce} is defined as a ratio of the S_{sc} of the network and the rated S_{equ} of the device. A device manufacturer has to specify the required minimum short-circuit ratio (at a POC) for connecting a device into the installation. The IEC 61000-3-12 standard also gives the evaluation method to assess the global impact of harmonic voltages to the connected device in the network.

Harmonic currents assessment procedure at a MV installation

The standard IEC 61000-3-6 is applicable for a MV installation and is based on the method of allocation of harmonic voltages. This standard recommends a two-stage assessment procedure for connecting an installation in the network. According to this standard, when the installation's capacity is small, the conditions of (9) are applicable (as per 'stage 1' evaluation).

$$\frac{S_i}{S_{sc}} \leq 0.2\%; \qquad \frac{S_{Dwi}}{S_{sc}} \leq 0.2\% \tag{9}$$

where,

- S_i: agreed power (in MVA) of the i^{th} customer
- S_{sc}: short-circuit power at the POC
- S_{Dwi}: weighted distorting power of the installation

S_{Dwi} is calculated by using a weighting factor (refer Table 4 of the IEC 61000-3-6 standard) for each type of disturbing load in an installation. For example, a single-phase power supply with a THD_I of 80% can have a weighting factor of 2.5, whereas a 12-pulse converter with a THD_I 15% will have a weighting factor of 0.5, etc. If the conditions of equation (9) are satisfied, the connection of the specified installation should not cause much nuisance to other customers. It is also assumed that the existing harmonic distortion level is sufficiently lower than the planning level values. If the 'stage 1' condition is fulfilled, the installation can be connected without any extra measure. If the actual system characteristics are considered, higher emission limits can also be allocated to a MV installation as per 'stage 2' evaluation rules of the IEC 61000-3-6 standard. The harmonic current emission limits for a MV installation are shown in Table 8 for the condition that the customer's agreed power (S_i) is less than 1MVA and the ratio of $S_i/S_{sc} < 1\%$.

Table 8. Harmonic current distortion limits at a MV installation

Applicable standard/report	Harmonic current emission limit (%) relative to the size of customer's installation for different harmonic order (n)						
	3	5	7	9	11	13	>13
IEC 61000-3-6	-	5	5	-	3	3	$(500/n^2)$

According to the 'stage 2' evaluation rules of IEC 61000-3-6 standard, another general approach is possible which is based on summation law concept. In this approach, the global harmonic voltage contribution is to be calculated first. Each customer is allocated only a fraction of the global emission limit for each order harmonic voltage. The maximum global emission limit for the harmonic voltage in the MV network can be calculated by (10). Further, the emission limits for each order harmonic voltage and current are to be estimated by (11). The harmonic voltage contribution of the LV installations in to the MV network is generally quite low and is neglected in the calculation.

$$G_{n,MV} = \sqrt[\alpha]{L_{n,MV}^{\alpha} - (T_{n,HM} \cdot L_{n,HV})^{\alpha}} \tag{10}$$

$$E_{Uni} = G_{n,MV} \cdot \sqrt[\alpha]{\frac{S_i}{S_t}}; \qquad E_{Ini} = \frac{E_{Uni}}{Z_{ni}} \tag{11}$$

where,

- E_{Uni}: harmonic voltage emission limit of harmonic order ‘n’ at installation 'i' connected to the MV network (in ‘%’ of installation's capacity current)
- S_t: total supply capacity of the MV network, including future growth
- E_{Ini}: harmonic current emission of harmonic order ‘n’ at installation ‘i’
- Z_{ni}: harmonic impedance at the i^{th} customer's POC for n^{th} order harmonic
- $G_{n,MV}$: maximum harmonic voltage allowance to all MV installations in the network, which is determined by subtracting contributions of all LV installations
- $L_{n,HV}$, $L_{n,MV}$: planning level values for HV and MV networks respectively
- $T_{n,HM}$: transfer coefficient from the HV to MV networks

If the ‘stage 2’ approach of summation law is fulfilled, the installation can be connected to the MV network without other special agreement with the network operator. In contrast, a different approach is needed for a long MV feeder in which the short-circuit power levels can vary significantly between the nodes located close to the MV substation and the nodes at the far end of the feeder (assuming no power generation source is connected on the feeder).Detailed description of harmonic current emission estimation in a long MV feeder can be found in [Iec11].

