Monitoring and regulation of voltage dips in the distribution network

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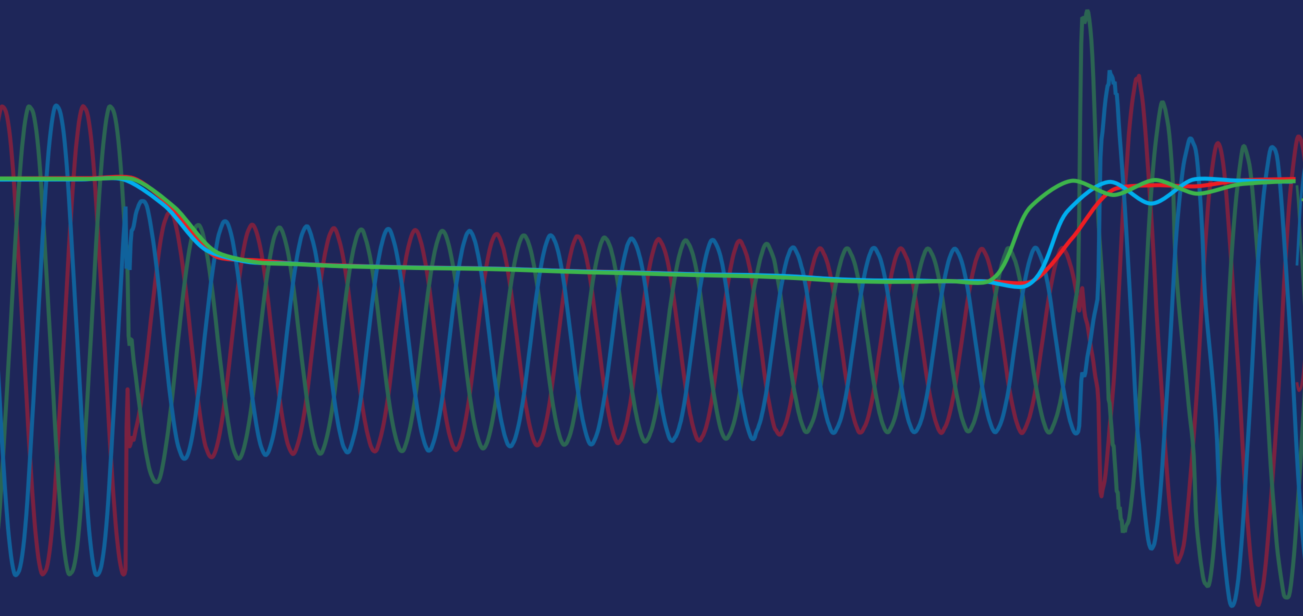

Leake Enqauy Weldemariam

Monitoring and Regulation of Voltage Dips in the Distribution Network

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To my beloved family

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Contact: leake84@gmail.com

Summary

In the present power delivery environment, both end-users and network operators have become increasingly concerned about the quality of supply. Because of an enormous increase of micro- and power electronic applications, modern electrical equipment and controls have become highly dependent on the deviations of the supply voltage, and energy users are highly dependent on the quality of supply delivered to them. Many industrial and commercial customers often have equipment that are sensitive to power disturbances, and, therefore, it is more important to understand the quality of supply being provided. When the proper supply voltage is not delivered, electrical devices may malfunction, fail prematurely or not operate at all. End-users have increased their awareness on voltage quality and they are challenging the network operators for getting appropriate information and better quality of supply delivered to them. The regulatory body also requests the network operators to provide information on the actual voltage quality levels.

System performance analysis is usually an issue for a network operator. To deal with the growing pressure from the customers and regulatory body, the network operators have to be aware of the quality of the supply in the networks. The growing interest in voltage quality has demanded the network operators to install more monitoring tools for measuring more data continuously. This has enabled network operators to get enough information about the overall quality of supply at different voltage levels, and to provide the customers and regulatory agency with appropriate information on the actual voltage quality levels. Voltage quality monitoring is also useful to check customer complaints and to verify if there is any link between the reported complaints and voltage quality limits.

From global and national point of view, voltage dip is one of the power quality (PQ) problems that causes large inconveniences and major financial losses for industrial and commercial customers. In the Netherlands, voltage dips are continuously monitored in the HV- and MV-networks and the customers are provided with annual reports. However, no indicative reference (maximum limit) on the acceptable number of voltage dips has been defined in the grid code. The customers, therefore, face challenges to make economic analysis to choose appropriate mitigation methods for reducing the expected economic damages caused by voltage dips. Recently, there has been a growing interest from the

Dutch regulatory body to include a limit for voltage dips in the national grid code and this PhD project aims to develop a proposal on voltage dip regulation for the Dutch MV-networks. This doctoral dissertation therefore examines the following central research question: *Where is the most optimal PQ-meter placement for monitoring voltage dips in the MV-networks; and which method can be used for estimating the impact of different types of voltage dips on aggregated customers and for building a voltage dip regulation proposal for the Dutch MV-network?*

To answer the research question, the necessary results obtained using approaches of computer simulations for a developed network model, analysis of practical field measurement data and laboratory experiments are presented in different chapters of this thesis.

The characteristics of voltage dips, with more emphasis in the MV distribution network, is explored in *Chapter 2* using computer simulations and based on the statistical failure rates of network components and probability of faults distribution. For the modelled generic MV-network, the frequency and severity of voltage dips are estimated at different points of connections (POCs). The main contributions of this chapter are the comparative studies performed to find the most optimal PQ-meter placement for monitoring voltage dips in the MV-network, and to analyze the effect of network modifications (such as changes in protection schemes, applications of coils and distributed generators) on the frequency and severity of voltage dips at a particular POC and on the choice of PQ-meter placement.

In *Chapter 3*, datasets of voltage events (voltage waveforms with high time resolution) collected from the PQ-meters in several Dutch MV-networks measured over long period are used to assess the frequency and characteristics of voltage dips occurring in the networks. The detection, characterization, classification and presentation dips from the recorded waveforms are described in several literature and standards. Even though the assessment technique has existed for many years, *Chapter 3* contributes to treating different types of dips separately and applying aggregation techniques for representing multiple-dips by a single dip for the customer reports or regulatory purpose. It is noticed that multiple-dips are common in the Dutch networks and the use of an aggregation technique with such events has reduced the average numbers of dips related to phase-to-ground and phase-phase voltages by 45% and 15% respectively. Besides, it was also necessary do the detailed assessment as the obtained results are needed in the succeeding chapters (Chapters 4 – 7).

The behaviors of industrial equipment commonly sensitive to voltage dips are described in *Chapter 4* based on results obtained from laboratory experiments. One of the aspects that define the effect of a voltage dip on a process is the robustness of equipment that make up the process. For a simple process, voltage-tolerance curves of the equipment within the process are compared with the sensitivity of the process at the same test conditions for analyzing the weak link component and for checking if the process dip immunity is always governed by the immunity of the weakest link component in the process. The equipment and process performances are also evaluated and compared against the voltage dip parameters from practical field measurement data.

Industrial processes are usually composed of several equipment and many customers of different category are connected to the MV distribution networks. The effect of voltage dips on the combined customers is, therefore, more complicated than the equipment dip immunity requirements specified by some industrial and national/international standards. An approach for estimating the impact of voltage dips on the aggregated customers connected to the MV distribution networks is described in *Chapter 5*. The approach considers the change of power for all customers connected to the MV-network between the pre-dip and post-dip event. Based on the weighted average of the relative loss of power for the aggregated customers, the estimation method is extended to obtain weighting factors representing the system average severity indices for various types of voltage dips. The obtained indices show a strong correlation between the severity of voltage dips and their impact on aggregated customers. That is, the relative loss of power and thus the impact on the combined customers increases when the dip gets deeper and longer; and the impact even gets worse when more phase-phase voltages are affected in the MV-network.

The difficulty of assessing the economic losses caused by voltage dips is still a challenge both for the network operators and the customers. Two approaches of estimating the economic impact of voltage dips relative to that of a complete interruption are elaborated in *Chapter 6*. In the first approach, a methodology based on equipment sensitivity analysis is demonstrated for estimating the economic impact of voltage dips in a fictitious industrial facility. The composition of process equipment (tested in *Chapter 4*), and their behavior and interaction against various types of voltage dips are considered for obtaining the plant-specific sensitivity indices; and this can easily be applicable in small industries. In the second method, the system dip severity indices obtained using the weighting factor method (*in Chapter 5*) are translated into a matrix of coefficients for making a rough economic loss estimation at a network-level.

In *Chapter 7*, a proposal on voltage dip regulation is developed for the Dutch MV-networks. When building the proposal for the regulatory purpose, different aspects including the frequency and severity of voltage dips occurring in the networks, the propagation of voltage dips, the classification of voltage dips, the aggregation of multiple-dips, and the effect of voltage dips on customers are taken into account. Based on system severity indices of dips, the weighting factor method is applied to make different clusters of voltage dips that define the responsibility-sharing of different parties involved in the delivery and usage of power. Because of the limited number of voltage dips occurring yearly, it is recommended that the maximum limits on the number of dips for the clusters are set and updated based on the historical performance of the networks in several years. For the network operators, this proposal can be important for evaluating the quality of supply in the grid, and for investigating the source of the disturbance and improving the supply voltage when the value is below the indicative minimum requirement. For the customers, this is useful to make economic analysis on the required mitigation measures for reducing the expected economic damages due to voltage dips.

Finally, *Chapter 8* summarizes the main findings of this dissertation. The main conclusions from this thesis are the following:

- It is found that a PQ-meter at the main MV busbar sees relatively higher number of voltage dips than at any other POCs of the feeder, and this can be considered as the most optimal meter placement for monitoring voltage dips in the MV-networks. The choice of optimal monitor placement is also hardly affected by the future network modifications.
- It is shown that the number and severity of voltage dips assessed for the customer reports or regulatory purpose can be significantly affected by the location of monitors, the type of monitor connection, and the method of aggregation with multiple-dips. Applying the proposed aggregation method with multiple-dip events over all monitoring locations has reduced the average numbers of dips related to phase-to-ground and phase-phase voltages from 27 and 10 dips per year to about 15 and 8.5 dips per year.
- It is shown that the process dip immunity can be significantly affected by the types of dips and loading conditions. In most cases, the equipment with the shortest process immunity time (PIT) is also found the weakest link component within the (tested) process. However, the actual PIT and voltage dip immunity of the process can be different from the PIT and voltage dip immunity of the weakest link component in the process.
- A new approach for estimating the impact of voltage dips on the aggregated customers connected to the MV-networks is proposed. Based on the approach, it is found that the relative loss of power and thus the impact on the combined customers becomes higher when the dip gets deeper and longer; and even gets worse when more phase-phase voltages are affected in the MV-networks. Moreover, the proposed approach is applied to obtain system severity indices (or weighting factors) which are very useful for estimating the economic loss of voltage dips and for setting voltage dip limits in the MV distribution networks for the regulatory purpose.

Contents

1 Introduction

1.1 Background

Historically, the quality of supply was determined mainly based on the reliability of the network. In the delivery of power, electrical networks supplying energy without being interrupted too frequently were considered to sustain sufficient quality. With the increase of micro- and power electronic applications in highly automated industrial processes over the years, energy users have become highly dependent on the quality of supply delivered to them. As a result, there has been a transition of interest towards the quality of supply which both the network operators and the customers are more and more interested mainly because:

- Equipment that are sensitive to voltage disturbances in the electrical system can significantly affect the proper operation of modern industries. Because of the huge costs, industrial customers have become less tolerant of the incorrect operation of equipment and poor quality of supply [1-3].
- End-users have increased their awareness on voltage quality. They are challenging the network operators for the appropriate information and better quality of supply delivered to them. This has increased the need for more PQ indicators and for better regulation [4, 5].

1.1.1 Definition of power quality

In a global term, power quality (PQ) is defined by the International Electrotechnical Commission (IEC) in the standard IEC 61000-4-30 [6] as:

"*Characteristics of the electricity at a given point on an electrical system, evaluated against a set of reference technical parameters*".

The characteristics of the electricity are related to both voltage and current which need to be satisfied by the supplier and the users. The reference parameters refer to the limits for both quantities which are defined in several standards. Without the proper supply voltage, electrical devices may malfunction, fail prematurely or not operate at all leading to significant inconveniences and large amount of financial losses for the (industrial) customers.

1.1.2 PQ related complaints and costs

PQ is an important issue for electricity consumers at all levels of usage, particularly for industrial and commercial sectors. As the quality of supply deteriorates below the limits in the standards and requirements in the contract, it may cause financial and technical problems to the customers. The network operators control the quality of supply in the grid and customers report their complaints to the network operator when they receive poor voltage quality at their points of connection (POC). Figure 1.1 shows an overview of the sources of PQ problems leading to the complaints received by Continuon (currently known by Liander), a grid operator in the Netherlands, during 2002-2005 [4]. Low voltage problems (56%) followed by the flickering (36%) are the main causes of complaints for domestic customers. For customers with a contracted power of more than 50 kVA, flickering is the leading cause of complaints (53%) followed by low voltage problems (41%).

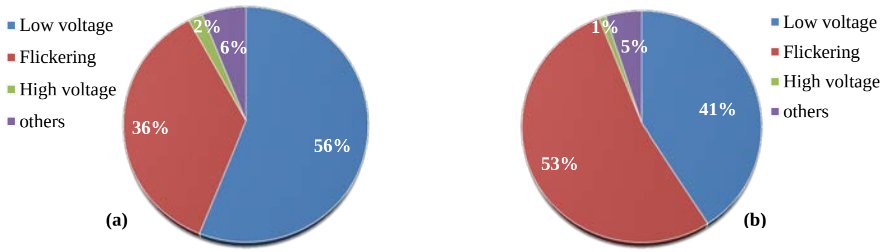


Figure 1.1: PQ complaints [4] – (a) domestic customers, and (b) contracted customers.

In general, the survey in the Netherlands shows that flicker and low voltage problems are the main cause of customer complaints. However, all the reported complaints may not always be a violation of the standard limits and the grid operator should check if the voltage quality is insufficient, in accordance with the standards and contracts, and if there is any link between the reported complaint and the voltage quality limits. For these reasons, PQ monitoring programs have been implemented by the grid operators to obtain more information about the quality of supply and to provide customers with sufficient information.

During the delivery of power to the customers, a PQ problem originating at one part of the network can also propagate to other parts of the network leading to damage of capital-intensive appliances, safety concerns, loss of reliability and above all a huge economic loss to industrial and commercial customers. Figure 1.2 shows an overview of percentage share of costs associated with different PQ disturbances in the Netherlands and in the EU-25 countries.

As described in [7] and indicated Figure 1.2(a), most of the cost to PQ problems in the Netherlands are related to the voltage dip problems (48%) followed by harmonics problems (22%). According to the survey report by the Leonardo PQ initiative team conducted on 62 companies from different industrial and service sectors in the EU-25 countries during 2003-2004, PQ problems caused a financial loss of more than 150 billion Euros per year [3]. It was also found that about 90% of the total financial losses accounted for the industries. As it can be seen in Figure 1.2(b), about 56% of the total financial loss in the EU-25 countries is also because of voltage dips and interruptions, while 28% of the costs are because of transients and surges. PQ problems including harmonics, flicker, earthing and other EMC related problems only account for 16% of the total financial losses in the EU-25 countries.

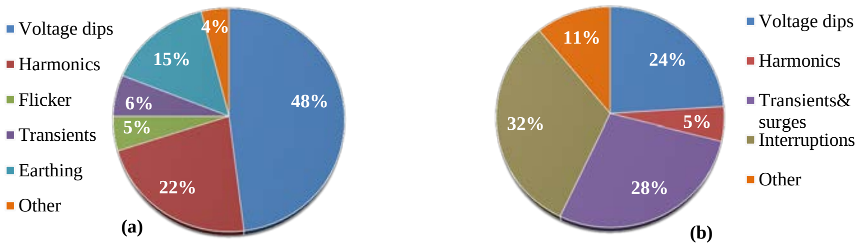


Figure 1.2: Share of costs for PQ problems in – (a) the Netherlands [7], and (b) EU-25 countries [3].

It can be noted that the level of PQ cost is not directly proportional to the frequency of customer complaints on the PQ disturbance. This can be seen from the flicker problem to which customers complain most (Figure 1.1) but its share of the economic impact is low (Figure 1.2). From the surveys, voltage dips and interruptions are PQ problems which have high economic impact on the customers. These PQ problems mostly originate from the grid and the grid operators can influence these phenomena.

1.2 Voltage variation and voltage dips

In different European countries, the National Regulators use the Standard EN 50160 [8] as a basis to describe the expected quality of the supply. The standard gives an overview of most voltage quality disturbances and sets limits or indicatives for many of them. According to the Dutch national grid code, which is also based on the standard EN 50160, the slow supply voltage variations at the point of connection of an MV [1] distribution system is considered as *normal operation* when 95% of the ten minute average RMS values during each period of one week are within +/- 10% of the nominal voltage, and all ten minute average RMS values are within +10%/-15% of the nominal voltage. The sudden and significant deviations of the supply voltage from the normal value are treated as voltage events and indicative values are given in the EN 50160. Because of changes in the system parameters following a disturbance, the voltage level may exceed these limits or indicative values and this can lead to voltage quality problems.

1.2.1 Voltage-level related problems

Figure 1.3 shows various voltage quality problems related to the deviation in the voltage levels with focus on voltage dips. Events shorter than ½ cycle in duration are considered as transients while events with magnitudes of RMS voltages below the lower threshold

[1] *Value for phase-to-phase nominal RMS voltage is between 1 kV to 36 kV.*

(U_{LT}) value are considered as interruptions. In the EN 50160 [8] and IEC 61000-2-8 [9], 5% of the nominal voltage on all phases of a polyphase system is considered as the lower threshold value while 10% of the nominal voltage on any phase is used in the IEEE 1159 [10]. Voltage swell happens when the RMS voltage at a point in the electrical supply system temporarily increases to above 110% of the reference voltage for a duration ranging from ½ cycle to 1 minute, and becomes an overvoltage when this is maintained for longer than 1 minute. When the remaining voltage is maintained at less than 90% of the nominal and for longer than 1 minute, the problem is classified as an undervoltage.

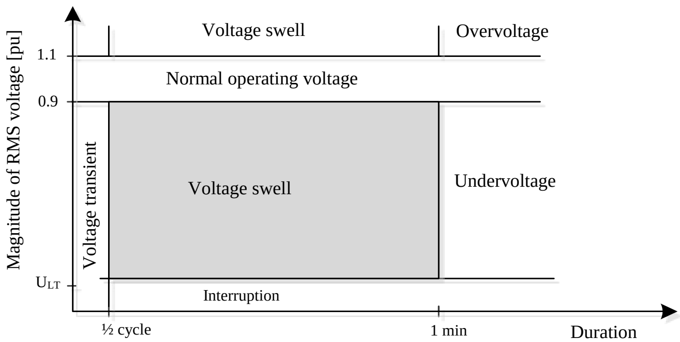


Figure 1.3: Power quality problems related to voltage magnitude events [8-10].

1.2.2 Voltage dip definitions

In several standards [8-10], a voltage dip (sag) is defined as:

"A temporary reduction of the RMS voltage at a particular point on an electricity supply system below a specified dip start threshold followed by its quick recovery to the dip end threshold after a brief interval". It is a two dimensional electromagnetic disturbance the level of which is determined by magnitude of the remaining voltage and duration.

The dip magnitude refers to the remaining voltage between the upper and lower threshold limits. The upper threshold limit separates the event from the allowed normal operating voltage and the lower threshold limit defines a voltage dip from interruption. These threshold limits are defined in the standards [8-10] usually expressed in percentage or per-unit relative to the reference voltage or nominal voltage or declared voltage. As with the dip magnitude, all power-quality standards define dip duration with regards to the upper and lower limits which are determined by the moments of dip start threshold and dip end threshold respectively. The upper limit is the longest allowed duration of a voltage reduction event for which it can be still identified as a voltage dip and this separates voltage dip events from undervoltage events. The lower limit is the shortest duration of a voltage disturbance that can be termed as a voltage dip and this separates voltage dip events from voltage transient.

In all PQ standards, a voltage event is counted as a dip when the remaining voltage magnitude is between the upper and lower thresholds during a period of ½ cycle to 1 minute. For a polyphase system, the dip magnitude is the lowest value of RMS voltage in all phases and the dip duration is the interval between the instant at which the RMS voltage for any phase falls below the start threshold and the instant at which the voltages in all phases rise to the end threshold. According to the standards EN 50160 [8] and IEC 61000-2-8 [9], an event in polyphase systems is treated as an interruption when the voltage on all phases falls below 5% of the reference voltage (otherwise, it is considered to be a dip).

Typically, a voltage dip is associated with the current increase on the system or installations during short-circuit faults mostly occurring in the grid, connection of heavy loads (such as big motors), or excitation of high-power transformers [1, 4, 11]. An example of simulated dip event affecting the two phase voltages is plotted in Figure 1.4. The dip is caused by a phase-to-phase fault created at a busbar 2 km away from the observation point in the 10 kV network detailed in *Section 2.4*. The upper plot shows the instantaneous voltages as a function of time and the lower plot shows the RMS voltages of the three phases (represented by solid, dashed and dotted lines) calculated using half-cycle sliding window. The dip is characterized by a magnitude of 0.45 pu and duration of 300 ms obtained from the RMS voltages.

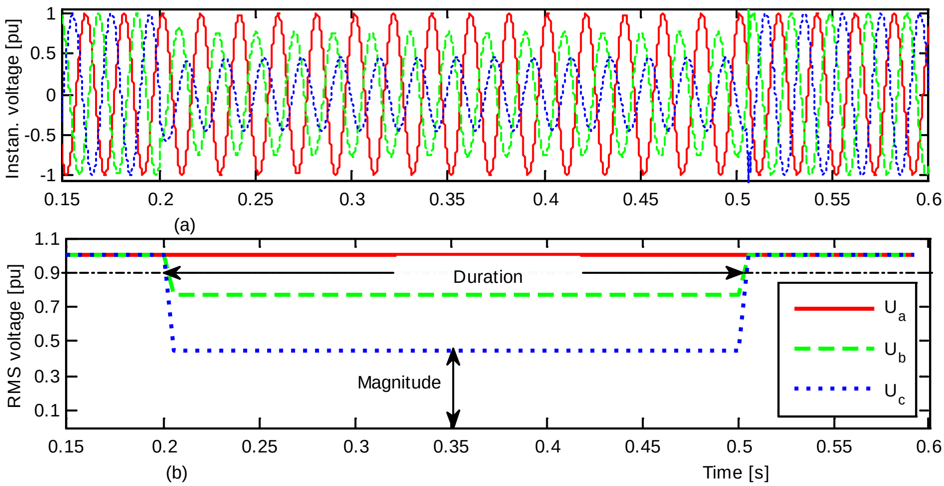


Figure 1.4: Example a simulated voltage dip in two phases – (a) Instantaneous voltages, and (b) RMS voltages.

1.3 Research objectives

In the Netherlands, voltage dips are monitored and there has been a growing interest from the regulatory body to include a limit for voltage dips in the national grid code. This PhD project is initiated by the Dutch network operators and aims to develop a regulatory framework regarding voltage dips in the MV-networks. To achieve this objective, the main research questions are formulated as follows:

- Where is the most optimal PQ-meter placement for monitoring voltage dips in the MV-networks? How will the monitor connection, transformers between the monitor and end-users, and aggregation techniques of multiple-dip events affect the assessment and reporting of voltage dips for customers?

- How can industrial customers utilize information of equipment and process sensitivities against voltage dips for analyzing the weak link component of a process and for estimating the expected economic losses in their facilities due to voltage dips?
- How can the impact of voltage dips on the aggregated customers be estimated? In what ways can the severity of voltage dips be correlated with their impact on all customers connected to the MV-networks? How can the system dip severity indices be estimated for various types of voltage dips and applied for estimating the economic impact of voltage dips?
- How can the dip severity indices (also called dip severity weighting factors) be applied for making a voltage dip regulation proposal, and which information needs to be considered in the setting of voltage dips limits in the MV-network for the regulatory framework?

1.4 Research approach

To achieve the main objectives, the research is approached in the following order:

- **Stochastic analysis of voltage dips:** An MV-network with isolated system grounding is modelled using DIGSILENT PowerFactory and the method of stochastic analysis is applied to find the most optimal PQ-meter placement for monitoring voltage dips in the MV-networks. Using input data about the network parameters and fault statistics, the expected frequency and severity of voltage dips are estimated at different points of connections (POCs) and comparative studies are made based on several simulations. Computers simulations are also performed to analyze the effect of network modifications (such as changes in protection schemes, applications of coils and distributed generators) on the frequency and severity of voltage dips at a particular POC and on the choice of PQ-meter placement.

- **Statistical assessment of voltage dips:** Datasets of voltage events (voltage waveforms with high time resolution) collected from several MV-networks measured over longer period are used to assess the frequency and characteristics of different types of voltage dips occurring in the Dutch MV-networks. Different methods of aggregation are described for representing multiple-dip events by a single dip per event for customer reports or regulatory purpose and different types of voltage dips are treated separately. Besides to this, an approach for estimating the impact of voltage dips on the aggregated customers connected to the MV-networks is described based on load changes from the field measurement data. Taking the frequency and severity of voltage dips affecting the end-users into consideration, system severity indices (or weighting factors) are obtained for various types of voltage dips.

- **Experimental tests on the voltage dip immunity of devices:** To investigate the effect of different voltage dip parameters on industrial equipment, immunity tests are conducted on several equipment and on a simple process. A short survey was conducted on 11 Dutch industrial customers to get better insight into the equipment that are commonly sensitive to voltage dips and causing problems in their industries. For a simple process, voltage-tolerance curves of the equipment that make up the process are compared with the sensitivity of the process at similar test conditions. This helps to analyze the weakest link component of the process and to compare the voltage dip immunity of the process with the voltage dip immunity of the weakest link component within the process. This is also useful for evaluating and comparing the equipment and process performance to field measured data. From the behavior and interaction of the tested equipment, an approach based on equipment sensitivity analysis is described for estimating the economic impact of voltage dips in a fictitious industrial facility.

- **Voltage dip regulation:** Information of voltage dips data along with the system severity indices, obtained using the weighting factor (WF) method based on the loss of power for the aggregated customers in the MV system, are used for building a proposal on voltage dip regulation.

1.5 Thesis outline

As graphically depicted in Figure 1.5, this thesis consists of three major parts which are described in Chapter 2 through Chapter 7. The first part of the thesis focuses on studying the characteristics of voltage dips in the distribution networks based on stochastic and statistical analysis. The second part of the thesis deals with the impact of voltage dips on end-user equipment and processes. This also covers the economic impact of voltage dips on customers. The last part of the thesis is about a voltage dip regulation proposal for the Dutch grid code. When building the proposal for the regulatory framework, different aspects including the frequency and severity of voltage dips occurring in the networks, the propagation of voltage dips, classification of voltage dips, aggregation of multiple-dips, and the effect of dips on individual devices and on the aggregated customers are taken into account along with the responsibility-sharing of different parties involved in the delivery and usage of power.

The content of each chapter, after the introductory chapter (Chapter 1), is as follows:

Chapter 2: This chapter provides an insight into the probabilistic voltage dips estimation using the fault positions method. Based on the input data of the network parameters and assumptions about the reliability of the network components, an MV-network is modelled using DIGSILENT PowerFactory and computer simulations are performed to estimate the number and severity of voltage dips at different POCs. This chapter describes the propagation of voltage dips caused by different types of faults to the LV-network. It presents comparative studies on the optimal meter placement for monitoring voltage dips in the MV-networks. Furthermore, the effect of network modifications (such as change of protection schemes, application of coils and distributed generators) on the expected number of voltage dips at a POC and on the choice of meter placement are also explored.

Chapter 3: This chapter focuses on several important aspects regarding monitoring data of voltage events in the Dutch MV-networks, including the detection, characterization, classification and reporting of voltage dips. Effects of the type of monitor connections and transformers between the monitoring locations and end-user equipment terminals are taken into account when assessing the number and severity of various types of voltage dips affecting end-user. Different aggregation techniques are described to avoid multiple-dip events occurring within short-intervals from counting several times.

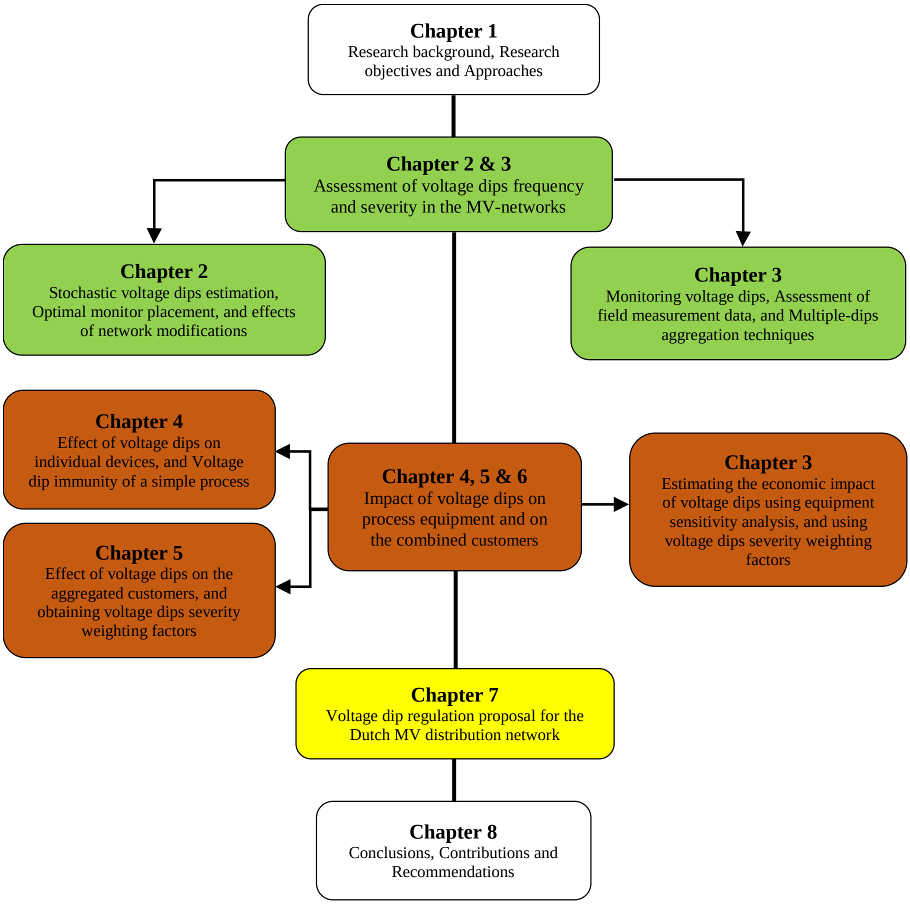


Figure 1.5: Thesis outline.

Chapter 4: In this chapter, several laboratory tests are conducted to study the equipment dip immunity. The effects variations in voltage dip parameters on the ride-through capabilities of devices commonly used in industries are studied. Using a simple process, the equipment sensitivities are compared with the process sensitivity against the same disturbance parameters to demonstrate the behavior and interaction of individual equipment that make up the process. The voltage-tolerance curves of the equipment and process are compared to check if the process dip immunity is governed by the immunity of the weakest link component in the process. Moreover, the performance of the tested process is described by comparing the severity of voltage dips from field measurements with the voltage-tolerance curves of the process under different conditions.

Chapter 5: A new approach for estimating the impact of voltage dips on the aggregated customers connected to the MV distribution networks is proposed in this chapter. Using monitoring data from several MV substations during several period of years, the estimation approach is extended to obtain system severity indices for various types of voltage dips. The correlation between the severity of voltage dips and the obtained severity indices is also explored in this chapter.

Chapter 6: This chapter presents two approaches of estimating the economic impact of voltage dips. Sensitivity indices and severity weighting factors, obtained from the equipment sensitivity analysis of a facility and from the relative impact of voltage dips on the aggregated customers, are described for evaluating the expected economic losses caused by voltage dips relative to that of an interruption.

Chapter 7: In this chapter, a voltage dip regulation proposal based on weighting factors is developed for defining different clusters for various types of voltage dips and for setting limits on the expected number of dips for the regulatory framework. The proposed method is also compared with another approach based on equipment dip immunity levels.

Chapter 8: Main findings and contributions of the thesis work are summarized in this chapter, and several recommendations for future research are presented.

2

Stochastic analysis of voltage dips

2.1 Introduction

The voltage dip performance of electric networks can be evaluated by simulation or by measurement. With the simulation approach, which is also called probabilistic approach, the method of fault positions is used. With the help of computer simulation, electric networks can be modelled and various types of faults can be considered at numerous locations throughout the network to obtain the expected number of voltage dips. The overall accuracy of the result depends on input data of the network model and assumptions made about the reliability of network components. The network model data comprises all parameters relevant to the network components, like the type and size of transformers, cables, loads, etc., and these data are obtained from the manufacturer specifications. The network reliability data deals with the failure probability of network components and fault distributions in the electric networks, and these values are obtained from observations on the behavior of components over several years in the past. Because of the changes of maintenance methods, the developments of new types of components, and variations of different activities by the third-party, the component failure-rate and fault-frequency values of the next years can be different from the previous years, leading to uncertainties about the network reliability data. Taking the uncertainties into account, the simulation approach can be used to assess the voltage dip performance of electric networks, especially with networks that have no continuous monitoring tools installed. The main advantages of using simulation approach are:

- To study the expected performance of electric networks that have no installed continuous monitoring tools,
- To estimate the expected performance of present networks instantly unlike to the field measurement approach which needs continuous measurements for a long time,
- To integrate the dynamic nature of network modifications (e.g. change of protection scheme, introduction of DGs, application of coils, adding new feeders, etc.) and to obtain indicative results about the possible future problems in the network that helps to make scenarios of the supply performance of electric networks for future planning,

- To observe the performance of customers' points of connections (POCs) that are far away from monitoring points,
- To compare different points of observations in order to find the most optimal placement of monitoring.

In this chapter, the characteristics of voltage dips caused by balanced and unbalanced short-circuit faults are studied using the method of symmetrical components. The propagation of voltage dips from one point to another and the transfer of dips from the MV-network to the LV-network are discussed. Then, a generic MV-network is modelled using DIGSILENT PowerFactory and computer simulations are performed to determine the expected frequency and distribution of voltage dips at a POC. Comparative studies are made for finding the optimal PQ-meter placement for monitoring voltage dips in the MV-networks. Effects of network modifications (such as change of protection schemes, application of coils and distributed generators) on the expected number and severity of voltage dips and on the choice of PQ-meter placement are also explored.

2.2 Distribution network in the Netherlands

The Dutch MV distribution networks almost entirely consist of underground cables mainly operating on 10 kV. Other voltage levels include 3, 6, 12, 20 and 25 kV, and the LV-networks are operated on 230/400 V. Figure 2.1 shows a general overview about the Dutch distribution network. The secondary side of the HV/MV transformer can be connected in delta or star. When the secondary side of the HV/MV transformer is connected in delta, the MV substation is isolated or an artificial neutral point can be created by means of an earthing transformer. When the secondary side of the HV/MV is connected in star, the neutral point can be earthed with impedance grounding and the cable sheaths of the MV cables are connected to the earthing system of the HV/MV substation and to the earthing system of the MV/LV transformers.

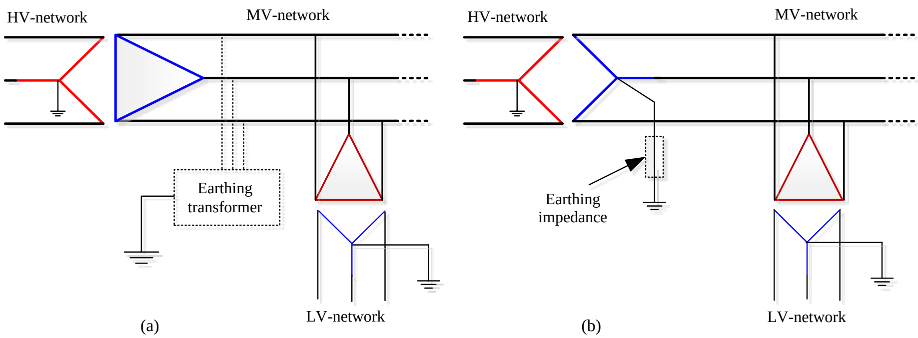


Figure 2.1: Structure of the Dutch distribution network with MV side of HV/MV transformer in – (a) delta, and (b) star.

Every MV/LV transformer feeds just a small amount of end-users that are connected to the MV-network through Dyn transformers. The primary delta winding of the MV/LV transformer converts the asymmetrical LV currents into symmetrical MV currents, preventing the zero-sequence currents from penetrating into the MV-networks [12].

2.3 Symmetrical component method

Voltage dips with detrimental impact on customers are mainly caused by short-circuit faults [9]. Short-circuit faults can be caused due to atmospheric events (by lightning and wind storms, snow, ice, deposition of salt), mechanical interference and damage (due to contact by vehicle, construction equipment, excavation equipment, animals, growing trees), breakdown of network plant (due to deterioration with age, corrosion, construction faults), accidents or errors in operation and maintenance, or major natural events (due to floods, landslides, earthquakes, avalanches).

The severity of voltage dips is expressed in terms of the magnitude of the remaining voltage and duration. Magnitude of voltage dips depends on the network impedance and type of short-circuit faults [1, 4]. The network impedance in turn depends on the system grounding type, location of fault and type of lines/cables between the fault location and observation point. The duration of voltage dips is related to the fault clearing time of protection devices installed in the electrical networks.

As described in many literatures [1, 13, 14], the symmetrical component method helps to study the variation of voltage dip magnitude caused by different types of faults occurring in the networks. For a radial network of a distribution system shown in Figure 2.2, short-circuit faults occurring along the cables in the MV-network or LV-network are considered and dependency of the dip magnitude on fault location is studied using the symmetrical component method. Network parameters used for the calculations and simulations are given in Table 2.1.

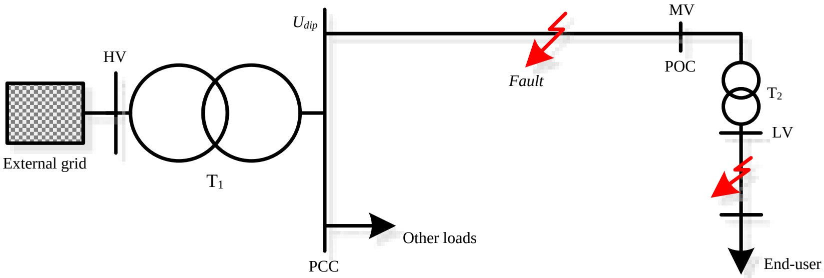


Figure 2.2: Simplified radial network for calculating voltage dips during short-circuit faults.

Table 2.1: Network parameters used for calculation and simulation

External grid	150 kV, S_k=5427 MVA, X/R=10		
Transformer	T_1: 150/10 kV, 150 MVA, Y_N d, u_k=22%; Z=0.029 + j0.147 Ω (MV side)		
	T_2: 10/0.4 kV, 400 kVA, Dy_n, u_k=4%; Z=0.005 + j0.015 Ω (LV side)		
	Type	Z_1=Z_2 *[Ω/km]*	Z_0 *[Ω/km]*
	240 mm² Al	0.125 + j0.085	0.500 + j0.340
	150 mm² Al	0.214 + j0.079	0.642 + j0.147
Cables	95 mm² Al	0.323 + j0.082	1.292 + j0.398
	50 mm² Al	0.643 + j0.109	2.573 + j0.437

When a balanced three-phase fault (3pf) occurs along the feeder in the MV-network, the short-circuit current (I_{SC}) at the fault location can be estimated using (2.1),

$$I_{SC} = \frac{U_{nom}}{Z_S + Z_F}, \quad Z_F = z \times d \tag{2.1}$$

where U_{nom} is the nominal voltage at the point of common coupling (PCC),
Z_s is the source impedance from grid to the PCC,
Z_F is the fault impedance from the PCC to the fault location,
z is cable impedance per unit length, and
d is the distance of the fault from the PCC.

The source impedance includes impedance of the external grid, HV/MV transformer and grounding of the HV/MV substation. The fault impedance depends on the fault location and the impedance of the cable between the fault location and observation point. At the PCC, the nominal voltage and the source impedance are fixed for a certain type of system grounding while the fault impedance changes depending on the fault location.

Using the principle of symmetrical components [15], the phase-to-ground voltages (in pu) obtained at the PCC can be expressed by (2.2),

$$\left[U_a \;\; U_b \;\; U_c\right] = \left[\frac{Z_F}{Z_S + Z_F} \quad a^2\frac{Z_F}{Z_S + Z_F} \quad a\frac{Z_F}{Z_S + Z_F}\right] \tag{2.2}$$

where 'a' is phasor rotation operator ($a = e^{j\frac{2\pi}{3}}$). With balanced faults, the source and fault impedances depend only on their respective positive sequence components (i.e., Z_S=Z_{S1} and Z_F=Z_{F1}). The voltages on the three phases have the same magnitude and phases are 120° shifted from each other. Therefore, a simple voltage divider model [1] is commonly used for one of the phases and the magnitude of the voltage dip (in pu) at the PCC can be expressed by (2.3).

$$U_{dip} = \frac{Z_F}{Z_s + Z_F}, Z_F = z \times d \tag{2.3}$$

The variations of short-circuit currents and magnitudes of the remaining voltage at the PCC during three-phase faults occurring at different locations along the feeder from the PCC are shown in Figure 2.3. It can be observed (Figure 2.3(a)) that a maximum short-circuit current is expected when the fault occurs at the PCC and the value decreases when the fault occurs far away from the PCC. Cables with smaller cross-section have higher intrinsic impedance and thus carry lower short circuit currents than cables with larger cross-sections. With regard to the dip magnitude, it can be seen from Figure 2.3(b) that the closer the fault location is to the PCC, the smaller the remaining voltage and thus the deeper the depth of the voltage dip is. When the fault distance increases, the impedance to the fault increases and thus the remaining voltages also increase. The higher the cable cross-section (the smaller the fault impedance) is, the higher the short-circuit current and thus the deeper the depth of the voltage dip is.

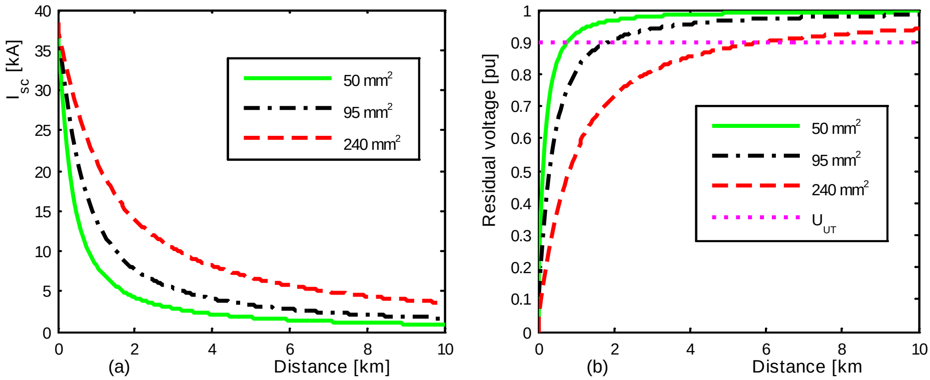


Figure 2.3: Effect of fault location with three-phase faults on – (a) short-circuit currents, and (b) dip magnitudes.

To demonstrate the propagation of voltage dips originating in the LV-network, an MV/LV transformer is considered 5 km from the PCC and the short-circuit power at the MV side of the transformer is estimated to be 130 MVA. As can be seen from Figure 2.4(a), the customer at the LV-busbar experiences voltage dips ranging from deeper to shallow magnitudes depending on the location of the fault. Figure 2.4(b) shows the propagation of the dips to the MV side of the transformer. In this case, the fault impedance component in (2.3) includes impedance of the LV cables and that of the MV/LV transformer (Z_{tra}) transferred to the MV side. Because of the large transfer ratio of the transformer ($k = \left(U_{MV} / U_{LV} \right)$), the fault impedance seen from the MV side of the transformer ($Z_F = k^2 \left(Z_{tra} + z \times d \right)$) is incredibly large. Even if the fault occurs on the LV busbar, the ratio of impedances $\left(\frac{Z_{tra}}{Z_s / k^2 + Z_{tra}} \right)$ is large and the customers at the MV side of the transformer experience very shallow dips (in this case, u~85%). When the fault distance increases, impedance of the cable along with the transformer referred to the MV side becomes larger and the voltage dip rises rapidly. In general, the propagation of dips from the LV- to the MV-network causes negligible effect for most of the customers.

Unbalanced faults, including single phase-to-ground, phase-to-phase, and two phase-to-ground faults, in a three-phase system result in asymmetrical voltages. With the help of symmetrical components, each phase voltage can be decomposed and represented by the three symmetrical components (positive, negative and zero sequence components). An overview of the symmetrical component analysis for unbalanced faults can be found in *Appendix-A*. The zero sequence component of the source impedance can be affected by the grounding topology in the MV-networks. This has an influence on the remaining voltages during single phase-ground and two phase-to-ground faults while the voltages during phase-to-phase fault are independent of the zero sequence component of impedances.

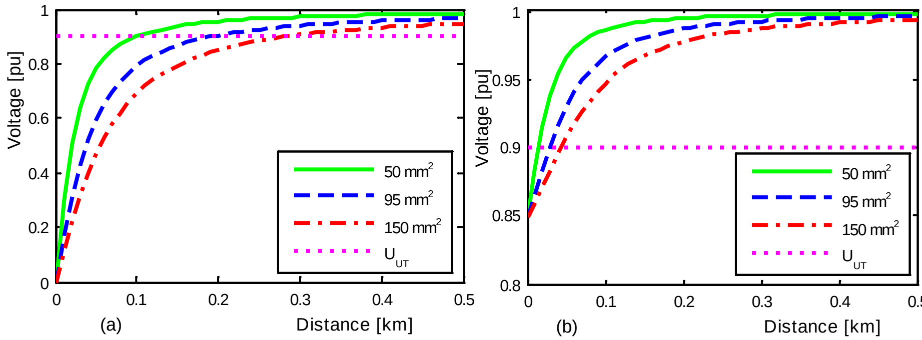
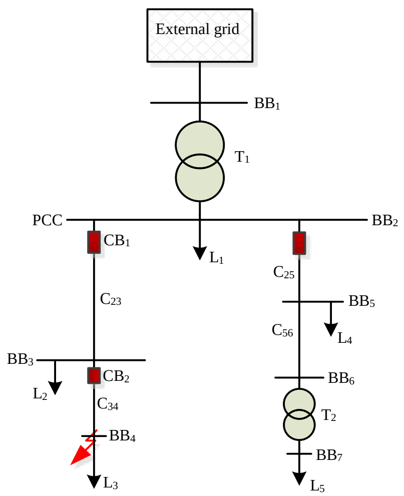


Figure 2.4: Voltage dips due to three-phase faults in the LV-network and observed at the – (a) LV side of the transformer, and (b) MV side of the transformer.

2.4 Voltage dip propagation

The variation in voltage dip characteristics (e.g. magnitude and phase-angle) depends on the fault conditions and system conditions of the three phase power system. The fault location can be close to or remote from the point of interest. System conditions including the number and type of transformers between the fault location and point of observation, type of system grounding affect the magnitude and phasor of the voltage during its propagation. To demonstrate the variation in magnitude and phase-angle jumps of voltage dips caused by balanced and unbalanced faults in the MV-network and to study their propagation to the LV-network, computer simulations are performed on a three-phase generic system shown in Figure 2.5.



Component	Details
Source (grid)	150 kV, S_k=5427 MVA, X/R=10
Transformer T_1	150/10 kV, 25 MVA, u_k=22%, YNd5
Transformer T_2	10/0.4 kV, 2 MVA, u_k=6%, Dyn5
Loads	L_1 = 6.5 MVA, L_2 = L_4 = 1.5 MVA, L_3 = 5 MVA, L_5 = 1.33 MVA, PF=0.9
Cables	C_{23} = C_{34} = C_{25} = C_{56} = 1 km, Z_1=0.0413+j0.0320 Ω/km; Z_2=Z_1 Z_0=0.1653+j0.1281 Ω/km

Figure 2.5: Generic model of a distribution system for simulation.