Harmonic current emission limits and total demand distortion (TDD) at a MV customer's POC are also given in the IEEE 519 standard. This standard gives limits based on the short-circuit ratio (SCR) of the installation that depends on the short-circuit capacity of the supply and the load current at a POC. Various limits are shown in Table 9. TDD is the ratio of total harmonic current and the maximum value of load current at a POC. For an approximate estimation, the maximum value of load current can be taken the same as an installation's current carrying capacity.

Table 9. Current distortion limits according to IEEE 519

Short-circuit ratio (SCR)	Harmonic current limits (%) for various harmonic orders					
	<11	11-16	17-22	23-34	>34	TDD
<20	4.0	2.0	1.5	0.6	0.3	5.0
20-49.9	7.0	3.5	2.5	1.0	0.5	8.0
50-99.9	10.0	4.5	4.0	1.5	0.7	12.0
100-999	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0

The standard IEEE 519 gives harmonic current emission limit at an installation in percent of the maximum load current demand (I_L). The limits for various harmonic orders depend on the ratio of the short-circuit current (I_{sc}) of the supply source and the load current (I_L) demand at an installation. This ratio is called short-circuit ratio (SCR). The standard also gives individual and total harmonic voltage distortion limits for different voltage levels. When the network voltage is 69kV or below, the individual harmonic voltage distortion limit (as a percentage of the fundamental voltage) is 3% and the THD_V limit as 5%. However, any proper technical reasoning or evidence is not mentioned in the standard about the selection of such limits [Oli01]. Moreover, many cases were recorded in the LV networks where the above recommended limits were violated because of the increase of harmonic sources in the network [Mcg02]. Presently, the IEEE standardization committee considers changing the THD_V limit from 5% to 8% [Fuc02] in line with the EN50160 standard limit.

Harmonic currents assessment procedure at a LV installation

In a LV network, different types of customers (such as household, commercial, and industrial) are found. For large LV customers, the IEC/TR 61000-3-14 suggests a detailed estimation procedure that is based on global contribution of harmonic voltage at a LV busbar. This document suggests a two-stage assessment procedure. As per 'stage 1' assessment, three conditions are given as follows:

- The customer does not use power factor capacitor and/or harmonic filter at his installation.
- The ratio of installation's agreed capacity (S_i) and short-circuit power (S_{sc}) at the POC should be small (S_i/S_{sc}<1%).

If the above conditions are not fulfilled, a detailed assessment procedure has to be followed as per 'stage 2' of the IEC/TR 61000-3-14. The estimation procedure of maximum global contributions at a point in the LV network and the harmonic current emission limit at a POC are discussed in section 5.3.2 of chapter 5.

As per IEEE 519 method, the SCR for the installation is 330 (because the supply source's short-circuit current is 8.3kA and the installation's current carrying capacity is 25A). Therefore, harmonic current emission limits for 999>SCR>100 (of Table 9) will be applicable for the considered installation.

In addition to the above standards, the technical report TR/DNO [Bar01] also describes an assessment procedure of the harmonic current emissions at a LV customer's installation. Equation (12) shows the estimation procedure of the harmonic current emission (I_n for n^{th} harmonic order) at a POC. The proportionality factor (p_n) can be taken from Table 10.

$$\frac{I_n}{I_i} \leq \frac{p_n}{1000} \cdot \sqrt{\frac{S_{sc}}{S_i}} \tag{12}$$

where,

- p_n: proportionality factor
- I_i: installation's rms current (A)
- S_{sc}: short-circuit power at the POC (kVA)
- S_i: connected loads of the customer (in kVA)

Table 10. Proportionality factor for various harmonic orders

N	3	5	7	11	13	17	19	>19
p_n	6	15	10	5	4	2	1.5	1

The report TR/DNO states the following conditions for connecting a MV and a LV installation to the network:

- Determine the ratio of short-circuit power at a POC (S_{sc}) and the installation's rated power (S_i). This ratio is to be higher than 150 for the LV network, and 300 for the MV network.
- If the first condition is not satisfied, a detailed assessment is needed. First, all loads are categorized in two groups: loads with 10%≤THD_I≤25%, will be named as 'group 1' and THD_I>25% as 'group 2'. Next, the total harmonic load (S_H) of the installation is calculated using equation (13).

$$S_H = 0.5 \cdot S_{H,Gr1} + S_{H,Gr2} \tag{13}$$

where,

- $S_{H,Gr1}$, $S_{H,Gr2}$: harmonic loads of group 1 and group 2 respectively

Further, the ratio of S_H/S_i is to be compared with the limits shown in Figure 8 [Bar01]. When S_H/S_i is below the curve, a connection is approved, otherwise the connection is not approved. Then, the customer has to consult with the network operator and asks for a special connection.

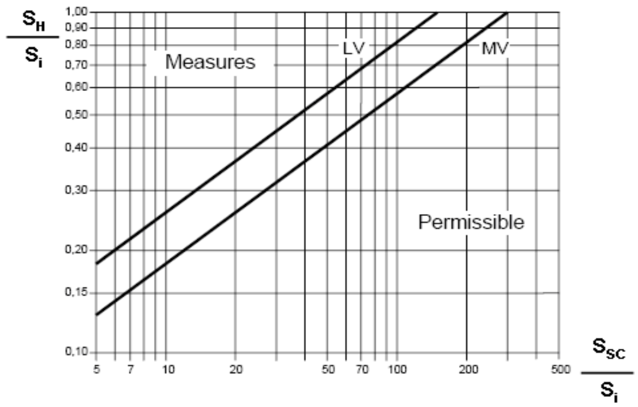


Figure 8. 'Stage 2' connection requirement as per the TR/DNO report

In the evaluation method of the TR/DNO report, the ratio of the short-circuit power at a POC (S_{sc}) and the installation's rated power (S_i) has to be higher than 150 for LV network. For the considered case, the ratio is found 69 (=1.2MVA/17.3kVA). So, the ratio of S_H/S_i is to be found out. For a 'high load demand' household, it is approximately 0.28 (=0.93*7.5/25), considering that 93% of the installation's demand (of 7.5A) is due to non-linear loads in the simulation case (see Table 4.3 of chapter 4).

Figure 9 compares the harmonic current emission limits at a 25A installation by using the above discussed methods. The limits given in the IEC document and the TR/DNO report are comparable, except for the 5th and 7th harmonics. The IEEE gives relatively higher emission limits for all harmonics orders as they are meant for any installation with in a specified SCR range.

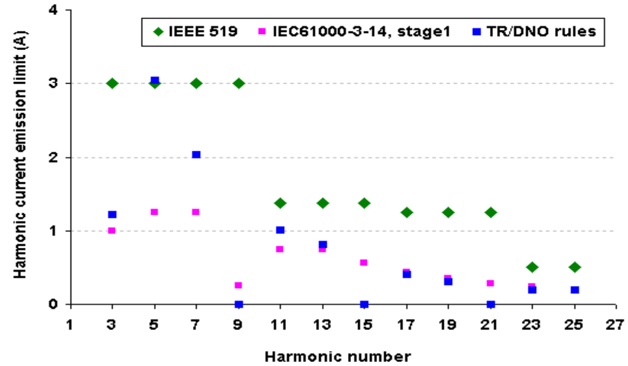


Figure 9. Harmonic current emission limits calculated for a 25A installation

Figure 10 shows a harmonic current field measurement for a day at a POC of a household. It shows that the 3rd, 5th and 7th harmonic currents have values in the range of 0.2A to 1A, and all other higher harmonics are mostly below 0.1A.