Single phase-to-ground, phase-to-phase, two phase-to-ground and three-phase faults are created at busbar BB_4 and the protection device CB_2 is set to clear the fault in about 300 ms. The change in phase-angle of the voltage following the voltage drop caused by the short-circuit faults in the system, called phase-angle jump (PAJ), is obtained by comparing the phase-angle of the voltage during the fault with the phase-angle of the voltage before the fault. Depending on whether the during-fault voltage leads or lags the pre-fault voltage, the phase-angle jump could be positive or negative. Magnitudes and PAJ associated with phase-to-ground and phase-to-phase voltage characteristics are observed at the PCC and the LV side of transformer T_2.

2.4.1 Single phase-to-ground fault

For a single phase-to-ground fault at BB_4, the variation in voltage magnitudes and PAJs in the MV- and LV-network are depicted by the phasor diagrams in Figure 2.6. At the PCC, the magnitude of the remaining voltage in the faulted phase (A) dropped to about 5% of the nominal voltage with +11° PAJ while fault-free phases show swells with phase-jumps of +28° and -30°. The large PAJ of the fault-free phases relative to the faulted phase should be due to the overvoltage on the fault-free phases. Figure 2.6(b, c) addresses that phase-phase voltages in the MV-network become phase-voltages in the LV-network, and the PAJs of the phase-phase voltages in the MV-network are the same as the PAJs of the phase-to-neutral voltages in the LV-network. Despite the large drop in magnitude with large PAJs of the phase-voltages in the MV-network, it can be seen in Figure 2.6(c, d) that star- or delta-connected devices in the LV-network will be negligibly affected by the magnitude and PAJs of voltage events caused by single phase-to-ground faults occurring in the MV-network.

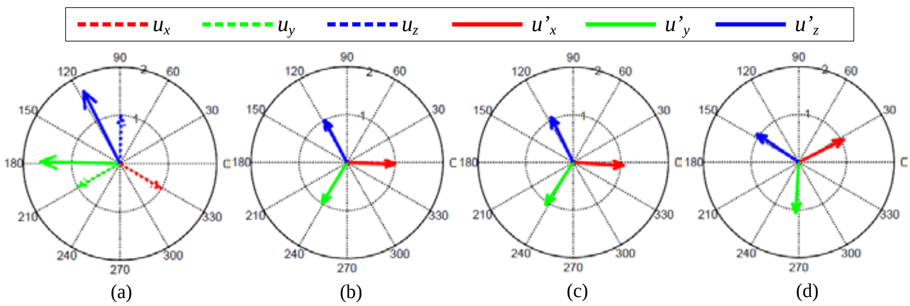


Figure 2.6: Phasors of pre-fault voltages (dotted lines) and during-fault voltages (solid lines) for – (a) MV-network phase-ground voltages, (b) MV-network phase-phase voltages, (c) LV-network phase-ground voltages, and (d) LV-network phase-phase voltages. (Note: **x/y/z** may refer to phase-ground or phase-phase voltage).

2.4.2 Two phase-to-ground fault

Figure 2.7 shows the variation in magnitudes and PAJs associated with the phase-to-ground and phase-phase voltages in the MV- and LV-networks during a two phase-to-ground fault. It can be clearly noticed that voltages drop in the faulted phases (u_b=0.39 pu, u_c=0.37 pu with PAJs 0° and -58°) while the fault-free phase shows voltage swell (u_a=1.5 pu with -1.5° PAJ). The phase-phase voltages in the MV-network become phase-to-neutral voltages in the LV-network. During this type of fault, Y- and Δ-connected devices in the LV-network will experience voltage dips of different magnitude and PAJs (Y-loads: $u'_x=u_{ab}$=1 pu; $u'_y=u_{bc}$=0.47 pu, $u'_z=u_{ca}$=0.83 pu with PAJs $\Delta\Psi'_x$=-19°, $\Delta\Psi'_y$=-30°, $\Delta\Psi'_z$=+16°; and Δ-loads: u'_{ab}=0.81 pu, u'_{bc}=0.48 pu, u'_{ca}=1 pu with PAJs $\Delta\Psi'_{ab}$=-35°, $\Delta\Psi'_{bc}$=+13°, $\Delta\Psi'_{ca}$=0°).

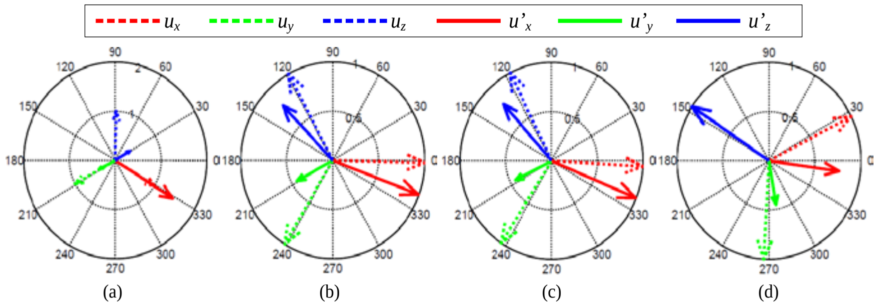


Figure 2.7: Phasors of pre-fault voltages (dotted lines) and during-fault voltages (solid lines) for – (a) MV-network phase-ground voltages, (b) MV-network phase-phase voltages, (c) LV-network phase-ground voltages, and (d) LV-network phase-phase voltages. (Note: **x/y/z** may refer to phase-ground or phase-phase voltage).

2.4.3 Phase-phase fault

As shown in Figure 2.8, a phase-phase fault at the same location considered earlier with the other faults results in voltage dips with remaining voltage magnitudes relatively shallower (u_b=0.75 pu, u_c=0.45 pu) than two phase-to-ground fault while magnitude of the fault-free phase is not affected (u_a=1 pu). Such faults also cause significant PAJs on the faulted phases (-35°, +13°), and no PAJ on the fault-free phase. Y-connected loads in the LV-network will experience two-phase dips with the same magnitude as the phase-phase dips in the MV-network, but PAJs in all phases (-19°, -30°, +16°). On the other hand, Δ-connected loads will experience two-phase dips with the same PAJs (-35°, +13°, 0°) as phase-dips in the MV but on different phases. Unlike the two phase-to-ground fault, the PAJs associated with the phase-voltages in the MV- and LV-network are comparable with phase-phase faults.

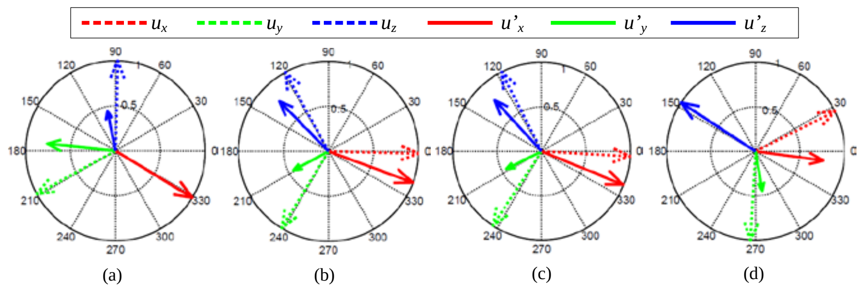


Figure 2.8: Phasors of pre-fault voltages (dotted lines) and during-fault voltages (solid lines) for – (a) MV-network phase-ground voltages, (b) MV-network phase-phase voltages, (c) LV-network phase-ground voltages, and (d) LV-network phase-phase voltages. (Note: **x/y/z** may refer to phase-ground or phase-phase voltage).

2.4.4 Three-phase fault

With a three-phase fault in the MV-network, Figure 2.9 shows voltages in the three phases drop to 0.44 pu with the same PAJs (-30°) relative to the phase-angles before the fault. The phase-phase voltages in the MV-network also show the same magnitude of voltages and PAJs. Furthermore, Y- or Δ-connected loads in the LV-network will experience voltage dips with the same magnitude of remaining voltages and PAJs as in the MV-networks.

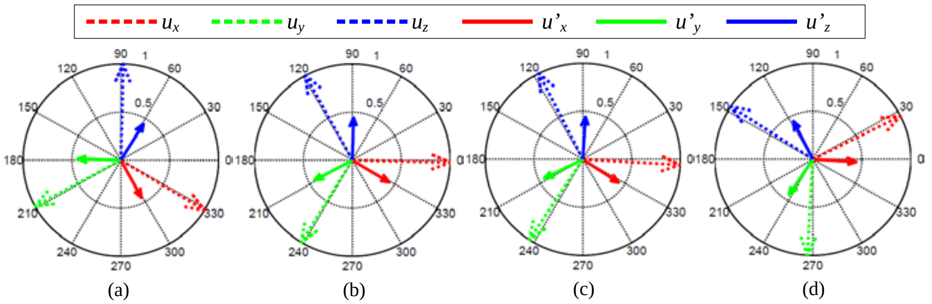


Figure 2.9: Phasors of pre-fault voltages (dotted lines) and during-fault voltages (solid lines) for- (a) MV-network phase-ground voltages, (b) MV-network phase-phase voltages, (c) LV-network phase-ground voltages, and (d) LV-network phase-phase voltages. (Note: **x/y/z** may refer to phase-ground or phase-phase voltage).

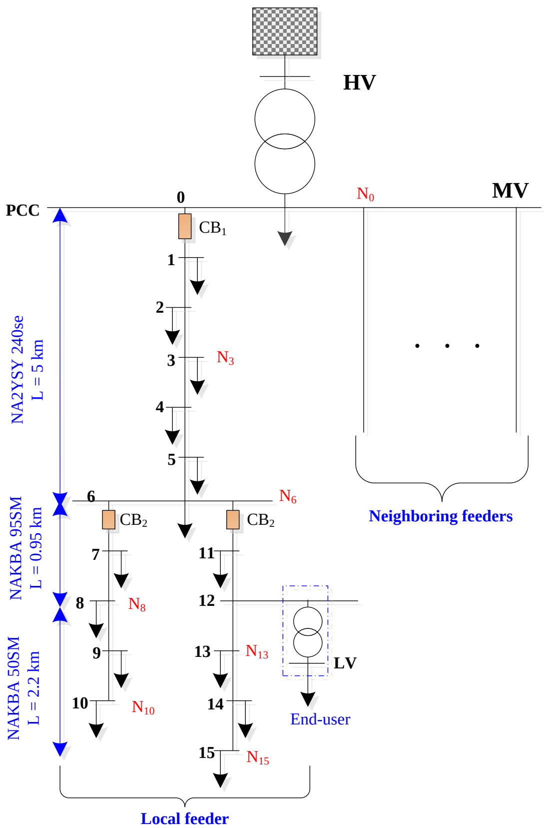
2.5 Voltage dip estimation

Information about the frequency and characteristics of voltage dips in the electric system is important for the network operators and customers. This information can be obtained from historical data or from monitoring. When there are no records available, voltage dip profiles can be obtained using computer simulations. In this case, the fault positions method is used.

The fault positions method [16-20] is a common method for determining the expected characteristics of voltage dips resulting from the short-circuit faults in the network. For any type of fault at every fault position (e.g. along cables, cable joints and busbars), the remaining voltage at a point of connection (POC) can be computed. From the magnitudes of remaining voltages, the exposed area leading to voltage dips can be determined. Based on the magnitude of the remaining voltage, voltage dips caused by a fault can be shallow or deep and this varies among different points of observations. Besides, the dips can be shorter or longer depending on the fault location and reaction of protection devices. The severity of a dip, therefore, depends on both magnitude of the remaining voltage and dip duration. Using the network parameters and fault statistics on the network, the number of voltage dips, their remaining voltages and durations can be estimated for every connection point.

2.5.1 Network description

The Dutch MV-network is mostly a meshed grid but it is operating as radial. Underground cables, mostly operating on 10 kV are used in the MV-network. Various types of cables are used and the length between two terminals also varies. To estimate the number and severity of voltage dips due to different types of faults occurring in the MV-network, a generic 10 kV Dutch network shown in Figure 2.10 is modeled using DIgSILENT PowerFactory.



Additional information on cables

From	To	Length [km]	Impedance [Ω/km] R	X
0	1	1.811	0.125	0.085
1	2	0.600	0.125	0.085
2	3	0.233	0.125	0.085
3	4	1.100	0.125	0.085
4	5	0.444	0.125	0.085
5	6	0.800	0.125	0.085
6	7	0.530	0.125	0.085
7	8	0.425	0.125	0.085
8	9	0.143	0.125	0.085
9	10	0.419	0.125	0.085
6	11	0.646	0.323	0.100
11	12	0.300	0.323	0.100
12	13	0.646	0.323	0.100
13	14	0.571	0.643	0.109
14	15	0.976	0.643	0.109

Figure 2.10: Schematic of a generic MV-network for simulation.

The MV-network comprises ten evenly placed outgoing feeders connected to the PCC at the main busbar. The maximum length of the feeder that consists of three types of cables is 8.127 km. Each feeder consists of 15 busbars where end-users are connected through Dyn transformers. The LV customers are aggregated and represented by uniform loads of 0.4 MW connected to each terminal of the POCs. Some customers are connected really far from the HV/MV substation while others are really close. Depending on the distance of the observation point and the fault location from the PCC, the severity of voltage dips caused due to faults cleared by the secondary protection can be different at various POCs in the same feeder.

In each feeder, primary and secondary protection devices are considered. Primary protection (CB_1) is used at the beginning of each feeder and clears faults occurring between N_0 and N_6 in 600 ms. During such conditions, all customers in the same feeder experience interruption while customers on the neighboring feeders connected to the main substation may experience voltage dips. The secondary protections (CB_2) are used in the branches of the feeders to clear faults occurring along the branches N_6–N_{10} or N_6–N_{15} in 300 ms. When CB_2 clears the fault, customers in the same branch will be interrupted while other customers in the same feeder and in the other neighboring feeders may experience voltage dips. If it happens that CB_2 fails, the primary device (CB_1) clears the fault after some delay. Network parameters used for simulation are summarized in Table 2.1.

2.5.2 Voltage dip exposed area

When estimating the annual frequency of voltage dips, the magnitude of remaining voltages are first obtained for various types of faults created at every terminal, cable joints and along the cables between two terminals. For a given POC, the total length of cables and number of terminals/joints within which faults will lead to voltage dips at the POC is called the total exposed area. To study the dependency of magnitude of the remaining voltage on fault location and type, four types of faults are considered. These are single phase-to-ground fault (pgf), phase-phase fault (ppf), two phase-to-ground fault (2pgf) and three-phase fault (3pf). For each type of fault, short-circuits are created at the terminals, cable joints and every 10% of the cables between two terminals/joints of the feeder.

According to the EN 50160 standard, magnitude drops below 90%, 80%, 70%, 40% and 5% of the nominal voltage are considered as standardized voltage-level variations for presenting the occurrence of voltage dips. For phase-ground voltages at the PCC, the exposed distances for different types of faults are summarized in Table 2.2. Single phase-to-ground fault has the longest exposed distance and three-phase fault has the shortest exposed distance to cause voltage dips with less than 90% of the nominal voltage.

Table 2.2: Exposed distance of faults leading to phase-dips with voltage levels according to the EN 50160 standard

Critical voltage	Exposed distance [km] from PCC for various faults			
	pgf	**ppf**	**2pgf**	**3pf**
u < 90%	>8.127	7.734	>8.127	6.515
u ≤ 80%	>8.127	5.814	>8.127	5.343
u ≤ 70%	>8.127	4.668	5.472	3.634
u ≤ 40%	>8.127	0	1.629	1.267
u ≤ 5%	5.182	0	0	0

In radial MV-networks with no distributed generation, voltage dip magnitudes can also be estimated from the short-circuit powers. If the short-circuit powers at the feeding busbar and other POCs are known, the voltage magnitudes at the PCC can be estimated from the fault levels using (2.4),

$$U_{pcc} = 1 - \frac{S_{sc,poc}}{S_{sc,pcc}} \tag{2.4}$$

where the short-circuit power ($S_{sc,poc}$) at any connection point, which depends on the nominal line-voltage (U_{nom}), the source impedance (Z_S), and the short-circuit fault impedance (Z_F), can be estimated by (2.5).

$$S_{sc,poc} = \frac{U_{nom}^2}{Z_s + Z_F} \tag{2.5}$$

With a three-phase fault at the PCC of the network considered here, the short-circuit power is estimated to be 707 MVA and the source impedance is 0.245 Ω. The variations of short-circuit power and network impedance with faults along the local feeder are shown in Figure 2.11. It can be observed that the short-circuit power gets its maximum value at the feeding station when the network impedance is minimum, and decreases along the feeder reaching minimum at the furthest end of the feeder when the network impedance is maximum. Table 2.3 gives the estimated magnitude of remaining voltages at the PCC calculated from short-circuit powers at the POCs along the local feeder.

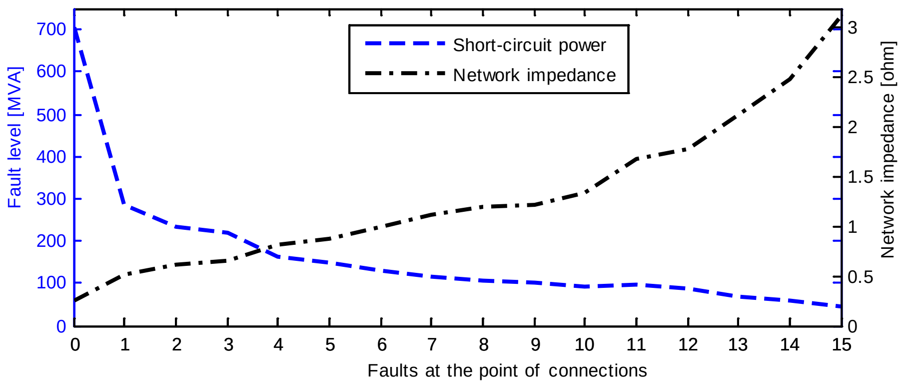


Figure 2.11: Short-circuit power and network impedance with three-phase faults at POCs along the local feeder.

Table 2.3: Dip magnitudes at the PCC from short-circuit powers of three-phase faults at various POCs

POC	Distance [km]	S_{SC} [MVA]	Z_F [Ω]	$Z_F + Z_S$ [Ω]	U_{dip} [%]
N_0	0.000	706.752	0.000	0.245	0
N_1	1.811	286.364	0.274	0.519	59
N_2	2.411	233.741	0.364	0.610	67
N_3	2.644	217.999	0.400	0.645	69
N_4	3.744	164.976	0.566	0.811	77
N_5	4.188	150.120	0.633	0.878	79
N_6	4.988	129.096	0.754	0.999	82
N_7	5.518	114.381	0.869	1.114	84
N_8	5.943	105.298	0.954	1.200	85
N_9	6.086	102.779	0.981	1.226	85
N_{10}	6.505	93.650	1.090	1.335	87
N_{11}	5.634	95.116	1.431	1.676	87
N_{12}	5.934	87.732	1.532	1.777	88
N_{13}	6.580	69.795	1.873	2.118	90
N_{14}	7.151	56.913	2.245	2.490	92
N_{15}	8.127	43.086	2.882	3.127	94

2.5.3 Transfer of voltage dips

Most end-users are in the LV-networks and they are connected to the MV-networks through Dyn transformers. The delta winding of such transformers block the zero-sequence component of the source impedance and this affects the transfer of voltage dips due to unbalanced faults. With a Dyn transformer between the MV- and LV-network, the phase-phase voltages in the MV-network transfer to phase-to-ground voltages in the LV-networks [21, 22].

For the network under consideration, variations of the remaining voltage magnitudes of the phase-to-ground voltages and phase-phase voltages as a function of the fault distance from the PCC are shown in Figure 2.12. One-phase faults occurring in the entire network cause deeper phase-dips but they are not seen as phase-phase dips. Moreover, the exposed distances with two-phase faults (phase-phase and double phase-ground faults) that lead to phase-phase dips at the PCC are smaller than the equivalent distance for phase-ground voltages. However, the exposed length of three-phase faults along the feeder resulting in phase-phase voltage dips is the same as the case for phase-dips. In contrast to the case for phase-dips, the exposed distance of multi-phase faults causing phase-phase dips at the PCC is the same.

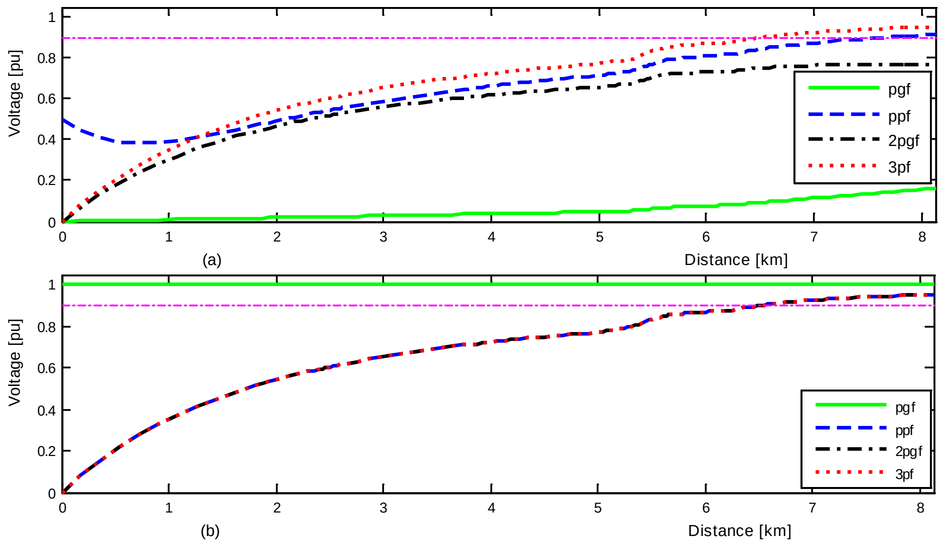


Figure 2.12: Variation of voltage magnitudes with fault location in the MV-network with isolated system grounding for – (a) phase-voltages, and (b) phase-phase voltages.

As compared to phase-dips (Table 2.2), the exposed distance of various types of faults resulting in different remaining voltage magnitudes is shown in Table 2.4 for the phase-phase dips at N_0. It should be recalled that the decrease in critical distance of unbalanced faults will attribute to the reduction in the expected number of phase-phase dips that end-users can see as phase-dips at their connection points.

Table 2.4: Exposed distance of faults leading to phase-phase dips with voltage levels according to the EN 50160 standard

Critical voltage	Exposed distance [km] from PCC for various faults			
	pgf	**ppf**	**2pgf**	**3pf**
u < 90%	0	6.515	6.515	6.515
u ≤ 80%	0	5.343	5.343	5.343
u ≤ 70%	0	3.634	3.634	3.634
u ≤ 40%	0	1.267	1.267	1.267
u ≤ 5%	0	0	0	0

2.5.4 Number of voltage dips

Once of the voltage dip exposed area from a POC is determined for a particular fault type, the number of terminals and cable joints, and the length of cables within the exposed area can be used to calculate the number of dips with a critical voltage u_{cr}. For a three-phase fault, for instance, the number of dips with the voltage magnitude below u_{cr} can be expressed by (2.6),

$$N_{u_{cr},3pf} = \frac{f_{d,3pf}}{100}\left(\sum_{c=1} \lambda_c l_{c(u_{cr},3pf)} + \sum_{t=1} \lambda_t T_{t(u_{cr},3pf)}\right) \tag{2.6}$$

where $N_{u_{cr},3pf}$ is the number of dips caused by three-phase faults and with magnitude below the critical voltage; $f_{d,3pf}$ is the fault distribution (share) of three-phase faults (%); λ_c is the failure rate of cables (-/yr/km); $l_{c(u_{cr},3pf)}$ is the exposed length of cable for three-phase fault and the critical voltage u_{cr} (km); λ_t is the failure rate for the terminals (or cable joints) (-/yr per component); $T_{t(u_{cr},3p)}$ is every terminal and cable joint exposed to three-phase faults and the critical voltage u_{cr}.. In the same way, the numbers of dips caused by single phase-to-ground, phase-to-phase and two phase-to-ground faults can be determined. The total number of dips with magnitude below the critical voltage and caused by all types of faults becomes

$$N_{u_{cr}} = N_{u_{cr},3pf} + N_{u_{cr},ppf} + N_{u_{cr},2pgf} + N_{u_{cr},pgf}. \tag{2.7}$$

The majority of faults in the Dutch distribution network occur due to ground digging, cable erection work and aging effects of the network components. The use of underground and relatively short cables in the Dutch distribution networks attribute to much lower failure frequency of network components than in most other European networks [23]. The average failure rates of cables and terminals used in the simulation are 0.0243/km/year and 0.012/year respectively [24]. Also, type I, type II and type III faults commonly occur in the Dutch distribution networks with the fault distributions of 50%, 25% and 25% respectively [4]. For estimating the annual frequency of voltage dips at a POC caused by short-circuit faults in the MV-network, the following points are taken into consideration:

- A voltage event is considered as a dip if the remaining voltage on any phase is below 90% of the nominal voltage and as interruption when the voltage in all phases is below 5% for a duration between ½ cycle and 1 minute [8, 9].

- Fault frequencies of 25-25-50% are used for three-phase, two-phase (phase-phase and two phase-to-ground) and one-phase faults [4].
- Same average failure rate of 0.0243/yr/km for all cables and same failure rate of 0.012/yr/component for all terminals and cable joints [24].
- Loads at all busbars are considered during the simulation of fault analysis.
- Only faults in the (isolated) MV-network with the secondary side of the HV/MV transformer connected in delta are considered in this simulation.

Based on computer simulations and using the fault position method, the number and distribution of phase-dips as compared to phase-phase dips at the feeding busbar is shown in Figure 2.13. Due to the fact that one-phase faults have larger exposed area than the other faults, a majority of the total phase-dips (58%) are one-phase dips. Moreover, about 60% of the phase-dips, mostly (~96%) caused by one-phase faults, are deeper with remaining voltages less than 50% of the nominal voltage. Two-phase and three-phase dips share 26% and 16% of the total phase-dips respectively. From Figure 2.13(b), it can be observed that the number of phase-phase dips is significantly lower than that of phase-dips. The reason for this is that phase-dips caused by one-phase faults are not seen as phase-phase dips in the MV networks. Besides, phase-phase dips caused by two-phase (phase-to-phase and two phase-to-ground) faults encompass shorter critical distance than the case for phase-dips.

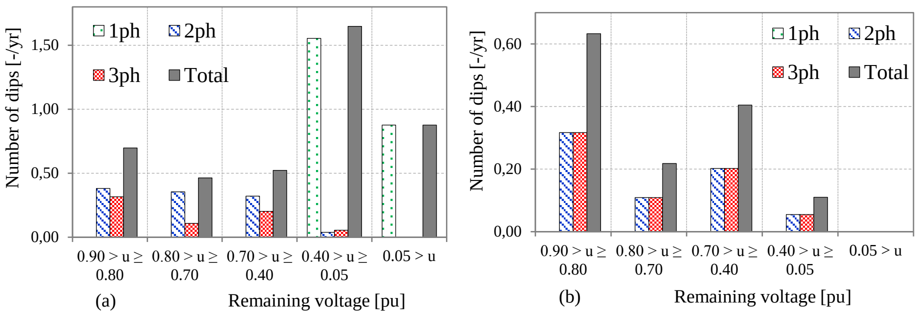


Figure 2.13: Distribution of voltage dips[2] frequency at the PCC for – (a) phase-dips, and (b) phase-phase dips.

2.6 Placement of monitoring systems

The actual quality of supply delivered to each customer may be evaluated if PQ monitors are permanently installed at every POCs. This can, however, incur substantial investments for the grid operator which may not be affordable for customers. Besides, the data handling problem is also an issue with monitors at each POCs. Thus, it is neither realistic nor economical for the grid operators to monitor voltage dips at every POCs. Therefore, computer simulations are performed to get better indication where the grid operators can install a PQ monitor so that sufficient overall information of the network can be obtained.

[2] *1ph, 2ph and 3ph → dips caused by one-phase, two-phase and three-phase faults respectively*

2.6.1 Optimal placement of monitors

For the network under study (Figure 2.10), the feeders are broadly grouped as local and neighboring feeders. On the local feeder, seven POCs at the busbars N_0, N_3, N_6, N_8, N_{10}, N_{13} and N_{15} are considered for the comparative study on monitoring dips. Depending on the point of observation, fault location and protection devices, short-circuit faults within the local feeder may lead to interruptions for some POCs and voltage dips for the others. In this particular case:

- Faults occurring between N_0 and N_6 of the local feeder may result in voltage dips to a POC at N_0 but they will cause interruptions to the other POCs downstream the local feeder.
- Faults occurring in either branch (below N_6) of the local feeder may lead to voltage dips for the POCs at N_0 through N_6 and POCs in the other branch, but POCs in the same branch where the faults occur will see interruptions cleared by the secondary protection.
- Faults occurring in the neighboring feeders may cause voltage dips at N_0 and the other POCs downstream the local feeder will experience these voltage dips.

Voltage dips originating from the HV-network can propagate to the MV-networks while dips from the LV-network are hardly experienced in the MV-network. In this comparative study, the number and distribution of voltage dips only originating from the MV-network and observed from seven POCs on the local feeder are estimated using the fault positions method. Based on computer simulations, the average numbers of voltage dips at the POCs estimated every year are shown in Figure 2.14. It can be seen that a monitor at N_0 (main busbar) sees the highest number of phase-dips but the lowest number of interruptions as compared to the other POCs downstream the local feeder. Between the two extreme POCs (N_0 and N_{15}), the number of phase-dips and phase-phase dips vary from 4.21–3.92 and 1.37–1.30 dips per year while the annual interruptions rise from 0 at N_0 to about 0.35 at N_{15}.

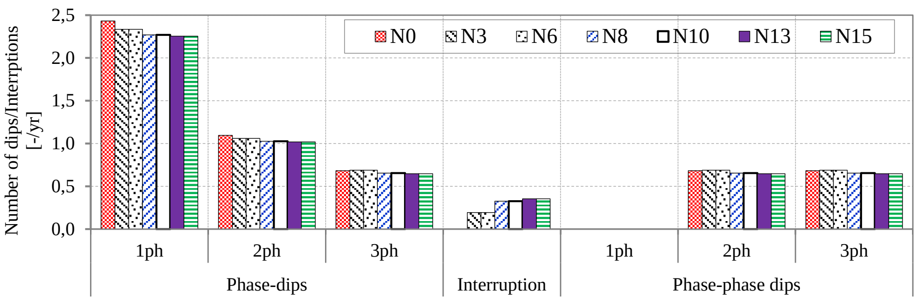


Figure 2.14: Average number of voltage dips and short interruptions at different POCs due to various faults.

For the assumed network structure (Figure 2.10), Figure 2.15 shows the share of local and neighboring feeders to the total number of dips at each POC. The majority of voltage dips at each POC originate from the neighboring feeders. For this particular case, about 90% of the voltage dips at N_0 are from the neighboring feeders, which are also seen at the other POCs downstream the local feeder. In this case, the feeder where the POCs are located generates maximum share to the number of voltage dips at N_0, and its contribution decreases in other POCs (e.g. 3% at N_{15}).

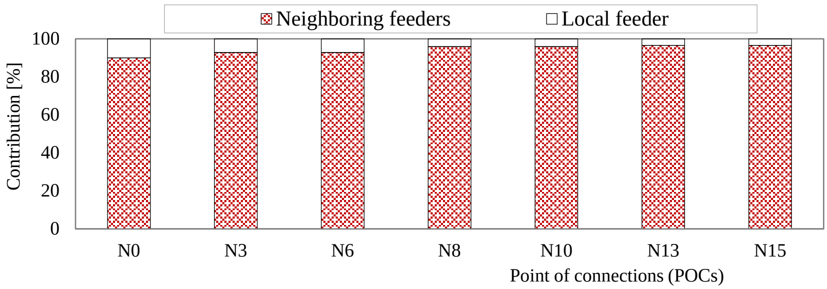


Figure 2.15: Share of local and neighboring feeders to the total number of voltage dips at different POCs.

Based on the comparative analysis, the main MV busbar, also recommended in [25], can be considered as the most appropriate monitoring location where grid operators can get better insight into all voltage dips at customers POCs connected to the same busbar. The monitor at N_0, however, records slightly overestimated number of (shallow) voltage dip events than it would see if it were installed at the POCs downstream the feeder. Because of the secondary protection, POCs downstream to N_0 may see a bit higher number of deeper dips with short duration caused by faults in the local feeder than N_0 can see.

Considering the magnitude and duration of voltage dips caused by different types of faults in the assumed MV-network, Table 2.5 and Table 2.6 show the annual dip profiles associated with phase-to-ground voltages and phase-phase voltages at the optimal monitoring location (N_0). About 60% of the total phase-dips (Table 2.5) have remaining voltages below 50% of the nominal voltage while about 54% of the dips have duration of the secondary protection. For phase-phase dips, the critical distances of two-phase and three-phase faults are the same and the same fault distributions are assumed in the simulation. Hence, the monitor at N_0 records equal numbers of voltage dips caused by two-phase and three-phase faults (Table 2.6). Due to the fact that multi-phase faults cover large areas within the primary protection, end-users connected close to N_0 experience relatively higher number of dips with long-duration (from primary protection) than dips with short-duration. Also, the short-dips due to faults cleared by the secondary protection are very shallow in magnitude (in this case u>80%).

Table 2.5: Voltage dips[3] density for phase-to-ground voltages at N_0 according to the EN 50160 standard

Remaining voltage [%]	**Duration, Δt [s]**												Tot.
	0.01 < Δt ≤ 0.2			*0.2 < Δt ≤ 0.5*			*0.5 < Δt ≤ 1*			*1 < Δt ≤ 60*			
	1ph	2ph	3ph	1ph	2ph	3ph	1ph	2ph	3ph	1ph	2ph	3ph	
90 > u ≥ 80	0	0	0	0.00	0.38	0.20	0.00	0.00	0.12	0	0	0	0.70
80 > u ≥ 70	0	0	0	0.00	0.23	0.00	0.00	0.12	0.11	0	0	0	0.46
70 > u ≥ 40	0	0	0	0.00	0.00	0.00	0.00	0.32	0.20	0	0	0	0.52
40 > u ≥ 5	0	0	0	1.47	0.00	0.00	0.09	0.04	0.06	0	0	0	1.65
5 > u	0	0	0	0.00	0.00	0.00	0.88	0.00	0.00	0	0	0	0.88
Total	0	0	0	1.47	0.61	0.20	0.97	0.48	0.48	0	0	0	**4.21**

[3] *1ph, 2ph, 3ph represent for dips in one-, two- and three phase-ground voltages.*

Table 2.6: Voltage dips[4] density for phase-phase voltages at N_0 according to the EN 50160 standard

Remaining voltage [%]	Duration, Δt [s]												Tot.
	$0.01 < \Delta t \leq 0.2$			$0.2 < \Delta t \leq 0.5$			$0.5 < \Delta t \leq 1$			$1 < \Delta t \leq 60$			
	L_{001}	L_{011}	L_{111}	L_{001}	L_{011}	L_{111}	L_{001}	L_{011}	L_{111}	L_{001}	L_{011}	L_{111}	
$90 > u \geq 80$	0	0	0	0.00	0.20	0.20	0.00	0.12	0.12	0	0	0	0.63
$80 > u \geq 70$	0	0	0	0.00	0.00	0.00	0.00	0.11	0.11	0	0	0	0.22
$70 > u \geq 40$	0	0	0	0.00	0.00	0.00	0.00	0.20	0.20	0	0	0	0.40
$40 > u \geq 5$	0	0	0	0.00	0.00	0.00	0.00	0.06	0.06	0	0	0	0.11
$5 > u$	0	0	0	0.00	0.00	0.00	0.00	0.00	0.00	0	0	0	0.00
Total	0	0	0	0.00	0.20	0.20	0.00	0.48	0.48	0	0	0	**1.37**

2.6.2 Impact of critical distance on monitoring

Critical distance (d_{cr}) is the maximum distance of a fault from the PCC that results in the upper threshold magnitude of a dip (U_{UT}). For balanced faults, the critical distance can be easily derived from the voltage divider model [1] and expressed by (2.8),

$$d_{cr} = \frac{Z_s}{z}\left(\frac{U_{cr}}{1-U_{cr}}\right) \tag{2.8}$$

where Z_s is the source impedance at the PCC, z is the per unit length impedance of the cable, and U_{cr} is the critical voltage under consideration. For unbalanced faults, the voltage expressions of each phase involve symmetrical components of the impedances and have different values when faults occur at certain distance from the PCC. In this work, the critical distance with unbalanced faults are evaluated using the iteration approach applied on the total distance of the feeder at a step size of 10%. Considering 90% of the nominal voltage as the upper threshold of voltage dips, it can be seen from Table 2.7 that various faults occurring along the local feeder (Figure 2.10) have different critical distances.

For the network considered here, a monitor at the PCC which is the most optimal place for monitoring voltage dips can miss recording voltage dips when faults occur far away from the critical distances shown in Table 2.7. In this case, phase-dips caused by single phase-to-ground and two phase-to-ground faults occurring in the entire network can be seen by the monitor at N_0 while the monitor misses some of the dips due to three-phase and phase-to-phase faults. On the other hand, the monitor at the PCC misses part of the phase-phase dips by all faults except single phase-to-ground faults. The “missing dips” can be estimated from the information about length of cables beyond the critical distance and voltage dips monitored within the critical distance.

Table 2.7: Critical distances of faults along the feeder from the PCC

	Phase-dips				Phase-phase dips			
	pgf	ppf	2pgf	3pf	pgf	ppf	2pgf	3pf
Critical distance [km]	>8.127	7.734	>8.127	6.515	0	6.515	6.515	6.515

Let ‘L_{cr}’ be the critical length encompassing ‘T_{cr}’ terminals and cable junctions for a particular type of fault, and the monitor sees annual dips of D_{cr}. If the monitor at N_0 would

[4] *L_{001}, L_{011}, L_{111} represent for dips in one-, two- and three phase-phase voltages.*

see all dips caused by the fault occurring along the total length 'L' of the feeder, the expected amount of voltage dips would be approximated by (2.9),

$$D_{\exp} = \frac{L}{L_{cr}} D_{cr} \tag{2.9}$$

and the number of 'missing dips' (D_{miss}) beyond the critical distance of the fault can estimated by (2.10)

$$D_{miss} = D_{cr}\left(\frac{L}{L_{cr}} - 1\right). \tag{2.10}$$

For the network structure considered here (Figure 2.10), the variations in the number of shallow (u>50%) and deeper (u≤50%) dips within the critical distances associated with phase-to-ground voltages and phase-phase voltages between the two extreme POCs (N_0 and N_{15}) are given in Table 2.8. It can be seen that a monitor at N_0 records 4.21 phase-dips and 1.37 phase-phase dips per year caused by various types of faults occurring in the MV-network within their respective critical distances indicated in Table 2.7. Using (2.9), it is estimated that a total of 4.44 phase-dips and 1.70 phase-phase dips could have been recorded by the monitor at N_0 if the dips caused by all types of faults occurring in the entire network were supposed to be seen by a single monitor placed at the PCC. This implies that about 95% of phase-dips and 81% of phase-phase dips of the entire network can be seen by the monitor at N_0, i.e. the monitor at N_0 misses about 5% of phase-dips and 19% of phase-phase dips because of the critical distances.

Table 2.8: Variation of shallow and deeper dips between N_0 and N_{15}

	N_0								N_{15}							
	Phase-dips				Phase-phase dips				Phase-dips				Phase-phase dips			
	1ph	*2ph*	*3ph*	*Tot*	L_{001}	L_{011}	L_{111}	*Tot*	*1ph*	*2ph*	*3ph*	*Tot*	L_{001}	L_{011}	L_{111}	*Tot*
Shallow	0.00	0.90	0.53	1.42	0.00	0.53	0.53	1.05	0.00	0.81	0.47	1.29	0.00	0.47	0.47	0.95
Deep	2.43	0.20	0.16	2.79	0.00	0.16	0.16	0.31	2.26	0.20	0.17	2.63	0.00	0.17	0.17	0.35
Total	2.43	1.10	0.68	**4.21**	0.00	0.68	0.68	**1.37**	2.26	1.02	0.65	**3.92**	0.00	0.65	0.65	**1.30**

It is also observed (in Table 2.8) that the total number of dips decreases while the ratio of deeper to total dips increases from the point of observations at N_0 through N_{15}. Although the monitor at N_0 overestimates shallow dips for downstream customers, deeper dips which are not seen by the monitor at N_0 but experienced by other POCs downstream the feeder are important as they can cause serious PQ problems to downstream customers. From POC at N_0 through N_{15}, 66–67% of phase-dips and 23–27%% of phase-phase dips are found to be deeper. From this perspective, the monitor at N_0 is expected to miss about 3.5% of deeper phase-dips and 5.2% of deeper phase-phase dips that could cause significant PQ problem to the most downstream customers in each feeder.

2.7 Effects of network modifications

2.7.1 Effect of secondary protections

In the previous discussions, primary and secondary protections with fault clearing settings of 600 ms and 300 ms are considered in all feeders. If only primary protections devices with fault clearance time of 300 ms were used, the frequency and severity of voltage-dips is affected. Table 2.9 shows comparison of the two cases.

Table 2.9: Effect of secondary protection over using only primary protection on the number of phase-dips (ph.), phase-phase (p-p) dips and short-interruptions

	(a) Primary + Secondary protection							(b) Only primary protection						
	$0.2<\Delta t\leq 0.5$ s		$0.5<\Delta t\leq 1$ s		Total dips			$0.2<\Delta t\leq 0.5$ s		$0.5<\Delta t\leq 1$ s		Total dips		
POC	*ph.*	*p-p*	*ph.*	*p-p*	*ph.*	*p-p*	Total inter.	*ph.*	*p-p*	*ph.*	*p-p*	*ph.*	*p-p*	Total inter.
N_0	2.28	0.40	1.93	0.97	4.21	1.37	0.00	4.21	1.37	0.00	0.00	4.21	1.37	0.00
N_3	2.34	0.51	1.74	0.87	4.08	1.38	0.19	3.79	1.23	0.00	0.00	3.79	1.23	0.49
N_6	2.34	0.51	1.74	0.87	4.08	1.38	0.19	3.79	1.23	0.00	0.00	3.79	1.23	0.49
N_8	2.21	0.44	1.74	0.87	3.95	1.31	0.33	3.79	1.23	0.00	0.00	3.79	1.23	0.49
N_{10}	2.21	0.44	1.74	0.87	3.95	1.31	0.33	3.79	1.23	0.00	0.00	3.79	1.23	0.49
N_{13}	2.18	0.43	1.74	0.87	3.92	1.30	0.35	3.79	1.23	0.00	0.00	3.79	1.23	0.49
N_{15}	2.18	0.43	1.74	0.87	3.92	1.30	0.35	3.79	1.23	0.00	0.00	3.79	1.23	0.49

According to Table 2.9, the total number of (phase and phase-phase) dips for a POC at N_0 is not affected if only primary protections or primary with secondary protections are used. However, using secondary protections introduce some voltage dips with long-duration and customers will experience more severe (longer) dips. Besides, other POCs downstream of N_0 would experience relatively higher number of voltage dips when secondary protections are used, with some of the dips even longer and hence more severe, than the case when only primary protections are used. In other words, the total number dips and their duration will be reduced for a POC downstream of N_0 when only primary protections are used. However, the customers connected to the POCs downstream of N_0 will experience more interruptions than the case when secondary protections are used. When secondary protections are used rather than only primary protections, the monitor at N_0, for this particular case, would overestimate the number of phase-dips and phase-phase dips for other POCs downstream of N_0 by about 10% and 8% respectively.

2.7.2 Effect of current limiting coils

Coil reactors are sometimes considered with new installations for limiting the fault currents. In the MV-networks, the coils are commonly mounted at the beginning of the feeders. For the network discussed previously, a coil with impedance of 0.42 Ω (2.8%) is considered at the beginning of each feeder and the short-circuit power at different POCs is calculated using formula (2.5) where the fault impedance now encompasses impedance of the coil. As can be seen in Figure 2.16, the short-circuit power at a point just after the coil and at each POC decreases when the coil is used. This will affect the depth and number of voltage dips. Unlike the farthest POC, the fault impedance at the POCs very close to the PCC is significantly affected by the coil resulting in the substantial reduction of the short-circuit power (up to 63%).

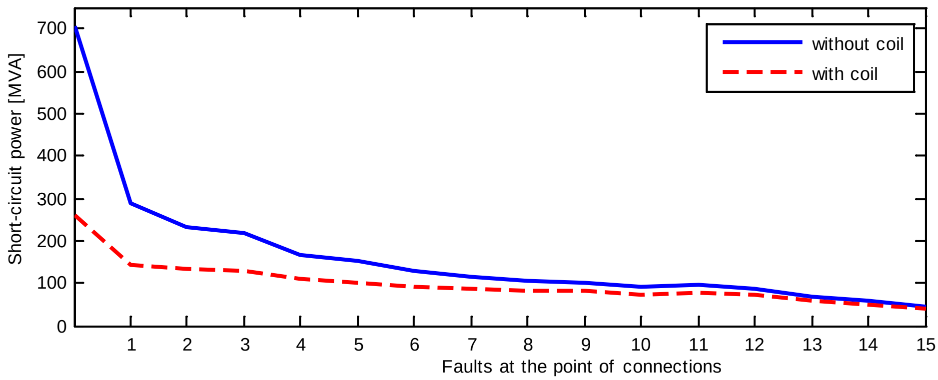


Figure 2.16: Effects of coil on the short-circuit powers with three-phase faults at different POCs.

According to Figure 2.17, the critical distance of faults is slightly shorter when the fault-current limiting coil is used than the case without coils. As a result, the remaining voltages for some of the dips before using the coil become above the dip threshold. Besides, the coil significantly improves the remaining voltage magnitudes even with faults closer to the PCC and this reduces the severity of voltage dips. Table 2.10 provides better insight into the effect of the coil on the number and depth (severity) of voltage dips for POCs at N_0 and N_{15}. In this work, the introduction of the coil reduced the number of phase-dips and phase-phase dips at the POCs by about 12% and 17% respectively. Moreover, almost all the phase-phase dips at N_0, which are experienced by most end-users, and more than 94% of the phase-phase dips at N_{15} become shallow dips (i.e. with remaining voltage above 50% of nominal voltage).

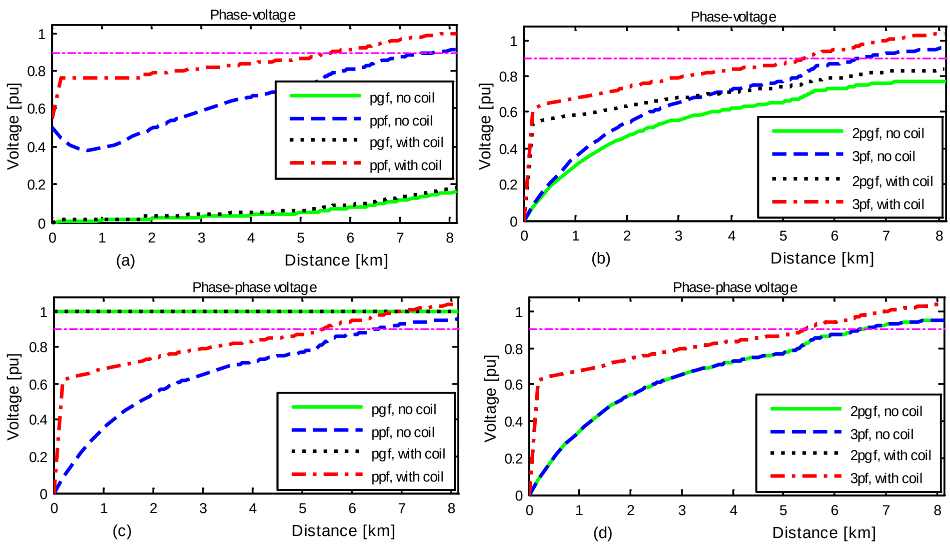


Figure 2.17: (Most affected) Phase-to-ground and phase-phase voltages at the PCC during various faults along the local feeder without and with a coil.