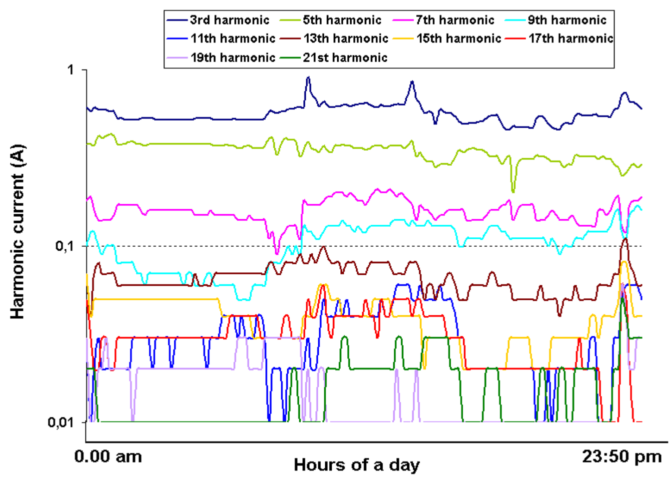


Figure 10. Daily harmonic current profile at a typical household's POC

Appendix C-4

Estimation of voltage dip events at a MV customer's terminal

Table 5.17 shows the average number of voltage dips recorded in the Dutch HV network for each year of the measurement period during 2006 to 2009. Based on those data, an average voltage dip table is made as shown in Table 11. The numbers shown in each cell represent the average of four years measured data.

Table 11. Average voltage dips based on yearly average in HV network

Residual voltage U (in % of U_{nom})	Duration 't' (ms)			
	10<t≤20	20<t≤100	100<t≤ 500	500<t≤ 5000
90>U≥70	0.15	3.7	1.35	0.23
70>U≥40	0.075	0.775	0.3	0.075
40>U≥1	0	0.825	0.475	0.142

The voltage dip classification method of EN50160 standard shows different residual voltage ranges. Therefore, to make it identical as per the EN50160 classification method, the values of each cell in Table 11 are equally distributed among the relevant residual voltage ranges. For example: the value of the cell for 90>U≥70 and 10<t≤20 is divided by 2, to make it evenly distributed for 90>U≥80 and 80>U≥70 for a duration of 10<t≤20. Similarly, the value 0.142 (that represents 40>U≥1 and 500<t≤5000) can be divided by 4 to get a value of 0.04 for each of the cells of 40>U≥30, 30>U≥20, 20>U≥10 and U<10 for a time duration of 500<t≤5000. Applying this method, Table 12 is made which indicates an extended voltage dip table for the Dutch HV networks.

Table 12. Extended voltage dip table based on yearly average in HV networks

Residual voltage (pu)	Duration of dips (ms)			
	10<t≤20	20<t≤100	100<t≤ 500	500<t≤ 5000
90>U≥80	0.075	1.85	0.675	0.115
80>U≥70	0.075	1.85	0.675	0.115
70>U≥60	0.025	0.258	0.100	0.025
60>U≥50	0.025	0.258	0.100	0.025
50>U≥40	0.025	0.258	0.100	0.025
40>U≥30	0	0.206	0.119	0.036
30>U≥20	0	0.206	0.119	0.036
20>U≥10	0	0.206	0.119	0.036
U<10	0	0.206	0.119	0.036

Voltage dips in the Dutch MV networks because of failures in the MV cables and terminals (based on simulation results) are shown in Table 13 (same as Table 4.7).

Table 13. Voltage dip events occurring in MV networks

Residual voltage (pu)	Duration of dips (ms)			
	10<t≤20	20<t≤100	100<t≤ 500	500<t≤ 5000
90>U≥80	0	0	0.074	1.525
80>U≥70	0	0	0.065	0.372
70>U≥60	0	0	0.082	0.288
60>U≥50	0	0	0.029	0.204
50>U≥40	0	0	0.006	0.084
40>U≥30	0	0	0.021	0
30>U≥20	0	0	0.007	0
20>U≥10	0	0	0.006	0
U<10	0	0	0.015	0

Now, by combining Table 12 and Table 13, the total number of voltage dip events in the MV network can be estimated as shown in Table 14. In this estimation, it is assumed that all (types of) dips registered in the HV networks have been propagated in to the MV network.

Table 14. Total number of voltage dip events occurring in MV networks

Residual voltage (pu)	Duration of dips (ms)			
	10<t≤20	20<t≤100	100<t≤ 500	500<t≤ 5000
90>U≥80	0.075	1.85	0.749	1.640
80>U≥70	0.075	1.85	0.740	0.487
70>U≥60	0.025	0.258	0.182	0.313
60>U≥50	0.025	0.258	0.129	0.229
50>U≥40	0.025	0.258	0.106	0.109
40>U≥30	0	0.206	0.140	0.036
30>U≥20	0	0.206	0.126	0.036
20>U≥10	0	0.206	0.125	0.036
U<10	0	0.206	0.134	0.036

The above information of Table 14 is used in Chapter 5 (see Table 5.18) for further estimation of average number of voltage dip events in a MV network. The dip profile found in Table 14 is again presented in the EN50160 format in combination of the SEMI graph (that represents an installation's voltage-time immunity characteristic) as shown in Figure 11.

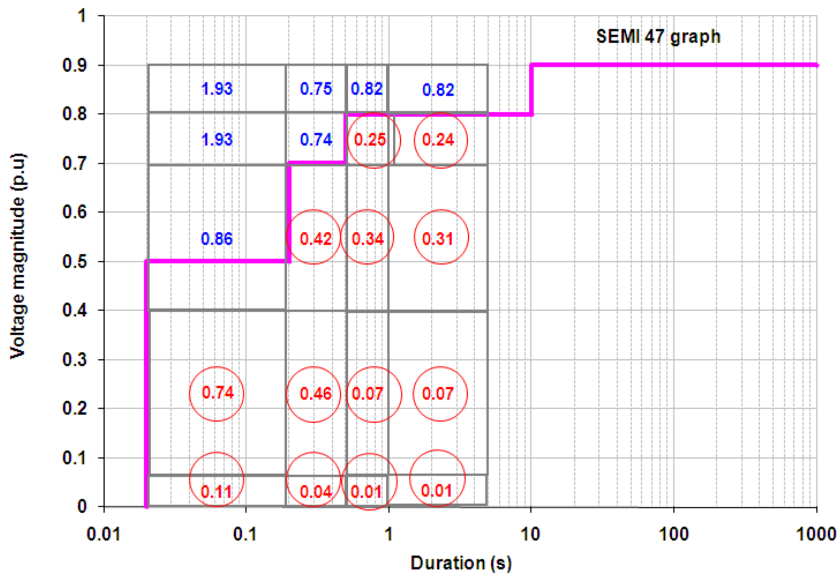


Figure 11. Voltage dip profile estimated at a MV POC (in EN50160 classification format)

The number of events that fall in the danger zone can be counted to estimate the frequency of process failures in a year. In this case, the number of voltage events that leads to process failure is 3.1 (=0.74+0.11+ 0.42+0.46+0.04+0.25+0.34+0.07+0.01+0.24+0.31+0.07+0.01), as found from Figure 11. Therefore, approximately 3 voltage dip events per year are likely to cause process interruptions at the customer's POC. Thus, by applying this procedure, the annual financial losses due to voltage dips for a customer can be estimated.