Table 2.10: Effect of coil on the number and depth of phase-dips and phase-phase (ph-ph) dips at N_0 and N_{15}

	N_0						N_{15}					
	Without coil			*With coil*			*Without coil*			*With coil*		
	Total	Shallow	Deep	Total	Shallow	Deep	Total	Shallow	Deep	Total	Shallow	Deep
Phase-dips	4.21	34%	66%	3.70	39%	61%	3.92	33%	67%	3.46	38%	62%
Ph-ph dips	1.37	77%	23%	1.14	100%	0%	1.30	73%	27%	1.09	94%	6%

Studies show that 3–5% impedance reactor eliminates about 95–99% of nuisance trips [26], and the estimated cost of line reactors for MV-network application ranges from €22,500–€75,000 [27]. Although there is little difficulty to accommodate reactors in new installations, finding a room and making the necessary connections could be the setback with existing installations.

2.7.3 Effect of distributed generation

Nowadays, the share of grid-connected distributed generators (DGs), such as wind turbines and compact heat and power (CHP) plants, is increasing because of the growing interest in environmental issues together with the advancement of technologies to connect renewable energy sources to the grid and the liberalization of the energy market. In spite of the growing number of distributed-generation (DG) units, their contribution of power delivered to the grid remains small as compared to the power injected by the large centralized power plants [28, 29]. Voltage dip ride-through capabilities are required by the grid operator to alleviate the stressing behavior of DG units on the grid [30, 31], which may cause power unbalance leading to instability. For generating plants to be connected to the LV- and MV-networks, the voltage ride-through requirements are defined in the new (draft) standards EN 50549-1/2 [32, 33].

Recently, DG units have been used for reducing the frequency of interruptions and mitigating the severity of voltage dips. To study the effect of DG on voltage dips, DG units of 1.38 MW is considered at each busbar N_{10}. The effect of DG on voltage dips mainly depends on the position of the DG units and the power generation capacity of the DG units. The contribution to the supply of DG units can be expressed in terms of penetration level given by formula (2.11) [34],

$$\%DG_{PL} = \frac{P_{DG}}{P_{DG} + P_{CG}} \times 100 \tag{2.11}$$

where DG_{PL} is the penetration level of DG-units, P_{DG} is the total power of DG-units and P_{CG} is the power of the central unit supplied through the HV/MV transformer. In spite of the positive impact that DG is considered to have on voltage dips, the presence of DG in the network comes with a number of concerning issues- protections issues, such as blinding of protection, false tripping of network of network protection, unnecessary tripping of distributed generators protection and difficulties in fault localization procedure [12]. In this work, these issues as well as the voltage dips ride-through capability of the DG units are not taken into consideration, and a simplified analysis of the impact of DG on voltage dips is performed.

Figure 2.18 shows the fault levels due to balanced faults at different POCs without and with the DG-units (for DG_{PL}=10.3%). It can be seen that the short-circuit powers at the POCs are higher with the DG-units as compared to the case without DG. As can be seen from Figure 2.19, the presence of DG units improves the voltage levels observed at the main MV busbar. With DG, the critical distances of faults are reduced from the case without DG units, and some of the remaining voltages become above the dip threshold.

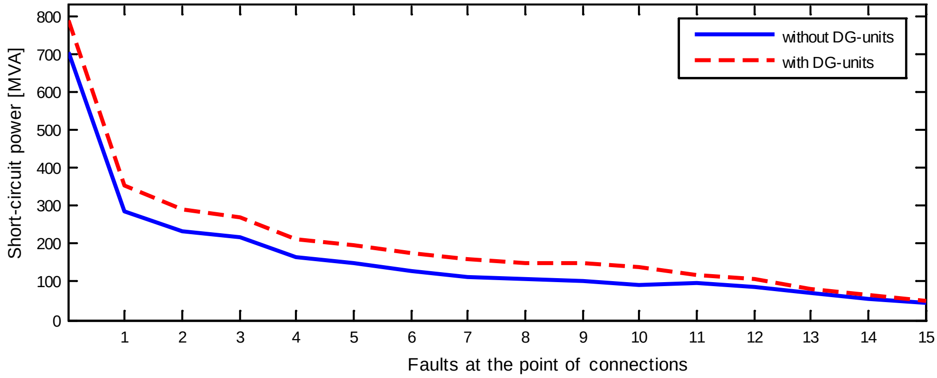


Figure 2.18: Effects of DG-units on short-circuit powers with three-phase faults at different POCs.

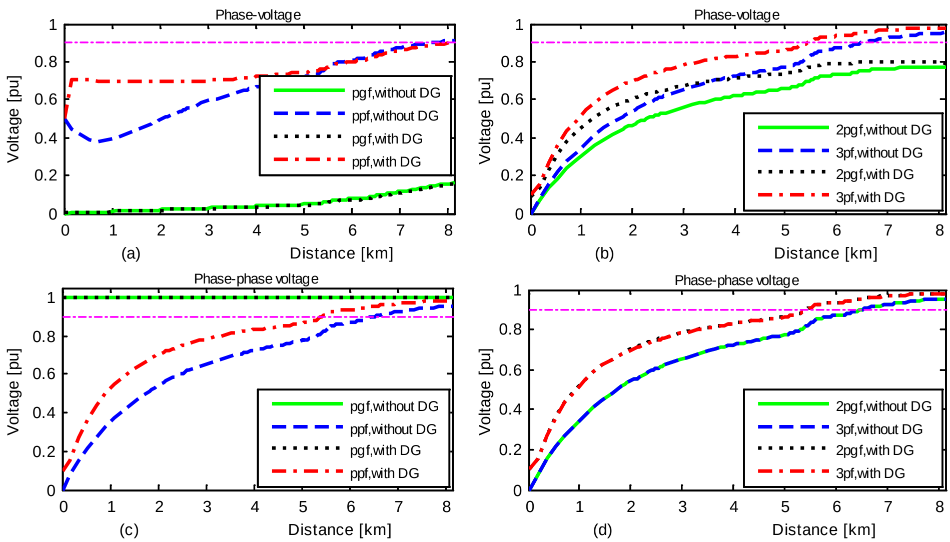


Figure 2.19: (Most affected) Phase-to-ground and phase-phase voltages at the PCC during various faults along the local feeder without and with DG-units.

The effect of DGs on the number and depth (severity) of voltage dips at N_0 and N_{15} are summarized in Table 2.11. Using DG reduces the total number of phase-phase dips, which are seen by most end-users, at N_0 and N_{15} from 1.37 and 1.30 to 0.62 and 0.36 dips per year- a reduction by 54% and 61% respectively. Moreover, deeper phase-phase dips at N_0 and N_{15} are reduced by 61% and 70%. The closer the DG-unit to a POC, the higher is its impact in reducing the number and severity of voltage dips.

Table 2.11: Effect of DG-units on the number and depth of phase-dips and phase-phase (ph-ph) dips at N_0 and N_{15}

	N_0						N_{15}					
	Without DG			*With DG*			*Without DG*			*With DG*		
	Total	Shallow	Deep	Total	Shallow	Deep	Total	Shallow	Deep	Total	Shallow	Deep
Phase-dips	1.42	2.79	4.21	0.98	2.57	3.55	1.29	2.63	3.92	0.77	2.37	3.14
Ph-ph dips	1.05	0.31	1.37	0.50	0.12	0.62	0.95	0.35	1.30	0.26	0.11	0.36

2.8 Summary

In this chapter, the stochastic approach of voltage dips estimation using computer simulations is discussed. For a generic MV-network consisting of 10 feeders, the numbers of voltage dips that can be seen at different POCs of a feeder are estimated using the fault positions method. The expected number of voltage dips at a POC depends on several network parameters (including the number of outgoing feeders from the main substation, length and type of feeder cables, number of busbars and cable junctions, failure rate of network components (such as cables, terminals and cable junctions), system grounding topology, protection philosophy and type of MV/LV transformer), and fault statistics (type of faults and their distribution of occurrence). The overall accuracy of the prediction, therefore, relies on the correctness of input data of the network model and assumptions made about the reliability of network components.

Based on the estimated voltage dips observed from several POCs, comparative results showed that a PQ-meter at the main MV busbar can see relatively higher number of voltage dips than at any other POCs of the feeder. From this point of view, the main busbar can be considered as the most optimal location for monitoring voltage dips in the MV-networks. However, this monitor can miss recording some events caused by short-circuit faults occurring at locations farther away from the critical distances. For the typical network considered, it is showed that a monitor at the main busbar can miss about 5% deeper phase-phase dips that could cause serious PQ problems to the customers connected to the most downstream POC.

To analyze the effect of network modifications- such as change of protection schemes, application of coils, and distributed generators, the estimation approach is extended for the typical generic MV-network. The use of a secondary protection will increase the number and severity of voltage dips but it will decrease the number of interruptions for POCs along the feeder. In the analyzed network, the use of DGs (with 10.3% penetration levels) in each feeder at a particular POC far from the main substation reduced the number of phase-phase dips at various POCs by about 55%–72%. Besides, the use of DGs reduced the severity (depth) of voltage dips. On the other hand, using current limiting coils (with 2.8% impedance) has reduced the number of phase-phase dips at different POCs by about 16%–17% and significantly lessened the severity of phase-phase dips. In all cases, a PQ-meter at the main MV busbar sees relatively higher number of voltage dips than at other POCs downstream the feeder. Location of the most optimal PQ-meter placement for monitoring voltage dips in the MV-networks is, therefore, not affected by the change of such network modifications.

3

Statistical assessment of voltage dips

3.1 Introduction

Power quality monitoring (PQM) is the process of gathering, analyzing, and interpreting raw measurement data into useful information. PQM programs are often driven by the demand for improving the system-wide power quality performance. Many industrial and commercial customers often have equipment that are sensitive to power disturbances, and, therefore, it is more important to understand the quality of power being provided. PQM helps the network operators to obtain more information about the overall quality of the supply at different voltage levels. In order to provide the customers with sufficient voltage quality, it is important the grid operators measure more data continuously for long periods and know more about the quality of the supply. Besides, monitoring is very crucial to provide the customers and regulatory agencies with information on actual power quality levels.

Voltage dip is considered as a very important PQ issue because it can lead to the trip or malfunction of sensitive equipment especially in industrial process installations and subsequently it can lead to high costs. Customers can protect their processes with the required mitigation techniques to reduce the expected economic damages caused by voltage dips but they should know about the frequency and characteristics of the dips at their connection points. Monitoring voltage events, therefore, is a crucial step in the process of assessing raw measurement data into useful information and analyzing the quality of supply voltage. The measurement based voltage dip performance evaluation of electric networks, which is also called statistical or deterministic method, is achieved by installing PQ tools in the networks often for continuous monitoring. In recent years, there has been a noticeable increase of PQ monitoring in the power systems in which detection, classification and characterization of voltage dips are crucial requirements for quantifying the monitored data.

This chapter deals with data assessment for extracting more information from large voltage dip monitoring databases in the Dutch MV-networks. An important step to this end is the characterization of voltage events (a set of voltage waveforms with high time resolution) that provides sufficient information for representing and classifying voltage dips in three-phase systems. Even though the assessment technique has existed for many years, different methods of aggregation are described for representing multiple-dip events by a single dip for customer reports or regulatory purpose and different types of dips are treated separately in this thesis. Besides, the obtained results are also needed in the succeeding chapters. In the analysis, the transfer of voltage dips from the MV-network to the LV-networks is considered for obtaining voltage dip profiles at the monitoring locations and at the customers POCs. To deliver more reliable dip information for end-users, measuring and reporting approaches are described.

3.2 Overview of previous works

3.2.1 Voltage dip parameters

As defined in several PQ standards [6, 8, 9, 35-41] , a voltage dip is the temporary reduction in the RMS voltage below a specified threshold followed by its quick recovery. It can be caused by the inrush current during the connection of heavy loads and power transformers, but it is mostly due to short-circuit faults occurring in the electricity network [13, 42]. In most PQ standards, a voltage dip is described as a two-dimensional electromagnetic disturbance the level of which is determined based on two parameters-magnitude and duration.

The magnitude refers to the remaining voltage between the upper and lower threshold values defined in the standards [8, 9, 36]. In the standards EN 50160 [8] and IEEE 1159 [36], 90% of the reference voltage is considered as the upper dip threshold. According to the standard IEC 61000-2-8 [9], typical values between 85–95% of the reference voltage can be considered as the upper dip threshold. In fact, the voltage dip thresholds can be different for different purposes. For monitoring purposes, for instance, upper threshold values are usually in the range of 85–95% (mostly 90%) of the nominal voltage [43], while the value can be as low as 70% of the nominal voltage for contractual purposes [44]. With regard to the lower dip threshold, 10% of the nominal voltage is used in the IEEE 1159 standard. Depending on the type of system (one-phase or three-phase), 5% of the nominal voltage or below this value is regarded in the standards EN 50160 and IEC 61000-2-8 as the lower dip threshold and this defines a voltage dip from interruption.

The dip duration is determined by the moments of dip start threshold and dip end threshold. The standards EN 50160 and IEEE 1159 define the same values for the dip start and dip end thresholds as the dip upper threshold (i.e., 90% of the reference). In the standard IEC 61000-2-8, the upper dip threshold is considered as the voltage dip start threshold and the same value as the start threshold or 1% above the start threshold is considered for the dip end threshold depending on the application of definition. In all PQ standards, a voltage event is qualified to a dip when the remaining voltage magnitude is between the upper and lower thresholds during a period of ½ cycle to 1 minute.

For polyphase voltage dips, phase and time aggregations are recommended in the standards [8, 9] to prevent dips due to the same root cause from being counted more than once. The standards often consider the lowest-magnitude and total-duration for evaluating the frequency of voltage dips occurrence over a certain period of time and for presenting statistical measurement results for the regulatory purposes. In this way, single-phase and three-phase balanced voltage dips can be characterized effectively but it fails to characterize unbalanced voltage dips without loss of information. From equipment point of view, there will be no relation– that is, single-phase equipment will respond according to the actual voltage of the phase to which it is connected while three-phase equipment will respond with regards to all three phase voltages, not just to the minimum one. In spite of the fact that behavior of certain equipment can be influenced by other characteristics of voltage dips (such as point-on-wave dip initiation, phase shift, dip shape), they are not considered in the standards as the possible additional voltage dip parameters.

3.2.2 Existing voltage dip classification methods

Depending on the characteristics of phase-voltages and their description in a three-phase system, voltage dips can be classified in different ways. The presence of symmetry, the number of phases being affected by the dip, the change of magnitude and phase-angles, magnitude and duration of the dips have been considered in several literatures [1, 8, 9, 14, 15, 35, 36, 41, 45] as the defining parameters for classifying voltage dips.

3.2.2.1 Classification based on symmetry

In a three-phase system, all three phase voltages are usually measured and used for characterization regardless of the number of phases that experience the voltage reduction. From this information, voltage dips can be broadly classified as:

- *Symmetrical three-phase voltage dips*- originate from symmetrical three-phase faults and have equal voltage magnitude in the simultaneously faulted phases.
- *Asymmetrical three-phase voltage dips*- with at least one faulted RMS phase voltage different from the other two faulted or fault-free RMS phase voltages.

3.2.2.2 Classification based on number of affected phases

This classification approach considers the actual number of phases involving the reduction of RMS voltage during the dip event. Accordingly, voltage dips can be classified as:

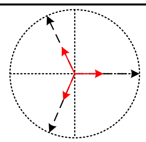
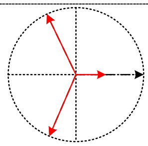
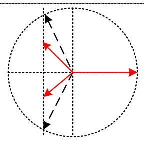
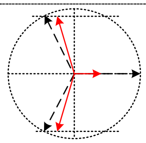
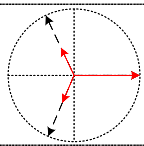
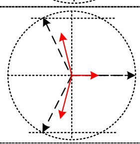
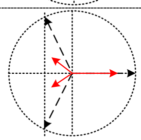
- *Single-phase dips*- when one-phase RMS voltage magnitude is below the dip threshold while the other two have phases RMS voltage magnitudes above the dip threshold limit.
- *Two-phase dips*- when two-phases have RMS voltage magnitudes below the dip threshold while the third phase has magnitude above the dip threshold limit.
- *Three-phase dips*- when all phases have RMS voltage magnitudes below the dip threshold magnitudes.

Depending on the value of the RMS voltage magnitudes, polyphase dips can be further categorized as symmetrical (two-phase, three-phase) and asymmetrical (two-phase, three-phase) voltage dips. In the general case, three-phase voltage magnitudes are necessary for the description of dip types in this method. This classification provides better information than the former, and the approach is widely used in practice.

3.2.2.3 Classification based on complex phase voltages

Instead of using the RMS phase-voltage values, complex phase voltages (magnitude and phase-angles) are used in [1, 14] to characterize voltage dips caused by short-circuit faults. Considering the four basic types of faults (single phase-to-ground, two phase-to-ground, phase-phase and three phase), type of winding connections of transformers between the load and fault points, voltage dips are classified into seven (A-G) types which are summarized in Table 3.1.

Table 3.1: Voltage dip classification with regards to complex phase voltages [1, 14]

Type of dip		Description of voltage dip	Origin	Change through transformer		
				$Y_N y_n$	Yy, Dd, Dz	Yd, Dy, Yz
A		Voltage magnitudes of all the three phases are equal and lower than the dip threshold limit. *No phase shift*	Three-phase fault	A	A	A
B		Voltage magnitude of one phase is lower than the dip threshold while the other two phases have equal voltage magnitudes higher than the dip threshold limit. *No phase shift*	Single phase–to-ground fault in solidly grounded network	B	D	C
C		Voltage magnitudes of two phases are equal and less than the dip threshold while voltage magnitude of the third phase is higher than the dip threshold limit. *Two affected phases experience phase-shift that moves them toward each other.*	Phase-to-phase fault, or Propagation of single phase-to-ground fault	C	C	D
D		Two phases have equal and higher voltage magnitudes than the third phase but lower than dip threshold limit. *Phases with higher voltage magnitudes experience phase-shift that moves them away from each other.*	Propagation of either single-phase fault, or phase-phase fault	D	D	C
E		Voltage magnitudes of two phases are equal and lower than the dip threshold while the third phase has higher than dip threshold limit. *No phase shift*	Two phase-to-ground fault	E	G	F
F		Similar to dip type 'D' but magnitudes in the less affected phases are deeper in type 'F' than dip type 'D'.	Propagation of two phase-to-ground fault	F	F	G
G		Similar to type 'C' but magnitude in the fault-free phase is higher than the faulted phases and lower than the dip threshold limit.	Propagation of two phase-to-ground fault	G	G	F

This classification is an extension of the second classification with the inclusion of voltage phase-angles. Type A can be related to a symmetrical three-phase dip while types D, F, G correspond to asymmetrical three three-phase dips with phase-shift in two phases and having equal magnitude. Similarly, symmetrical two-phase dip corresponds to type E when no phase-shift and to type C with phase-shift. Dip type pairs D/F and C/G are so similar and their distinction from the recordings in actual power systems would be difficult without further knowledge about the fault types that caused them. This method is suitable to describe the propagation of voltage dips through transformers and for equipment testing. However, it is not recommended for characterization of voltage dips from recorded waveforms.

3.2.2.4 Classification based on magnitude

According to the CIGRE/CIRED/UIE JWG C4.110 [2, 46], voltage dips that may occur at the terminals of sensitive equipment are classified in to three as:

- *Type I*- when there is a major drop in voltage magnitude in one of the three phase-to-ground voltages, and no drop or a much lesser drop in the other two phases,
- *Type II*- when there is a major drop in magnitude of two of the three phase-to-ground voltages, and no drop or a much less drop in the other one,
- *Type III*- when the there is almost identical drop in magnitude of all three phase-to-ground voltages.

This classification is a reduced form of the preceding classification by considering the number of most affected magnitudes of the three phase-to-ground voltages at the equipment terminals. Single phase-to-ground fault or unbalanced three-phase faults can cause a higher drop in magnitude on one phase, and dip types B/D/F are related to Type I. Dip types C/E/G involve much higher drop in two phases which can be related to Type II while Type A is basically associated with Type III. According to this classification, associated phase-angles can also be considered to fully describe the characteristic voltages of the three dip types in terms of magnitude and phase-angle (Figure 3.1). As this classification approach relies basically on magnitude, the variation in magnitude values will account for the counting and presentation of events. However, the same type of dips may have different severity and implication to end-users. For instance, Type I dip from single-phase fault and Type I dip due to unbalanced three-phase fault may be represented the same, in terms of the most affected magnitude phase voltage, while their severity and impact on end-users could be different. If measurement is also performed in the MV-networks, a Type I dip in high impedance grounded (or isolated) system may be quantified as more severe dip than Type III/II dip. However, a customer behind Dy transformer experiences severe dips of the latter case. In all of the previous classification methods, variations in values of dip durations, which are important for reporting the quality of supply, are not explicitly considered.

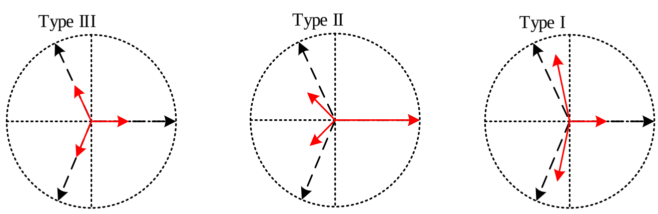


Figure 3.1: Phasor diagram of the three voltage dip types [2, 46].

3.2.2.5 Classification based on duration

Considering the impact on the voltage during fault conditions, the IEEE 1159 Std [36] categorizes voltage dips as instantaneous, momentary and temporary based on the duration. These are defined as:

- *Instantaneous dips*- when the duration ranges from ½ cycle to 30 cycles,
- *Momentary dips*- when the dip duration is in the range of 30 cycles to 3 s, and
- *Temporary dips*- when the dip duration is between 3 s – 1 min.

This is a general classification of dips that considers none of the dip parameters are changing in time. Different duration ranges for counting and presenting the dips can be easily attached to each particular dip type but variations in dip magnitudes are not considered in this classification.

3.2.2.6 Classification based on minimum magnitude-total duration

This considers magnitude of the phase with the lowest RMS voltage during the dip and total duration of the dip regarding to all affected phases for classifying voltage dips. This approach is widely used in most standards. Voltage dip magnitude and durations are simply divided in to several ranges, usually assembled in tabular forms for inputting the number of occurrence related to the dip types. This classification approach is applicable for comparing, benchmarking, and statistical reporting of system dip performances. Table 3.2 is an example of such classification used in the standard EN 50160 [8]. It provides standardized classification of voltage dips for evaluating and presentation of measurement data collected throughout Europe. With small variations in magnitude and/or duration ranges, similar classifications of voltage dips, in terms of the lowest-magnitude and total-duration, are also used in the IEC 61000-2-8 [9], IEEE Std [35], and NRS 048-2 [47].

Table 3.2: Voltage dip classification based on dip magnitude and duration according to the EN 50160 standard [8]

Remaining voltage [%]	**Duration [s]**				
	$0.01 \le \Delta t \le 0.2$	$0.2 < \Delta t \le 0.5$	$0.5 < \Delta t \le 1$	$1 < \Delta t \le 5$	$5 < \Delta t \le 60$
$90 > u \ge 80$	A_1	A_2	A_3	A_4	A_5
$80 > u \ge 70$	B_1	B_2	B_3	B_4	B_5
$70 > u \ge 40$	C_1	C_2	C_3	C_4	C_5
$40 > u \ge 5$	D_1	D_2	D_3	D_4	D_5
$5 > u$	X_1	X_2	X_3	X_4	X_5

Although this classification is simple and widely used for providing useful information about the system voltage dip performance, it lacks to deliver further information about the dip type, magnitude and duration values of all phases with polyphase dips. With regard to end-user equipment, the equipment sensitivity can be overestimated due to the use of the minimum-magnitude and total-duration approach. Besides, additional information, like phase-shift during the dip and actual shape of dips are not included.

3.3 Monitoring devices and measured data

System performance analysis is usually an issue for a network operator. To deal with the growing pressure from customers and regulatory agencies to provide information on the actual power quality levels, the network operators have to be aware of the quality of supply in the networks. The use of PQ monitors, installed in the electric power systems, have enabled network operators to get more information about the voltage quality in the grid and to provide appropriate information to the customers. Nowadays, different PQ monitors are available for this purpose. Some PQ monitors measure RMS values while others record digitalized waveforms of voltage and current signals sampled at high frequency.