SYMBOLS AND ABBREVIATIONS

List of symbols

AF_n	Harmonic attenuation factor
C	Capacitance
Da	Incremental cost due to premature aging of a device
DF_n	Harmonic diversity factor
D_H	Harmonic non-active power (in ‘VAr’)
D_I	Current harmonic distortion power (in ‘VAr’)
D_V	Voltage harmonic distortion power (in ‘VAr’)
Dw	Present worth of the operating costs of all components
d_{max}	Maximum relative voltage change
E_{vs}	Voltage dip energy index
E_{Uni}	Harmonic voltage emission limit at installation 'i' for nt^h harmonic (‘%’)
E_{Ini}	Harmonic current emission limit at installation 'i' for nt^h harmonic (‘%’)
F	Shape factor
$G_{Pst,LV}$	Maximum global emission limit of P_{st} in the LV network
$G_{Plt,LV}$	Maximum global emission limit of P_{lt} in the LV network
$G_{Pst,MV}$	Maximum global emission limit of P_{st} in the MV network
$G_{Plt,MV}$	Maximum global emission limit of P_{lt} in the MV network
$G_{n,MV}$	Maximum global contribution of n^{th} harmonic in MV network (in ‘%’)
$G_{n,LV}$	Maximum global contribution of n^{th} harmonic in the LV network (in ‘%’)
I	Connection capacity at the POC (in ‘A’)
I_1	Current component at fundamental frequency (in ‘A’)
I_n	Harmonic current component at harmonic number ‘n’ (in ‘A’)
I_H	Sum of all harmonic current components (in ‘A’)
I_i	Installation's rms current (in ‘A’)
I_{inrush}	Actual inrush current of a device (as per design in ‘A’)
K_{exp}	Weighting factor given to a network operator for his experience in handling power quality problems in the network
K_{nB}	Reduction factor at harmonic order 'n'
k	Short-circuit power ratio which is calculated based on S_i/S_{sc}
$L_{Pst,LV}$	Planning level value for short-term flicker severity in LV network
$L_{Plt,LV}$	Planning level value for long-term flicker severity in LV network
$L_{Pst,MV}$	Planning level value for short-term flicker severity in MV network
$L_{Pst,HV}$	Planning level value for short-term flicker severity in HV network

$L_{n,LV}$	Planning level for harmonic voltage of order 'n' in LV network (in '%')
$L_{n,MV}$	Planning level for harmonic voltage of order 'n' in MV network (in '%')
$L_{n,HV}$	Planning level for harmonic voltage of order 'n' in HV network (in '%')
n	Harmonic number
P_{st}	Short-term flicker severity
$\Delta P_{st,LV}$	Flicker (short-term) emission limit at a POC in LV network
$\Delta P_{st,MV}$	Flicker (short-term) emission limit at a POC in MV network
P_{lt}	Long-term flicker severity
$\Delta P_{lt,LV}$	Flicker (long-term) emission limit at a POC in LV network
$\Delta P_{lt,MV}$	Flicker (long-term) emission limit at a POC in MV network
PF	True power factor in the network (in the presence of harmonics)
PF1	Displacement power factor in the network
P	Total active power (in 'W')
P_1	Active power at fundamental frequency (in 'W')
P_{cable}	Active power losses in a cable/unit length due to harmonics (in 'W')
P_{cap}	Dielectric loss in a PFC capacitor due to harmonics (in 'W')
P_H	Harmonic active power (in 'W')
P_T	Total load losses of a transformer (in 'W')
R_{sce}	Short-circuit ratio of a device
R	Resistance (in 'Ω')
r	Repetition rate of a load in a minute
S	Total apparent power (in 'VA')
S_1	Apparent power at fundamental frequency (in 'VA')
S_e	Voltage dip severity index
S_N	Apparent power at non-fundamental frequency (in 'VA')
S_H	Harmonic apparent power (in 'VA')
S_{sc}	Short-circuit power at an installation (in 'kVA')
S_i	Customer's agreed power (in 'VA')
S_t	Total supply capacity of a MV system supplying to the MV and LV installations, including future load growth (in 'VA')
S_{MV}	Total supply capacity of a MV system supplying to the MV installations, including future load growth (in 'VA')
S_{LV}	Total supply capacity of a LV system supplying to the LV installations, including future load growth (in 'VA')
S_{Dwi}	Weighted distorting power of the installation
t_f	Flicker impression time
t	Duration of a voltage dip (in 'ms')
THD_I	Total harmonic current distortion (in '%')
THD_V	Total harmonic voltage distortion (in '%')