The guidelines by CEER [25] and CIGRE/CIRED [48] documents recommend that PQ should be permanently monitored in the HV- and MV-networks. In the Netherlands, voltage dips have been monitored in the HV-networks since 2006/07 [49] and annual reports have been published [50-53]. Since then, PQ monitors have been introduced in the MV-networks; and even more monitors are installed during 2014/15 for continuous voltage dips measurements in the MV-networks. Figure 3.2 shows a simplified schematic of electric network where MV-distribution networks are connected to the meshed HV-networks through star/star or star/delta transformers. Depending on the type of HV/MV transformer and system grounding topology, the voltage characteristics may vary at different voltage levels [22].

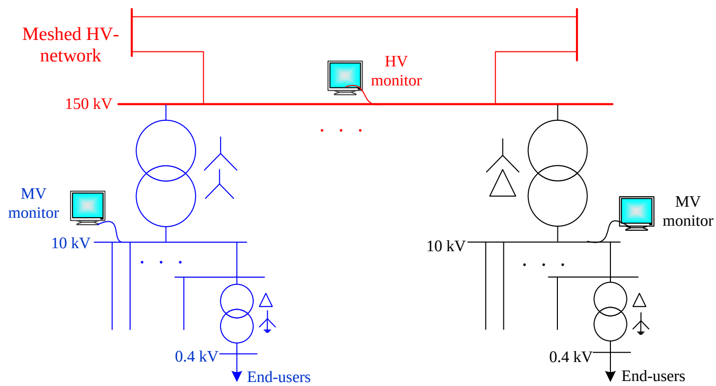


Figure 3.2: Simplified schematic with PQ monitoring systems on different voltage levels.

The Dutch MV-networks, mainly operating on 10 kV, consist of radially operating feeders connected to the main busbar at the MV side of the HV/MV substation. Most end-users are in the LV-networks and they are connected to the 10 kV buses through Dyn transformers. As also recommended in [25, 48], permanent PQ measurements are mostly done on the MV side of the transformer in the HV/MV substations. It is desired that the PQ measurements are performed in a cost effective way and this can be achieved by integrating the measurements to a system that is installed to the transformer substation, considered as the most optimal monitoring location [54].

3.3.1 Meter requirements and monitoring campaigns

In the Dutch MV-networks, various types PQ monitors are in use for performing measurements. Some among others are the SASensors, ION7650 meters, and EM720 devices. In this chapter, field measurement data collected from different MV-networks with EM720 devices, which are Class A PQ-meters, and with SASensors are used.

The SASensor system is installed at the MV side of the HV/MV substation and results in a significant amount of measured data acquisition at the central control unit that is connected through fiber optics to current and voltage sensors [55]. All recorded voltage and current measurements are uploaded to the central control unit of the substation. SASensor interface produces digital fault recorder (DFR) files that become available from the SASensor web server for processing. In 2014/2015, EM720 devices have been installed in many MV substations for monitoring voltage dips. With this device, a transducer with a voltage ratio of 5.7:1 interfaces the actual voltage in the MV substation and the signal data of the monitor.

Voltage waveforms that are collected from several locations over different years of measurement period are used in this work. The voltage event data are grouped into two categories based on the type of monitoring devices used and the measurement campaigns. Table 3.3 delivers additional information regarding the monitoring requirements of the two devices and the monitoring campaign.

Table 3.3: Measurements requirements and measurement campaigns

		Group-1	***Group-2***
Monitoring requirements	Meter type	SASensor	EM720
	Data type	Voltage and current waveforms	Voltage waveforms
	Connection	Phase-to-ground (voltage)	Phase-to-ground
	Sampling frequency	4 kHz (80 samples/ cycle)	1.6 kHz (32 sample/cycle)
Monitoring campaign	Monitoring locations	6 substations	47 substations
	Measurement period	4 years (2010–2013)	1 year (2015)

3.3.2 Voltage dip detection

PQ monitors often measure digitalized waveforms of voltage and current signals sampled at high frequency. Despite the waveforms contain useful information, it is difficult to give an overview about the voltage quality in the grid using the data in its original form. The waveform, therefore, can be processed to obtain a number of characteristics that help to describe the nature of supply voltage before, during and after the disturbance.

To detect a voltage dip following a disturbance and to determine the parameters that characterize the event, the characteristic RMS voltage as a function of time is determined from the voltage waveform. According the guidelines recommended by the IEC 61000-4-30 [6], the method of one-cycle or half-cycle sliding window can be used. Using the one-cycle sliding window approach, value of RMS voltage measured over one cycle is calculated using (3.1) and refreshed each-cycle,

$$U_{rms}(\mathrm{k}) = \sqrt{\frac{1}{N}\sum_{i=1+k-N}^{k} u_i^2} \tag{3.1}$$

where N is the length of the sliding window determined by the number of samples per cycle, u_i is the sampled voltage waveform (in time domain), and k represents time instant stamps (index, 1, 2, 3, …) of the sampled voltage to make RMS voltage to be a function of time. Half-cycle sliding window is an alternative way of determining the value of RMS voltage measured over one-cycle and refreshed each half-cycle. In this case, the window length has to be an integer multiple of one half-cycle.

An example of a voltage dip event in one phase is demonstrated in Figure 3.3. The first plot (Figure 3.3(a)) shows a waveform of the voltage as a function of time. The second plot (Figure 3.3(b)) shows the RMS voltage characteristics as a function of time calculated using half-cycle sliding window (dashed line) and one-cycle sliding window (solid line). The half-cycle window is sensitive to changes in the voltage and has a faster response to detect an event than the one-cycle window. Because of the higher time resolution, the voltage shows relatively a sharp drop and rise in half-cycle window. One-cycle window gives a relatively smoother profile of voltages than a half-cycle window at the cost of lower time resolution. For Class A measurement methods, it is recommended that the RMS phase-to neutral or phase-to-phase voltage characteristics as a function of time are calculated using the half-cycle sliding window method [6].

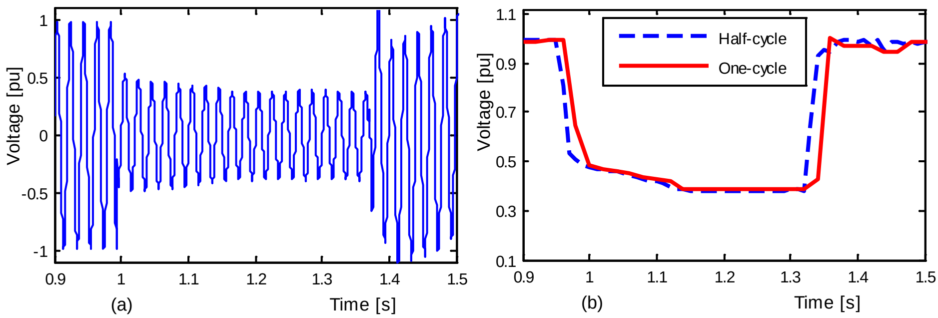


Figure 3.3: Example of a voltage dip – (a) instantaneous voltage, and (b) calculated RMS voltage.

3.3.3 Voltage dip characteristics

In this work, half-cycle window is used for calculating the RMS characteristics as a function of time of all voltage events from the PQ monitors. Depending on the shape of the RMS voltage, different categories of voltage dips are studied in this section. These are broadly classified into rectangular, nonrectangular and multiple-dip events.

Rectangular voltage dips can be single-phase or polyphase dips depending on the number of phases with voltage reduction. Rectangular single-phase dip occurs when only one phase experiences constant magnitude reduction below the dip threshold, and two others phases have magnitudes above the dip threshold. An example of rectangular single-phase dip is shown in Figure 3.4(a). Rectangular polyphase dips have at least two phases with a relatively constant magnitude reduction below the dip threshold, and such polyphase dips could be either symmetrical (if voltages in two or three phases drop by equal magnitude) or asymmetrical dips (if voltage drop in two or three phases are different in magnitude). Figure 3.4(b) shows an asymmetrical two-phase dip caused by a two phase-to-ground fault. Figure 3.4(c) demonstrates a rectangular symmetrical three-phase dip initiated by a phase-to-ground fault, which caused the spikes on the fault-free phases, and quickly evolving into a three-phase fault.

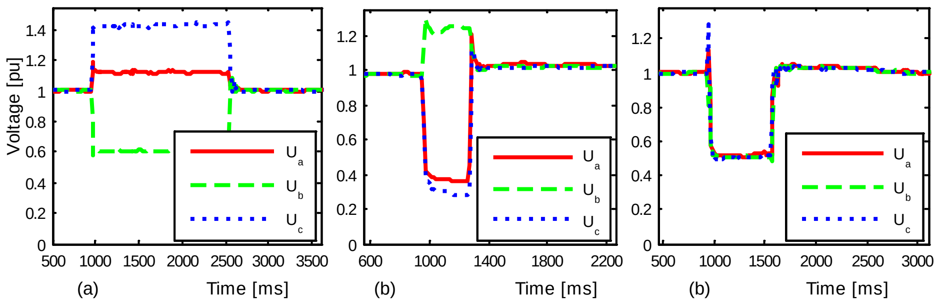


Figure 3.4: Example of rectangular dips – (a) single-phase, (b) polyphase unbalanced, and (c) polyphase balanced.

Nonrectangular voltage dips occur when the RMS voltage values suddenly change in several stages. The changes may arise due to developing faults (e.g. initiated as single-phase fault and evolving into two-phase or three-phase fault). Such dips (sometimes called developing or multistage dips) are not uncommon in the MV-networks. Figure 3.5(a) depicts a multistage voltage dip caused by one-phase fault developing into three-phase dip. Another possible reason for multistage dips is due to the difference in fault clearing procedure of protection devices. A fault on a transmission line is cleared by opening the breakers on both sides of the line which may not often happen at exactly the same moment. When a fault occurs in the zone of secondary protection in the MV-network, the primary protection is tempted to clear the fault if the secondary protection fails before it completely clears the fault. An example of such dips is shown in Figure 3.5(b). Duration of multistage dips can be longer and may cause severe impact on end-user equipment than the typical voltage dips. Voltage dips caused by the switching of heavy loads (e.g. motors) and the excitation of transformers also have nonrectangular shapes (see Figure 3.6).

In some cases, events with several short-circuits occurring within a short-time interval can cause multiple-dips. Such events may arise due to self-extinguishing faults during adverse conditions (e.g. lightning, thunder storms), or due to the reclosing actions of breakers after a fault. Figure 3.7 illustrate examples of multiple-dips occurring during a short interval of time.

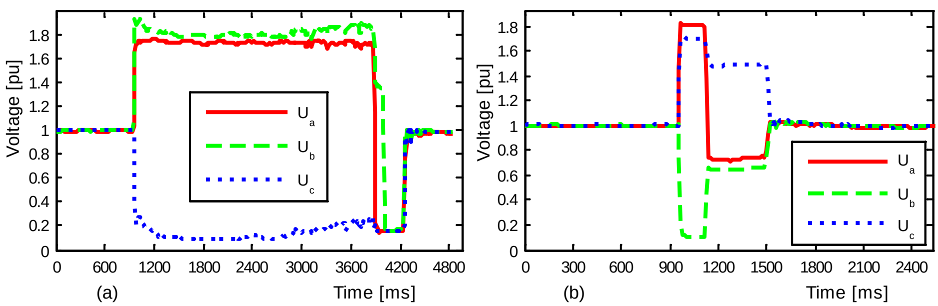


Figure 3.5: Nonrectangular multistage dips – (a) one-phase dip evolving into three-phase dip, and (b) single-phase dip developing into two-phase dip.

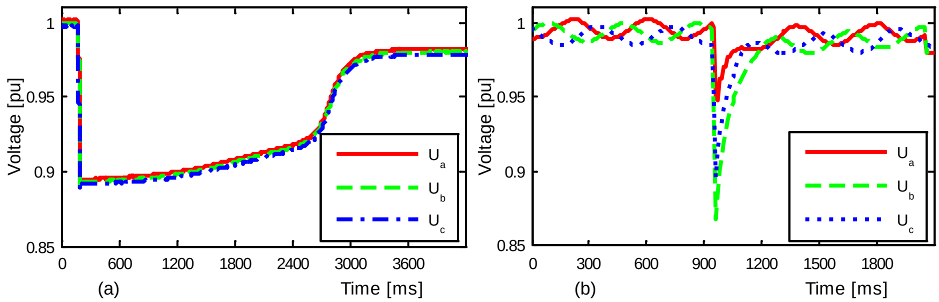


Figure 3.6: Nonrectangular voltage dips due to – (a) motor starting, and (b) transformer excitation.

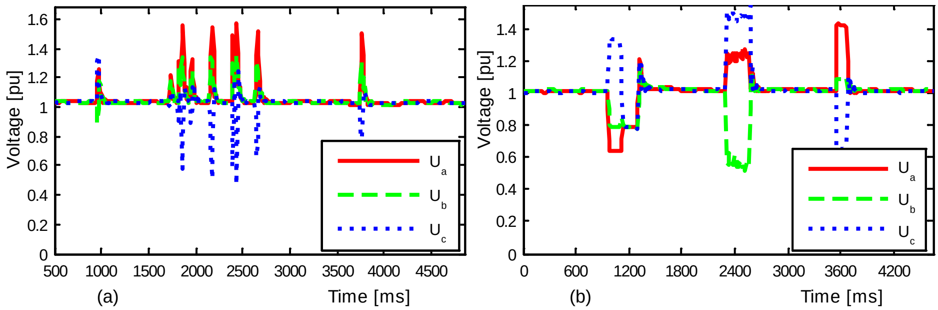


Figure 3.7: Multiple-dips due to – (a) self-extinguishing faults, and (b) reclosing of actions of protection device.

To reduce the loss of information when characterizing a voltage dip with one magnitude and one duration values, a "dip segmentation method" is proposed in [2] to describe voltage events caused by short-circuit faults, and switching of heavy loads or power transformers. Considering different segments from the shapes of the recorded voltages, the distinct characteristics are:

- Voltage dips caused by short-circuit faults have at least two-transition segments and a during event segment. The transition segments indicate that voltages are not abruptly changing from nominal to the minimal magnitude and back to the nominal value (e.g. see Figure 3.4).
- Dips due to motor starting are characterized by one-transition segment when slowly recovering from the minimal to about nominal value (Figure 3.6(a)). A sudden increase in the current at the instant of switching causes an abrupt decrease in voltage magnitude and such voltage events have no clear during-event segment.
- Magnitude of dips due to the switching of a power transformer suddenly drops to minimal values and start recovering to about nominal values (Figure 3.6(b)). These events are also characterized by the second-transition segment and have no clear during-event segment. Such events, unlike events with motor starting, mostly lead to unbalanced three-phase voltages with short recovery time.

Because of the Dyn transformers between the MV busbars and end-users in the LV-network, the shapes and characteristics of voltage dips at the equipment terminals can be different from the monitoring point. Depending on the type of faults and system grounding, the number and severity of voltage dips at the end-user terminals can be different [22, 56]. When phase-to-ground voltages are monitored in the MV-networks, voltage dips affecting the end-user devices can be obtained from the phase-to-phase characteristic voltages using (3.2).

$$
\begin{aligned}
u_{ab}(t) &= u_a(t) - u_b(t) \\
u_{bc}(t) &= u_b(t) - u_c(t) \\
u_{ca}(t) &= u_c(t) - u_a(t)
\end{aligned}
\tag{3.2}
$$

From the monitored data, examples of voltage characteristics as a function of time for phase-dips caused by various type of faults and phase-phase voltages propagating into phase-dips in the LV-network are given in *Appendix-B.1*. Voltage dips due to single-phase faults in isolated MV-networks are hardly experienced by end-users. Besides, the magnitude of voltage dips caused by two-phase faults in the MV-network is slightly shallower (even in the most affected phase) at the customer terminals than at the monitoring point. Balanced three-phase dips, however, are transferred to the customer terminals without any change in magnitude.

3.3.4 Evaluation of voltage dip parameters

Notionally, the voltage during a dip is assumed to be a constant RMS value and this simplified approach is usually considered during the analysis to obtain statistical data. In reality, voltage dips are often complex in shape and the RMS value varies during the dip. An event can be described very accurately when more number of characteristics are considered [57] although this requires more calculations and complicates the reporting of the voltage quality.

When evaluating the voltage dips parameters from the recorded waveforms, the following considerations are made in this thesis:

- RMS voltage characteristics as a function of time of voltage events are obtained using half-cycle sliding window method. The RMS voltage characteristics of events is used to detect if each voltage event is qualified for a voltage dip.
- 90% of the nominal voltage is considered as the dip *start threshold* and dip *end threshold level*, and the interval between these two defines the dip duration. To define the allowable dip magnitude of events, 5% of the nominal voltage for three-phase balanced events and above zero for unbalanced voltage events is considered as a *lower dip threshold limit*. A voltage event is, therefore, considered as a dip if the event consists a remaining voltage between the upper threshold level and lower threshold limit for a duration ranging between ½ cycle to 1 minute.
- In case of polyphase events, asymmetrical (or unbalanced) faults can lead to voltage dips in two or three phases with different drops in magnitude below the dip threshold. As recommended in several standards [6, 8, 9, 39], *phase aggregation* and *time aggregation* are applied such that: the magnitude of the lowest phase voltage during the dip is used as the voltage dip magnitude, and the

time between the first instant the RMS voltage of any phase drops below the dip start threshold to the instant that the RMS voltages of all phases rise just above the dip end threshold is considered as the voltage dip duration. Each qualified voltage dip is characterized by three parameters- the dip magnitude, dip duration and dip type.

- Voltage events with the same common cause may comprise several dips within a short-time interval. Counting each dip separately would have a significant impact on the regulation as they can considerably affect the total number of voltage dips despite of the fact that the impact on end-user equipment is usually very similar to a single event. Therefore, different methods of aggregation are considered to represent multiple-dips with a single dip per event.
- Voltage characteristics can change during propagation through transformers. Therefore, voltage dips at the monitoring points and at the end-user equipment terminals are treated separately.

3.4 Voltage dips statistical indices

In order to compare power quality in different networks, network regulators need to have common, standardized quality indices. The number of these indices should be kept at minimum, easy to assess, and be representative of the disturbance being characterized. Regarding voltage dips, any dip index can be within categories of single-event index, single-site index and system index [39]. Each category uses parameters indicating the severity of a voltage event, voltage quality at a specific site, and voltage quality for the whole or part of a power system. The procedure for evaluating the power system performance of voltage dips involves five basic steps [39]. These, also shown in Figure 3.8, are:

- Obtaining sampled voltage events with a specified rate and resolution,
- Calculating the event characteristics as a function of time from the sampled voltage waveforms,
- Determining single-event indices from the voltage characteristics of each event,
- Calculating site indices from single-event indices of all events measured during a certain period of time, and
- Finding system indices from the site indices for all sites within a certain power system.

The modified procedure shown in Figure 3.8 detects the number of affected phase-to-ground and phase-to-phase voltages in order to treat the different dip types separately. The procedure also considers the principle of aggregation for multiple-dip events.

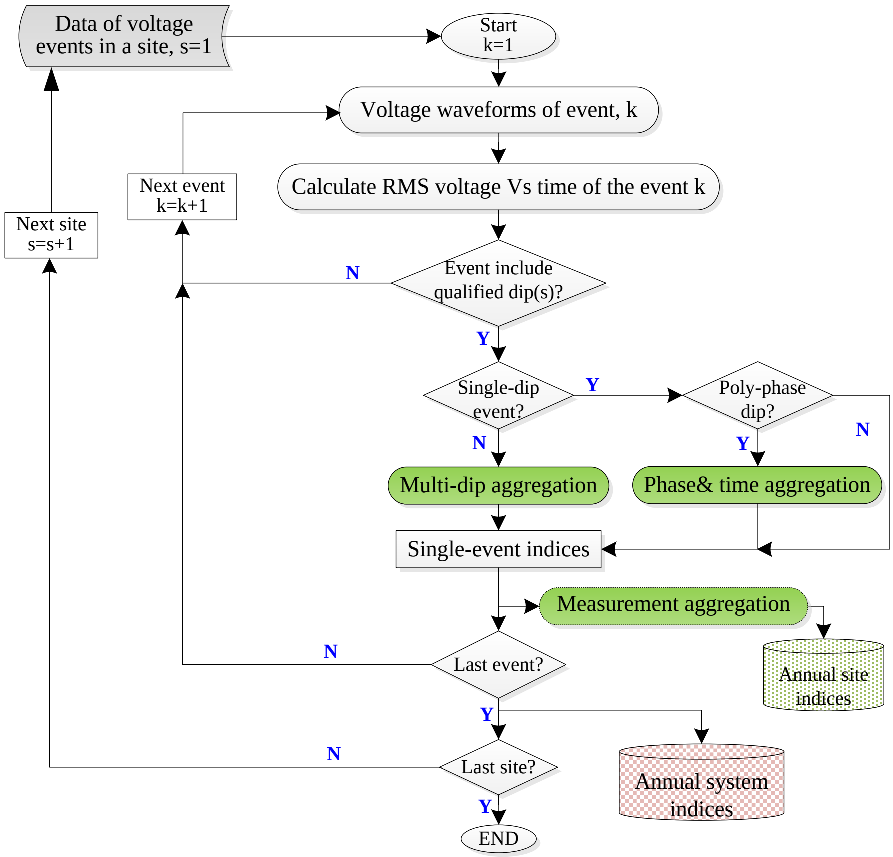


Figure 3.8: Modified procedure for obtaining the dip indices of a system, adopted from IEEE 1564 [39].

3.4.1 Single-dip and multiple-dip events

The voltage-dip events in the MV-network are categorized as phase-dips (dips associated with phase-to-ground voltages at the measurement points) and phase-phase dips (dips propagating to phase-to-ground voltages in the LV-network). For each category, voltage-dip events that consist of a single-dip or multiple-dips are identified. Table 3.4 gives general information about the voltage-dip events, from all monitoring locations, consisting of single-dips and multiple-dips associated with phase-to-ground and phase-phase voltages.

The number and characteristics of voltage dips can be affected by the measurement type and measurement location. For voltage-dip events monitored in the MV-networks, it can be observed that higher numbers of dip-events and multiple-dips per event are expected with the phase-to-ground measurement than phase-phase measurement. In the measurements used, about 29% of phase-dips in Group-1 substations and 40% of phase-dips in Group-2 substations consist of multiple-dips. If all qualifying dips are counted separately (i.e., if no aggregation is applied), on average each event of Group-1 and Group-2 substations with multiple phase-dips comprise about 2.7 times and 3.2 times more dips; and contribute to 52% and 68% of the total phase-dips respectively. Similarly, about 17% of phase-phase dips in Group-1 substations and 12% in Group-2 substations consist of 2.4 times and 2.3 times more dips respectively that contribute to 33% and 23% of the total dip in the two groups of substations. On average, about 67% of the phase-dips and ~24% of phase-phase dips are contributed by multiple-dip events.

Table 3.4: Single-dip and multiple-dip events from the two groups of measurement data

	Group-1		**Group-2**	
	Phase-dips	***Phase-phase dips***	***Phase-dips***	***Phase-phase dips***
Single-dip events	122	77	451	376
Multiple-dip events	49	16	298	50
Total voltage-dip events	171	93	749	426
Total[5] qualified dips	254	115	1390	490

If no aggregation technique is applied with multiple-dips and all qualifying dips are counted separately, the variation in magnitude and duration of the dips obtained from multiple-dip events can be observed from Figure 3.9. When phase-to-ground voltages are monitored, statistics indicate that a majority of the multiple-dips are due to one-phase faults most of which will not be seen in the phase-phase voltages and do not propagate to the end-users. Scatter plots of all qualifying dips can be found in *Appendix-B.2*.

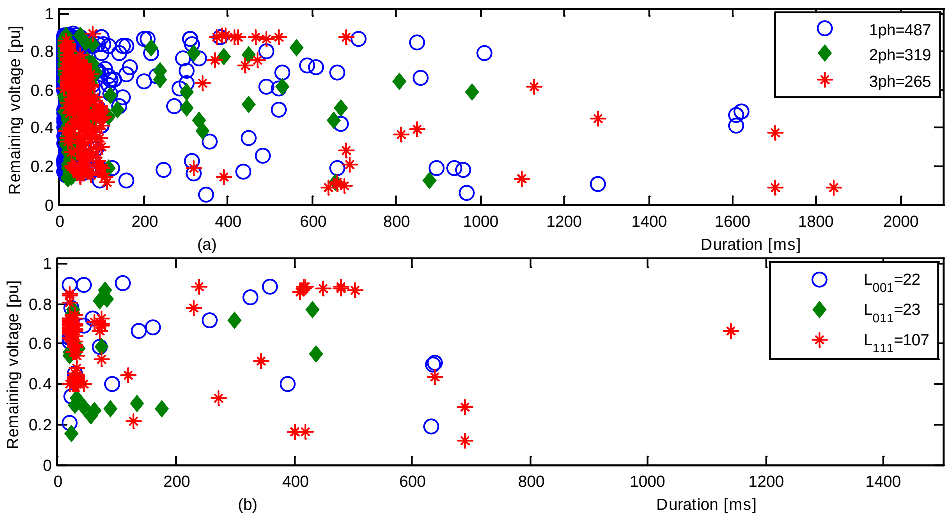


Figure 3.9: Scatter plots for individual dips of multiple-dip events from all monitors related to the – (a) measuerd phase-to-ground voltages, and (b) calculated phase-to-phase voltages.

As can be seen from Figure 3.10, more than 94% of phase-dips and 82% of phase-phase dips from multiple-dip events (presented in Figure 3.9) have short-duration (less than 200 ms). Another aspect which may be important to deal with multiple-dips is the

[5] *Multiple-dips are counted separately before aggregation is applied.*

duration between repetitive dips. It can be seen from Figure 3.11 that the time between more than 90% of phase-dips and more than 70% of phase-phase dips from multiple-dip events is less than 1 s. In fact, more than 95% of the multiple-dips have time interval (gap) less than 2 s between them. For end-users, counting these dips individually may imply that their equipment can recover within 1–2 s from the first voltage dip and may trip when the second dip occurs (very unlikely to happen).

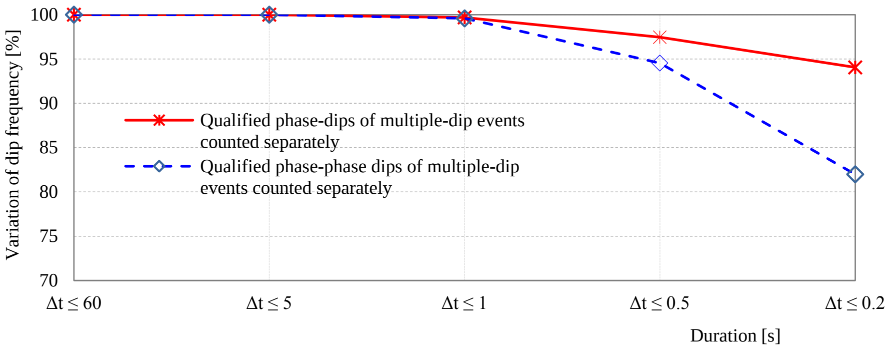


Figure 3.10: Frequency Vs duration of multiple-dips occurring in short time interval.

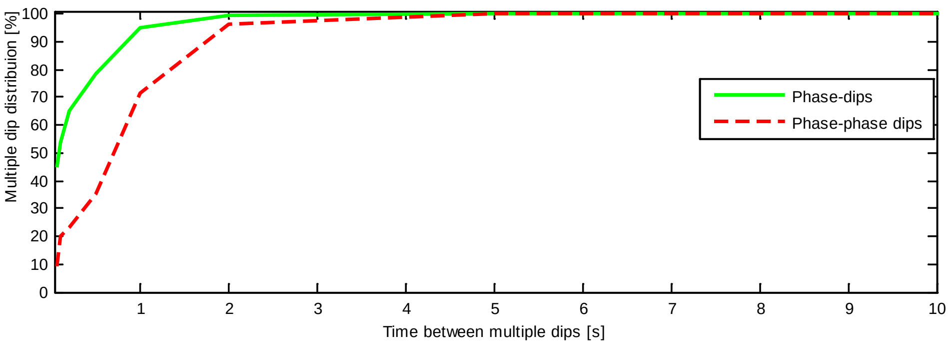


Figure 3.11: Distribution of time-intervals between successive multiple-dips.

3.4.2 Aggregation of multiple-dips and short-time events

Repetitive dips may occur within a short measurement interval due to re-closure of a circuit breaker or self-healing faults in cables or joints. Figure 3.12(a) illustrates a voltage event consisting of three dips occurring within the measurement window of the PQ-monitoring device and the dips are characterized by different magnitude and duration. When the measurement window is too short to capture all the multiple-dips in one waveform, the PQ-monitoring device may also register them as separate events each containing one or more dips (e.g. Figure 3.12(b) shows two events occurring within a short-time) that are recorded separately). From end-users point of view, it is unlikely that equipment and processes will be affected multiple times in such a short period. If the equipment or process fails for the first dip, the successive dips most likely will occur before the equipment recovers.

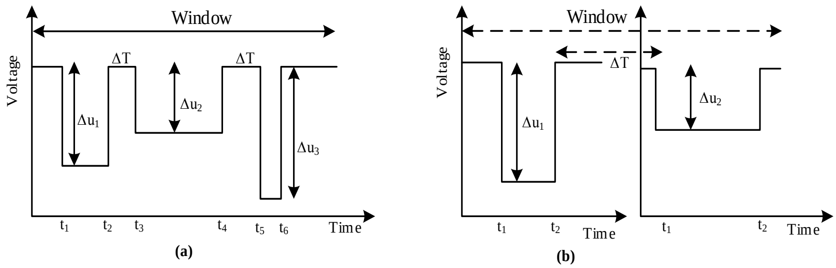


Figure 3.12: (a) A three-dip event, and (b) two events occurring in a short-time and recorded separately.

Multiple-dips can have the same common cause (e.g. defect cable joint). Counting them separately would have a significant impact on regulation as they considerably affect the total number of voltage dips while the impact is usually very similar to a single event. Important are the dips leading to a complete or partial interruption of the industrial process. Multiple-dips occurring within short-time interval could therefore be counted as one event instead of multiple-dips. On the other hand, aggregating such dips with lowest-magnitude and total-duration, which is mostly used in the standards, would overestimate the severity of the voltage dip. For statistical analyses and regulatory or customer reports, it is suggested that the concept of aggregation be applied for characterizing group of events occurring within a limited interval of time. In this work, some methods of aggregating multiple-dips into a single-dip per event are discussed below.

3.4.2.1 Lowest-magnitude and total-duration: method-1

This method is commonly used with most standards. The aggregated single-dip corresponding to multiple-dips occurring within the time of aggregation window (1 min, in this case) is characterized by the lowest RMS voltage and total duration of the event obtained from the characteristic voltage as a function of time. This can be expressed by (3.3),

$$\begin{aligned} &\text{magnitude, } u = min[u_1,\ u_{2,}\ ..., u_n] \\ &\text{duration, } \Delta t = t_{e,n} - t_{s,1} \end{aligned} \tag{3.3}$$

where u_1, u_2,…,u_n represent the remaining voltage magnitudes of individual dips, $t_{e,n}$, and $t_{s,1}$ are the end-time of the last dip and start-time of the first dip. This method may reasonably be applied if the voltage event consists of only few dips (e.g. 2 dips) with very short-interval (few cycles) in between, the individual dips have short-duration and the remaining voltages are close to each other. This is the simplest but probably also the most unreliable method.

3.4.2.2 Lowest-magnitude and sum of durations: method-2

When multiple-dips having short-time between the events occur within relatively short-time aggregation window (e.g. between few cycles and few seconds [39, 58]), it may be more appropriate to consider the sum of the duration of individual dips as the duration of the aggregated event than the previous method. The remaining voltage is chosen as the lowest value of the individual dips. The dip parameters can be represented using (3.4).

$$\begin{aligned} &\text{magnitude, } u = min[u_1,\ u_{2,}\ ..., u_n] \\ &\text{duration, } \Delta t = \Delta t_1 + \Delta t_2 + ... + \Delta t_n \end{aligned} \tag{3.4}$$

From end-user equipment perspective, this may have different implications. If the equipment trips on the first dip, the method may imply that the equipment may not be recovered from the first voltage dip when the second dip occurs. On the other hand, the equipment may still be affected by the second dip even if it tolerates the first voltage dip. In either case, the duration of the dip may be overestimated if end-user equipment trips for one of the dips only.

3.4.2.3 Lowest-magnitude and longest-duration: method-3

Another method of aggregating multiple-dips into a single-dip event is by choosing the longest-duration and lowest-voltage of individual dips, determined by (3.5).

$$\begin{aligned} &\text{magnitude, } u = min[u_1,\ u_{2,}\ ..., u_n] \\ &\text{duration, } \Delta t = max[\Delta t_1, \Delta t_2, ..., \Delta t_n] \end{aligned} \tag{3.5}$$

This method may reasonably be applied when the time between multiple-dips, occurring within relatively longer-time aggregation window (e.g. longer than 10 s [39, 58]), is relatively long (e.g. more than 1 s) and remaining voltages of individual dips are close to one another. For end-users, the implication is that the equipment will more likely trip on the longest dip. However, it is difficult to determine the most severe dip when a short-deeper dip is followed by a long-shallow dip, or vice versa.

The previous methods consider the lowest-voltage of individual dips. However, a dip with the deepest magnitude may have the shortest duration or vice versa, and different equipment may respond differently to such multiple-dips. That is, a dip that trips one type of device may not trip another device, or vice versa. In such cases, none of the above aggregation methods may represent the most severe dip. Not only the duration but also the magnitude should, therefore, be considered when finding the most severe dip on which a device will most likely trip during the multiple-dip event.

3.4.2.4 Voltage sag energy method: method-4

Voltage sag energy (E_{vs}) represents the energy that is not delivered to an impedance requiring a constant power. For dips involving multiple phase-to-ground (or phase-phase) voltages, the sag energy proportional to the energy not delivered to a constant impedance load with rated power of the load as a base can be given by (3.6)[39],

$$E_{vs} = \int_{t_{1x}}^{t_{2x}} \left(1 - \frac{u_x^2}{u_n^2}\right) dt + \int_{t_{1y}}^{t_{2y}} \left(1 - \frac{u_y^2}{u_n^2}\right) dt + \int_{t_{1z}}^{t_{2z}} \left(1 - \frac{u_z^2}{u_n^2}\right) dt \tag{3.6}$$

where u_x, u_y and u_z represent the RMS voltage values below the dip threshold, u_n is the RMS value for the nominal voltage, t_1 and t_2 are the dip-start and dip-end times of the dips associated to each phase-to-ground or phase-phase voltage. Voltage sag energy has a unit of time and the value represents the non-delivered energy caused by the dip equivalent to an interruption with a duration of the calculated value.

This method of quantifying single-event indices can be used to determine the most severe dip of multiple-dip events. Once voltage sag energies of individual dips are obtained using (3.6), parameters (magnitude, duration and type) of the dip with the highest voltage sag energy, which is considered as the most severe dip, are considered to characterize the multi-dip event.

3.4.2.5 Voltage dip severity index method: method-5

Voltage dip severity of an event can be calculated from the event magnitude and duration along with the reference curve. The value can be calculated using (3.7) [39],

$$S_e = \frac{1-u}{1-u_{ref}(d)} \tag{3.7}$$

where u is the remaining voltage magnitude (in pu), $u_{ref}(d)$ is the magnitude value of the reference curve during the same event duration d. With this method, severity of each event can be compared with voltage-tolerance curves of equipment (such as SEMI F47, ITIC or other curves when available).

Once severity indices of individual dips are obtained by (3.7), parameters of the dip with the highest severity index value, which is considered as the most severe dip, are used to represent the multiple-dip event. This method is more appropriate to apply for phase-phase dips in the MV-network, which will become phase-dips in the LV-network. For devices with known reference voltage-tolerance curves, severity of the aggregated voltage dip (characterized by magnitude and duration) can be compared with the dip ride-through capability of devices. However, different equipment behave differently and their voltage-tolerance curves vary. Although parameters of the most severe dip can be determined with this method, end-user equipment can trip for any dip before the most severe dip.

For the purpose of computing site and system indices, any of the above techniques can be used in order to aggregate multiple-dips into a single dip. Voltage dip parameters representing the aggregated events do not necessarily reflect the actual impact on equipment and processes. To illustrate the effect of the above-mentioned aggregation methods on the parameters of the aggregated dip, a multi-dip event shown in Figure 3.13 is considered here. The voltage event consists of two dips within 5 s measurement window related to both measured phase-to-ground voltages (Figure 3.13(a)) and calculated phase-phase voltages (Figure 3.13(b)). In the first dip, the drop in voltage magnitude on two of the phase-to-ground voltages resulted in a dip affecting two of the phase-phase voltages but with higher magnitudes of remaining voltages. In the second dip, the drop in voltage magnitude on one phase of the phase-to-ground voltages developed into the three phases and this also resulted in a dip affecting three of the phase-phase voltages. In this case, part of the dip that affects only one of the phase-to-ground voltages is not seen in the phase-phase dip and this affects the dip duration. Important information on individual dips, required by the various aggregation methods, are obtained from the characteristic voltages and parameters of the aggregated dips are compared in Table 3.5.

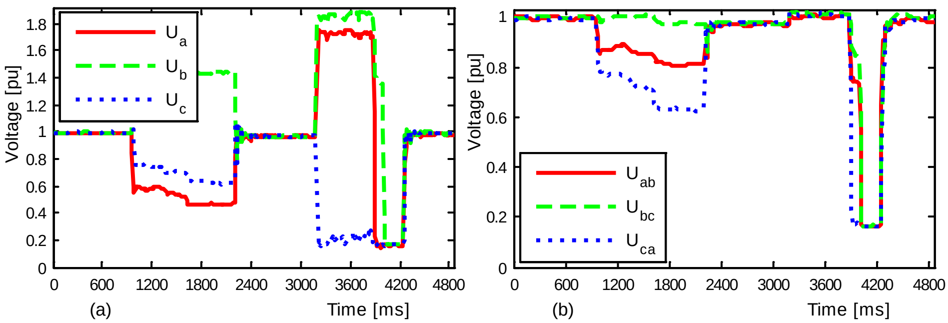


Figure 3.13: A two dip event with – (a) phase-to-ground voltages, and (b) phase-phase voltages.

It can be seen from Table 3.5 that the parameters characterizing the recorded event can be significantly affected depending on the choice of aggregation method. With the first three (classical) methods (M1–M3), the variation of magnitudes between the two dips is not considered. Using the SEMI F47 as a reference curve with method-5 (M5), both method-5 and method-4 (M4) indicate the second dip is more severe than the first. Method-5, however, requires a reference curve which is difficult to define one that is applicable for all equipment and/or group of customers. On the other hand, method-4 considers variation of the RMS voltages in all phases for comparing the severity of the dips. From this perspective, the method based on voltage sag energy index (M4) is chosen for aggregating multiple-dips for the regulatory or customer report. Nevertheless, it is likely impossible to define the best and most accurate aggregation method that can be applied to any kind of analysis needs.

Table 3.5: Parameters of the aggregated dips based on the different methods

	(a) Information on individual dips from the voltage characteristics											
			First dip						**Second dip**			
	t_{s1}[ms]	t_{e1}[ms]	u_1[%]	type	E_{vs1}	S_{e1}	t_{s2}[ms]	t_{e2}[ms]	u_2[%]	type	E_{vs2}	S_{e2}
Phase	970	2250	45	2	1320	2.73	3200	4380	14	3	1457	4.3
Ph-ph.	980	2260	63	2	758	1.87	3900	4300	16	3	830	2.79
	(b) Parameters for the aggregated dip with different methods (M1–M5)											
			Phase-dip						**Phase-phase dip**			
	M1	***M2***	***M3***	***M4***	***M5***		***M1***	***M2***	***M3***	***M4***	***M5***	
u [%]	14	14	14	14	13		16	16	16	16	16	
Δt [ms]	3300	2380	1280	1100	1100		3320	1680	1280	400	400	
type	3	3	3	3	3		3	3	3	3	3	

3.4.2.6 Measurement aggregation

During severe weather conditions, chronological list of voltage dips occurring within short interval of time (e.g. 1 minute) may be recorded by a monitor. This is highly possible especially when the monitoring device has a narrow measurement window, and counting such dips individually may significantly increase the number of dips in a particular site. Voltage dips recorded during extreme weather conditions are outside the scope of EN 50160. During such situations, multiple-dips within each event need to be aggregated and then *measurement aggregation* can be applied to represent a group of dip events within a fixed window by a single dip. An example of such a case is addressed in Table 3.6 for a single site where 45 phase-phase dips were recorded in the year 2015.

Table 3.6: Measurement aggregation for voltage events consisting of successive dips occurring within short-time during the same hour of a day in the year 2015

s/n	Dips occurrence time stamps					Dip parameters: Before aggregation		Dip parameters: After aggregation	
	Month	Date	Hr.	minute	sec.	u [%]	Δt [ms]	u [%]	Δt [ms]
1	1	24	14	27	34	69	90	69	90
2	1	29	19	47	44	45	110	45	110
3	1	29	20	29	1	41	30	41	30
4	1	29	21	6	11	64	30		
5	1	29	21	6	12	42	60		
6	1	29	21	6	15	42	60		
7	1	29	21	6	16	41	70		
8	1	29	21	6	19	58	30		
9	1	29	21	6	22	41	40		
10	1	29	21	6	24	40	30		
11	1	29	21	6	25	40	60		
12	1	29	21	6	28	41	90		
13	1	29	21	6	29	41	60		
14	1	29	21	6	31	42	30		
15	1	29	21	6	32	42	60		
16	1	29	21	6	33	41	60		
17	1	29	21	6	35	41	90		
18	1	29	21	6	36	40	60		
19	1	29	21	6	38	40	30		
20	1	29	21	6	41	39	30		
21	1	29	21	6	43	40	60		
22	1	29	21	6	44	39	30	39	130
23	1	29	21	6	46	41	40		
24	1	29	21	6	47	41	60		
25	1	29	21	6	48	40	30		
26	1	29	21	6	50	40	30		
27	1	29	21	6	52	41	30		
28	1	29	21	6	53	42	30		
29	1	29	21	6	54	41	60		
30	1	29	21	6	56	41	60		
31	1	29	21	6	57	40	40		
32	1	29	21	6	59	40	30		
33	1	29	21	7	1	40	130		
34	1	29	21	7	3	56	70		
35	1	29	21	7	5	42	30		
36	1	29	21	7	10	67	30		
37	3	27	9	37	51	81	60	81	60
38	4	6	15	6	13	58	40	58	40
39	4	6	15	12	4	48	60	48	60
40	4	6	15	12	18	56	30		
41	4	6	15	13	8	40	30	40	30
42	5	12	12	43	41	52	90	52	90
43	6	11	1	43	39	82	20	82	20
44	6	15	17	14	13	66	30	66	30
45	7	15	8	51	1	68	30	68	30

Before applying measurement aggregation, some of the voltage dip events actually had multiple-dips adding up to 99 phase-dips and 66 phase-phase dips if all qualified dips were counted individually. Using the *voltage sag energy index* aggregation method (M4) of multiple-dips, the annual dips are reduced to 80 phase-dips and 45 phase-phase dips. Despite aggregating multiple-dips into a single dip per event, it can be clearly pointed out from Table 3.6 that 33 of the phase-phase dips are recorded within less than 1 minute time on the 29th January 2015. Similarly, two dips are recorded within 14 seconds on the 6th April 2015. If *measurement aggregation*, based on the lowest-magnitude and the longest-duration, is further applied to these phase-phase dips using 1 minute aggregation window, the total number of phase-phase dips would be reduced into 12 dips per year.

3.4.3 Variations in voltage dip performance

Depending on the various activities and weather conditions, the frequency and probability of the occurrence of voltage dips is highly unpredictable both in time and place. The stochastic and random nature of voltage dips both in time and place can be demonstrated by Figure 3.14 for phase-dips and phase-phase (line) dips from six MV substations during four years. In NK1, for instance, the least and the highest number of phase-dips during the four years are monitored in 2012 and 2013 respectively. In some networks (e.g. ZBM1 and ZVH1), the number of phase-dips and phase-phase dips are the same during each year and varies from time to time.

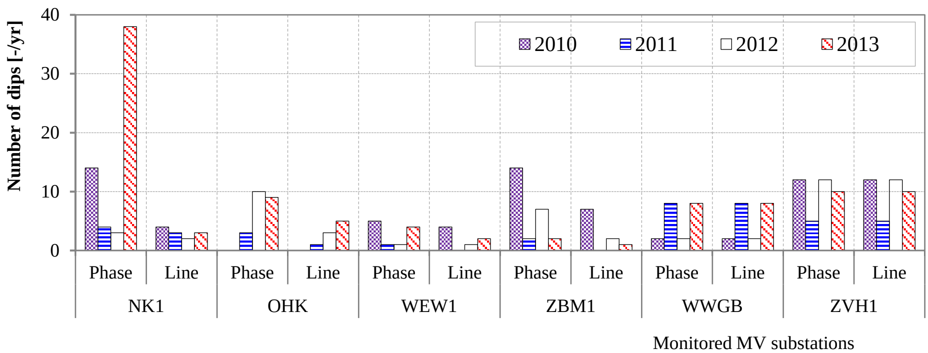


Figure 3.14: Variation in occurrence of voltage dips[6] in time and place in the MV-networks.

In the NK1 network, it can be recalled from Figure 3.14 that a remarkably high number of phase-dips were monitored in the year 2013 while only few dips could propagate to the LV-networks. Further zooming on for the variations in the number of dips over the months for the year 2013 is presented in Figure 3.15. It can be observed that a majority of these dips occurred in February. Investigations by the network operator indicated that a defect cable was the source of repetitive self-extinguishing faults that resulted in a high number of phase-dips. After replacement of the defect cable, the number of dips significantly reduced in the upcoming months.

The distribution on the number of dips recorded in the 53 monitoring locations significantly varies from place to place. As can be pointed out from Figure 3.16, some substations have small number of dips while only two substations have very large number of dips per year. A majority of the substations, however, have 3–10 dips per year. This wide range of variation in the number of dips can highly influence the evaluation of voltage dip profiles for the system performance.

[6] *Phase and Line refer to dips associated with phase-to-ground and phase-phase voltages respectively.*

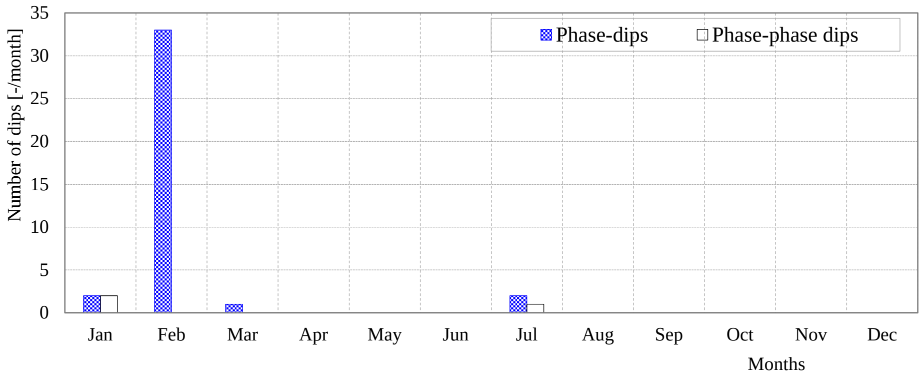


Figure 3.15: Monthly variation of voltage dip occurrence in the NK1 10kV network for the year 2013.

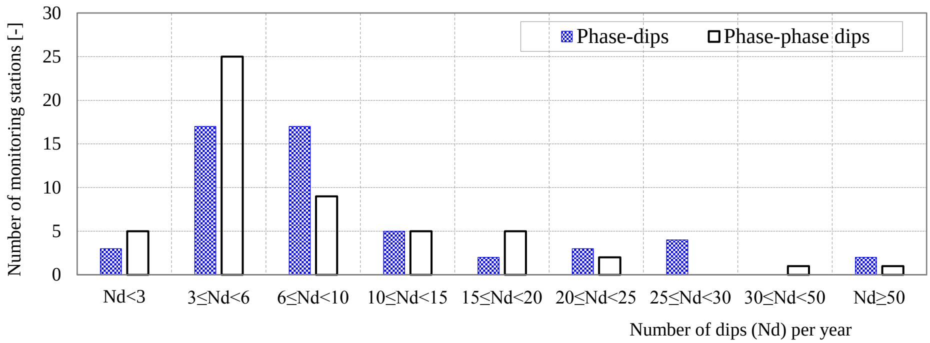


Figure 3.16: Variation in the number of voltage dips in different monitoring locations.