T_p	Evaluation period (for flicker simulation)
T_{Pst}	Transfer coefficient of flicker (for short-term flicker severity)
T_{Un}	Transfer coefficient of harmonic voltage for harmonic order ‘n’
$T_{n,HM}$	Transfer coefficient for harmonic order 'n' from the HV to MV networks
$T_{n,ML}$	Transfer coefficient for harmonic order 'n' from the MV to LV networks
U	Residual voltage (in 'pu')
U_{dip}	Magnitude of voltage dip at a point (in 'pu')
U_{nom}	Nominal voltage (in 'pu')
U_c	Declared voltage at an installation (in 'pu')
U_1	Voltage component at fundamental frequency (in 'pu')
U_H	Sum of all harmonic voltage components (in 'pu')
U_n	Harmonic voltage component at harmonic number ‘n’ (in 'pu')
U_0	Pre-fault voltage at the point of connection (in 'pu')
X	Reactance (in 'Ω')
Z_{ref}	Reference impedance as per the standard IEC 60725 (in 'Ω')
Z_f	Fault impedance (in 'Ω')
Z_s	Source impedance at the point of connection (in 'Ω')
Z_g	Maximum grid impedance (in 'Ω')
Z_{ni}	Harmonic impedance for order n at an installation 'i' (in 'Ω')
Z	Impedance (in 'Ω')
α	Harmonics summation coefficient
α_f	Flicker summation coefficient
$\theta°$	Device temperature (it is sum of rated temperature & rise of temperature)
ρ	Lifetime of a device referred to temperature $\theta°$
ρ_{rat}	Lifetime of a device referred to rated temperature
λ_l	Line failure rate
λ_t	Terminal failure rate

List of abbreviations

AC	Alternating current
AFE	Active front end
AHF	Active harmonic filter
CBEMA	Computer business equipment manufacturers association
CEER	Council of European energy regulators
CENELEC	European committee for electrotechnical standardization
CFL	Compact fluorescent lamp
CHP	Combined heat power

CIGRE	International council on large electric system (translated)
CIRED	International conference on electricity distribution
CNC	Computerized numerical control
DC	Direct current
DFC	Dynamic flicker compensator
DG	Decentralized/distributed generation
DNO	Distribution network operator
DPQ	Distribution power quality
DVR	Dynamic voltage restorer
EHV	Extra high voltage
EMC	Electromagnetic compatibility
EPRI	Electric power research institute
ERGEG	European regulators group for electricity and gas
EOS-LT	Energie onderzoek subsidie voor lange-termijn (in Dutch language)
EU	European Union
FprEN50160	Final report of the EN50160 standard (published in 2010)
HD	Harmonic distortion
HV	High voltage
HVAC	Heating ventilation air conditioning device
HVC	Hybrid Var compensator
IEC	International electrotechnical commission
IEEE	Institute of electrical and electronics engineers
IGBT	Insulated gate bipolar transistor
IRR	Internal rate of return
ITIC	Information technology industry council
IT	Information technology
JWG	Joint working group
KTI	Kwaliteit van de spanning in Toekomstige Infrastructuren (in Dutch language)
LED	Light emitting diode
LPQI	Leonardo power quality initiative
LV	Low voltage
MV	Medium voltage
NPV	Net present value
NRS	South African standard for electric supply
PC	Personal computer
PCC	Point of common coupling
PFC	Power factor corrector
PIT	Process immunity time

PLC	Programmable logic controller
POC	Point of connection
PQ	Power quality
PQM	Power quality monitoring/ measurement
pu	Per unit
QoS	Quality of service
rms	Root mean square value
SCR	Short-circuit ratio which is calculated based on a system's short-circuit power and installation's current carrying capacity
SEMI	Semiconductor equipment and materials international group
SVC	Static Var compensator
TCR	Thyristor controlled reactor
TDD	Total demand distortion
THD	Total harmonic distortion
TSC	Thyristor switched capacitors
TV	Television
TR/DNO	Technical rules for assessment of network disturbances that is published by the distribution network operators from Austria, Czech Republic, Germany and Switzerland.
UIE	International union for the application of the electricity
UK	United Kingdom
UMIST	University of Manchester
UNIPEDE	International union of producers and distributors of electric energy
UPS	Uninterrupted power supply
US	United States of America
VC	Vacuum cleaner
VCR	Videocassette recorder
VSD	Variable speed drive
WIP	Work in progress
XLPE	Cross linked polyethylene

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CURRICULAM VITAE

Sharmistha Bhattacharyya was born on 18th February 1972 in Calcutta, India. She received her bachelor degree (with honours) in Electrical Engineering from Jadavpur University, Calcutta, India in 1994.

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Her research interests are power quality issues in the electricity networks, network design and analysis, and application of sustainable energy sources in the networks.

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