3.4.4 Measurement and presentation of dips for system performance

If monitors in the HV- and MV-networks are meant to measure phase-to-ground voltages, TSOs and DSOs may get more information about the total frequency of faults in the network. However, publishing these dips will overestimate the number of dips that end-users in the LV-network can experience. This can lead to misleading and erroneous conclusions about the number and severity of the dips, and the possible impact on the end-users. For end-users, either the measurement method or reporting approaches can be modified in order to attain voltage dip statistics with more reliable information. With multiple-dips and recursive dip-events occurring within short time, aggregation methods can be considered to reduce the number of dips into a reasonable amount.

It is observed from the analysis that the voltage dip characteristics often vary from site to site, and time to time. Voltage dip profiles of the site with minimum dip density and maximum dip density may be far from each other and none of the two situations could give a good indication into the dip profile of the MV system. Considering the average of voltage dips over the 53 monitored substations, an improved and recommended approaches of reporting dips of the MV-networks are described here.

3.4.4.1 Improved approach of reporting voltage dips

If the installed monitors are meant to measure phase-to-ground voltages, the reporting can be improved to include the type of dips in the dip table. This will give the network operator additional information about the type and frequency of dips in the networks, and to estimate which dips could be transferred to the low voltage levels. One-phase dips from the HV- or MV-networks hardly transfer to the LV-networks and end-users may consider to deal with two-phase and three-phase dips. With this approach, the profile of average phase-dips over all monitoring locations before aggregating (M0) and after aggregating multiple-dips using the voltage sag energy method (M4) is given in Table 3.7. It can be seen that one-phase dips share about 38% and 32% of the total phase-dips before and after applying the aggregation method with multiple-dips. This implies, on average a customer connected to the MV-network can experience not more than 68% of the total dips. The use of aggregation with multiple-dip events over all monitoring locations also reduced the average number of voltage dips related to phase-to-ground voltages by about 45%. Regarding the data on each dip type, the number of one-phase, two-phase and three-phase dips after aggregation reduced by about 55%, 43% and 35% respectively.

Table 3.7: Average annual density using improved approach of reporting dips without aggregation (M0) and aggregating multiple-dips based on voltage sag energy method (M4)

Remaining voltage [%]		Duration [s]															
		Δt ≤ 0.2			*0.2 < Δt ≤ 0.5*			*0.5 < Δt ≤ 1*			*1 < Δt ≤ 5*			*5 < Δt ≤ 60*			
		1ph	2ph	3ph	1ph	2ph	3ph	1ph	2ph	3ph	1ph	2ph	3ph	1ph	2ph	3ph	Tot.
90>u ≥80	M0	2.74	2.82	0.55	0.08	0.02	0.21	0.07	0.02	0.17	0.00	0.00	0.00	0.00	0.00	0.00	6.67
	M4	1.25	1.45	0.29	0.04	0.00	0.21	0.07	0.02	0.16	0.00	0.00	0.00	0.00	0.00	0.00	3.48
80>u ≥70	M0	2.11	2.95	0.66	0.05	0.04	0.05	0.06	0.02	0.02	0.05	0.00	0.06	0.00	0.00	0.00	6.08
	M4	0.62	1.75	0.32	0.05	0.04	0.05	0.06	0.02	0.02	0.05	0.00	0.06	0.00	0.00	0.00	3.03
70>u ≥40	M0	3.03	2.69	3.46	0.08	0.12	0.08	0.11	0.15	0.02	0.04	0.06	0.07	0.00	0.00	0.00	9.90
	M4	1.36	1.46	1.87	0.03	0.09	0.08	0.10	0.15	0.02	0.04	0.06	0.06	0.00	0.00	0.00	5.33
40>u ≥5	M0	1.65	0.83	1.56	0.14	0.03	0.06	0.11	0.05	0.16	0.12	0.00	0.06	0.00	0.00	0.00	4.76
	M4	0.70	0.43	1.24	0.14	0.03	0.05	0.11	0.05	0.16	0.12	0.00	0.06	0.00	0.00	0.00	3.08
5>u	M0	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02
	M4	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02
Sub. Total	M0	9.53	9.29	6.25	0.34	0.21	0.40	0.35	0.24	0.37	0.20	0.06	0.19	0.00	0.00	0.00	**27.42**
	M4	3.93	5.09	3.73	0.26	0.16	0.38	0.34	0.24	0.36	0.20	0.06	0.18	0.00	0.00	0.00	**14.94**
Total	M0	10.43	9.79	7.20													
	M4	4.74	5.55	4.66													

3.4.4.2 Recommended approach of measuring and reporting dips

As end-users are connected to the MV-networks through Dyn transformers, the phase-phase dips in the MV become phase-dips in the LV-networks. If phase-to-ground voltages are monitored in the MV-networks, phase-to-phase voltages can be calculated and the dips that may influence the end-users can be reported as in Table 3.8. As compared to the results shown in Table 3.7, the calculated number of phase-phase dips in the MV-networks propagating to the LV-networks are about 36% and 57% of the average monitored phase-dips before and after using the aggregation method with multiple-dips. It is also noticed that the calculated number of phase-phase dips can be less than the combined occurrence of two-phase and three-phase dips (in this case, 83%).

Table 3.8: Average annual density using recommended approach of reporting dips without aggregation (M0) and aggregating multiple-dips based on voltage sag energy method (M4)

Remaining voltage [%]		Duration [s]															
		$\Delta t \leq 0.2$			$0.2 < \Delta t \leq 0.5$			$0.5 < \Delta t \leq 1$			$1 < \Delta t \leq 5$			$5 < \Delta t \leq 60$			
		L_{001}	L_{011}	L_{111}	L_{001}	L_{011}	L_{111}	L_{001}	L_{011}	L_{111}	L_{001}	L_{011}	L_{111}	L_{001}	L_{011}	L_{111}	Tot.
90>u ≥80	M0	1.69	0.37	0.27	0.04	0.00	0.21	0.02	0.02	0.17	0.02	0.00	0.02	0.00	0.00	0.00	2.85
	M4	1.67	0.34	0.25	0.00	0.00	0.20	0.02	0.02	0.17	0.02	0.00	0.02	0.00	0.00	0.00	2.72
80>u ≥70	M0	0.55	0.39	0.46	0.02	0.08	0.03	0.02	0.02	0.00	0.00	0.00	0.04	0.00	0.00	0.00	1.60
	M4	0.51	0.35	0.31	0.02	0.08	0.03	0.02	0.02	0.00	0.00	0.00	0.04	0.00	0.00	0.00	1.37
70>u ≥40	M0	0.30	0.53	2.84	0.04	0.04	0.05	0.08	0.19	0.14	0.00	0.02	0.05	0.00	0.00	0.00	4.28
	M4	0.19	0.45	2.26	0.04	0.04	0.05	0.08	0.19	0.14	0.00	0.02	0.04	0.00	0.00	0.00	3.50
40>u ≥5	M0	0.06	0.25	0.23	0.00	0.04	0.08	0.06	0.12	0.07	0.00	0.00	0.00	0.00	0.00	0.00	0.89
	M4	0.02	0.13	0.21	0.00	0.04	0.07	0.06	0.12	0.07	0.00	0.00	0.00	0.00	0.00	0.00	0.71
5>u	M0	0.04	0.02	0.00	0.00	0.00	0.00	0.00	0.06	0.04	0.00	0.02	0.00	0.00	0.00	0.00	0.17
	M4	0.04	0.02	0.00	0.00	0.00	0.00	0.00	0.06	0.04	0.00	0.02	0.00	0.00	0.00	0.00	0.17
Sub. Total	M0	2.64	1.55	3.81	0.10	0.16	0.36	0.17	0.42	0.42	0.02	0.04	0.11	0.00	0.00	0.00	**9.79**
	M4	2.42	1.30	3.03	0.06	0.16	0.34	0.17	0.42	0.42	0.02	0.04	0.11	0.00	0.00	0.00	**8.48**
Total	M0	2.92	2.16	4.70													
	M4	2.67	1.91	3.90													

When dips influencing the end-users are the main target, the connection of monitors for measurement can be adjusted as indicated in Table 3.9 by taking the type of HV/MV transformers into consideration. If size of the data storage is not an issue, it is highly recommended to measure both phase-to-ground and phase-phase voltages and report the phase-phase dips in the MV-networks as in Table 3.8.

Table 3.9: Proposed approaches of PQ monitor connections for monitoring dips in the HV- and MV-networks [22]

Case	**Transformer configuration**		**Monitor connection to measure intended voltage**	
	HV/MV	*MV/LV*	*HV-network*	*MV-network*
I	YNyn	Dyn	Phase-to-phase voltages	Phase-to-phase voltages
II	YNd	Dyn	Phase-to-ground voltages	Phase-to-phase voltages
III	Both I and II	Dyn	Phase-to-ground and Phase-phase	Phase-to-phase voltages

From Table 3.7 and Table 3.8, it can be observed that the aggregation method reduced the number of phase-dips from 27.42 dips per year into 14.94 dips per year. Similarly, the aggregated phase-phase dips are reduced from 9.79 dips per year into 8.48 dips per year. The fact that higher numbers of voltage-dip events and multiple-dips per event are measured in the phase-to-ground voltages than phase-phase voltages, a very significant reduction in the number of dips due to the aggregation methods is pronounced for phase-dips than phase-phase dips. The total number of aggregated dips are same but the different methods of aggregations affect the severity of various types of voltage dips (characterized by magnitude and duration). Voltage dip profiles using other aggregation methods can be found in *Appendix-B.3*.

The occurrence of voltage dips can significantly vary from country to country depending on several factors such as type network (overhead lines, underground cables, or mixed), length of MV cables or lines, number of MV customers, type of system grounding, etc. As can be noticed from Table B.3 (*Appendix-B.3*), the assessed number of voltage dips in the Netherlands is significantly lower than in the other European countries.

When evaluating the average dip profiles, the mean value is between extreme situations (extremely minimum, extremely maximum). To discriminate the effect of extreme values, 95- or 99-percentile can be applied for the dip data from more monitoring locations for longer periods and value closer to the reality can be obtained. This will be described later with regulation of voltage dips in *Chapter 7*.

3.5 Summary

When assessing voltage dip indices, the number and severity of voltage dips can be affected by the number and location of monitors, the type of monitor connection, and method of aggregation with multiple-dips and recursive dip events occurring within short-time intervals. Because of the fact that voltage dips caused by different faults can have different impact on end-users, different classification of voltage dips should be considered and regarded separately. Taking the change in characteristics of voltage dips between the monitoring locations and end-user equipment terminals into account, voltage dip profiles consisting of reliable information can be reported. This helps customers to take measures in order to tackle financial losses related to voltage dip problems.

Using the monitored data from the 53 Dutch MV substations and counting all qualified dips separately, on average about 27 phase-dips and 10 phase-phase dips occur every year. It is observed that the occurrence of dips varies from location to location and from time to time. When multiple-dip events and recursive dip-events occurring within short-time intervals are aggregated over 1 minute measurement window, the average numbers of dips related to the phase-to-ground and phase-phase voltages are reduced to about 15 and 8.5 dips per year. Depending on the purpose of the dip measurements, it is suggested that the various types of voltage dips that can propagate to the end-user terminals shall be reported separately.

4

Voltage dip immunity of equipment

4.1 Introduction

The detrimental impact of voltage dips is mainly associated with industrial and big commercial customers. The proper operation of modern industries rely on electronic controls and equipment which are highly susceptible to voltage dips mostly coming from the grid [35, 59-65]. When such devices are subjected to a brief reduction in the voltage magnitude, a failure or malfunction of a single device may cause a cascading failure of the entire manufacturing process. The response of end-user equipment on voltage dips depends on the severity of the disturbance and the robustness of the process equipment. The severity of voltage dips is expressed in terms of the magnitude and duration of the disturbance while the robustness of equipment is a measure of the ride-through capability of the device against the disturbance.

Depending on the characteristics of the voltage dips, various type of equipment exhibit different sensitivities. In this chapter, existing standards regarding voltage dip immunity of equipment are briefly described. Based on laboratory experiments, voltage-tolerance curves of sensitive devices commonly used in industries are presented. With a case study of a simple process, the behavior and interaction of individual equipment that make up the process are compared with the sensitivity of the process against the same disturbance parameters. The voltage-tolerance curves of the equipment and process are compared to check if the process dip immunity is always governed by the immunity of the weakest link component in the process. From field measurements in the distribution network, the performance of the process is evaluated by comparing the severity of voltage dips at a site with the voltage-tolerance curve of the process.

4.2 Standards on equipment dip immunity

In order to meet better power quality requirements, both equipment manufacturers and users use standards. Standards associated with voltage dips are intended to be used as means of reference documents for describing the quality requirements of the equipment demanded by customers, as guidelines for equipment manufacturers in order to develop products that meet customer requirements, and for testing and evaluating if the product complies with the customer's specifications.

Not all power disturbances affect modern equipment. There is an acceptable range of AC voltage variation that equipment power supplies will tolerate over short periods of time. In fact, a supply that is acceptable for one device may be inadequate for the others. Different standards are available to provide specifications, guides, test methods, terminologies, practices, etc. associated with industrial equipment. In the PQ standards, the remaining voltage magnitude and duration are the parameters used for describing the dip immunity of equipment to different disturbance levels.

The international standard IEC 61000-2-4 [66] defines three classes of the electromagnetic environment. Class 1 applies to protected supplies and has compatibility levels lower than those on public networks. Class 2 applies to PCCs and in-plant point of couplings (IPCs) in the environments of industrial and other non-public power supplies, and has compatibility levels identical to those of public networks. Class 3 applies only to IPCs in industrial environments and it has higher compatibility levels than those of Class 2 for the same disturbance. Regarding the voltage dip immunity of devices belonging to the different classes, recommended testing levels are specified in the international standards IEC 61000-4-11 [37] and IEC 61000-4-34 [38]. The IEC 61000-4-11 is intended to be used for equipment with mains current not exceeding 16 A per phase while the IEC 61000-4-34 is intended to be used for equipment with mains current greater than 16 A per phase. Test levels and durations for voltage dips recommended during compliance testing of devices corresponding to each class of industrial environment are specified in the standards are summarized in Table 4.1.

Table 4.1: Preferred test levels and durations for different equipment class according to IEC 61000-4-11/34 [37, 38]

	Test level and duration for voltage dips	
	IEC 61000-4-11	*IEC 61000-4-34*
Class 1	Case-by-case according to equipment requirement	Case-by-case according to equipment requirement
Class 2	(0%, 10 ms), (0%, 20 ms), (70%, 500 ms)	(0%, 20 ms), (70%, 500 ms)
Class 3	(0%, 10 ms), (0%, 20 ms), (40%, 200 ms), (70%, 500 ms), (80%, 5 s)	(0%, 20 ms), (40%, 200 ms), (70%, 500 ms), (80%, 5 s)

The standards SEMI F47 [67] and ITIC [68] are used for describing the ride-through requirements of devices used in industries. The SEMI F47 curve is offered by the Semiconductor Equipment and Materials International (SEMI) providing voluntary technical agreements between manufacturers and end-users to ensure the compatibility and interoperability of semiconductor processing. It specifies voltage ride-through requirements of equipment during 0.05–1 s with voltage dips of remaining voltage 50% for 200 ms, 70% for 500 ms and 80% for 1s. The standard also recommends that equipment tolerate voltage drops to 0% for 20 ms and 80% for 10 s. In the Information Technology industry, the ITIC curve is used for describing the behavior of most IT equipment. This document specifies that IT equipment are required to withstand a voltage dip of 80% lasting for 10 s and a dip of 70% for 500 ms. According to this application note, IT devices are recommended to continue operating for 20 ms after the supply is lost. Even though it was primarily developed for 120 V computer equipment and is not intended for a design specification, this curve has been applied to general PQ evaluation and used as a reference to define the withstanding capability of various loads and devices.

As applied to certain industries, a comparison in the different power acceptability areas of the SEMI F47, ITIC and IEC 61000-4-11 (for class 3) is shown by voltage-tolerance curves in Figure 4.1. For equipment products complying with the voltage-tolerance curves must be able to ride-through and continuously operate without interruption during conditions identified in the areas above the respective curves. However, equipment complying with the requirements of one standard specifications may not always comply with another.

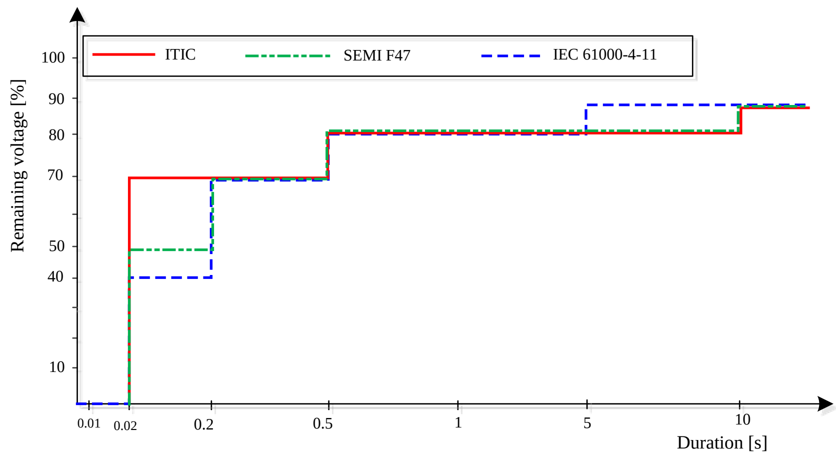


Figure 4.1: Immunity levels recommended by the standards ITIC, SEMI F47 and IEC 6100-4-11 (for Class 3).

Although industrial and national/international standards are available as guidelines for manufacturers and users, the equipment dip immunity can be influenced by additional factors (e.g. the dip type and loading) and the actual behavior can be different from the product specifications. Besides, not all standards contain mandatory requirements and a wide range of equipment exhibiting different sensitivities against voltage dips are used in industries [35, 59-61, 63, 69]. In practice, different brands of the same equipment type, and even different models of the same equipment brand can have different sensitivity to voltage dips. This makes it difficult to develop a single standard that defines the immunity of process equipment. In order to simplify the selection and ordering process of equipment, and to easily conduct tests on limited number of test points, the CIGRE/CIRED/UIE JWG C4.110 [2, 46] proposed five equipment immunity classes against balanced and unbalanced voltage dips. According to this proposal, Class A provides the highest level of equipment dip immunity and Class D specifies a basic level of equipment dip immunity. Voltage dip immunity Class B and Class C are in between the two while Class E covers equipment dip immunity falling into none of the other immunity classes.

In practical applications, the behavior of equipment and processes to voltage dips may be affected by other parameters- like types of dip, phase-angle jump, point-on-wave dip initiation, loading condition in addition to magnitude and duration of voltage dips. If customers know the ride-through capability of their equipment, they can evaluate if their equipment will be expected to fail to operate as intended against voltage dips of different severity levels. This will help customers for choosing appropriate mitigation methods for protecting their equipment and process against voltage dip problems. One way to solve the problems caused by voltage dips is to make the manufacturing process more robust against voltage dips. In order to increase the immunity of the manufacturing process against voltage dips, it is important that customers understand the response of individual components, which make up the process, as well as the interaction between the components for various types of voltage dips under different conditions. From this point of view, customers can obtain the realistic behavior of equipment and processes in their facility under different situations from laboratory test.

4.3 Voltage dip immunity test of individual devices

Generally, the sensitivity of equipment to voltage dips may be categorized into three [70] described as:

- Equipment that is primarily sensitive to the magnitude of voltage dip only- this includes process controls, motor drive controls, and automated machines.
- Equipment that is sensitive to both voltage dip magnitude and duration- this includes all equipment that use electronic power supplies.
- Equipment that is sensitive to characteristics other than voltage dip magnitude and duration- some devices are also affected by other characteristics such as the phase unbalance, point-on-wave dip initiation, etc.

Most of the affected industrial equipment involve the use of electric power supplies that are sensitive to both magnitude and duration of voltage dips. In many literatures and surveys [35, 59-61, 63, 69, 71], relays/contactors, adjustable speed drives (ASDs), programmable logic controllers (PLCs), and personal computers (PCs) are identified as common industrial devices sensitive to voltage dips. In this section, the effect of voltage dips on AC contactors, an ASD, PLCs, PCs, an Air conditioner, and on a simple process are described based on laboratory experiments.

4.3.1 Testing methodology

For testing the sensitivity of various equipment against voltage dips, the simplified experiment setup shown in Figure 4.2 was built at the TU/e PQ lab. Main components of the experimental setup include a voltage dip generator source, the device under test, PQ analyzers, and a load. A 45 kVA programmable voltage source, MX45 from California Instrument, is used to generate various types voltage dips with different characteristics.

The voltage dip immunity tests are conducted on different types of equipment including six AC contactors, an AC adjustable speed drive (ASD), three programmable logic controllers (PLCs), four personal computers (PCs), and an Air Conditioner (A/C). The list of tested devices and their specifications are summarized in Table 4.2.

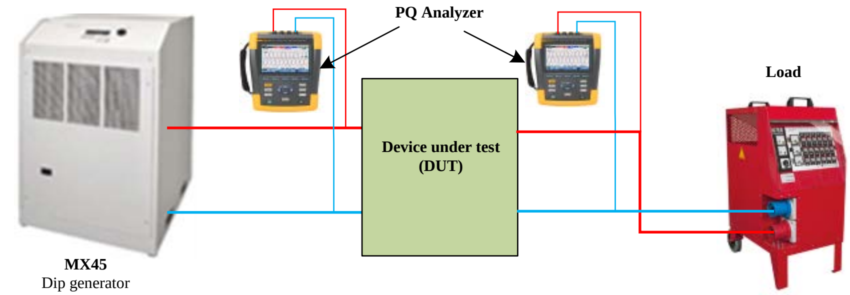


Figure 4.2: Experimental setup for testing equipment dip immunity.

Table 4.2: Test equipment and their specification for testing the voltage dip immunity

	Device name	Specifications
Source (dip generator)	MX 45 California Instrument	3 phase, S: 45 kVA, Vph: 0–300 V
Monitor	PQ analyzer	Fluke 434, and Fluke 435
Devices under test	AC contactors	C_1: Moeller Dil2M: 230–460 V, 90 A C_2: Moeller Dil4AM-22: 220 V, 55–90 A C_3: Moeller S-PKZ-2: 230 V C_4: Moeller DilR40: 220–240 V C_5: Moeller Dil2V-22: 220 V C_6: Omron: 24 V Load: Three-phase variable resistive load, 11 kW
	Adjustable speed drive (ASD)	ABB ACS550-01-023A-4 (unidirectional drive) Rated supply: 50/60Hz, 380–480 V, 11 kW, 23 A Loadings: No load, 25%, 50%, 75%, 100% rated
	Programmable logic controllers (PLCs)	PLC_1: SR3 B261FU PLC_2: LOGO! 230RCE 0BA7 PLC_3: easy 719-AC-RC Supply voltage: 115 VAC/ 230 VAC Category: PLC-control module
	Personal computers (PCs)	PC1: CPU=Intel Pentium 4, 3GHz processor, 1 GB RAM (2002) OS=Windows XP; Supply= 115/230 VAC (50/60 Hz), 6/3 A, 280 W PC2: CPU= Pentium III, 640 MHz processor, 256 MB RAM (2000) OS=Windows 2000; Supply= 100–240 VAC (50/60 Hz), 9/4A, 300 W PC3: CPU=Intel Pentium 5, 3.2 GHz processor, 4 GB RAM (2005) OS=Windows XP; Supply: 115/230 VAC (50/60 Hz), 5/2A, 230 W PC4: CPU=Intel Core 7, 3.4 GHz processor, 8 GB RAM (2009) OS= Windows 7; Supply= 100–240 VAC (50/60 Hz), 5.5 A, 260 W
	Air conditioner (A/C)	Model: PROline CL300 Plus HEATER Rated supply: 1-phase, 220–240 VAC (50/60 Hz), 4.3 A Heating/Cooling capacity: 1.75 kW/2.75 kW Intended temperature: 18–32 °C

The tests were carried out to investigate the response of the devices against voltage dips. With the singe-phase devices (contactor-coil, PC, PLC, and A/C), the effect of variations in voltage dip parameters related to the phase supplying the device were tested. During the sensitivity test of contactors and PLCs, a PQ analyzer connected to the terminals between the DUT and the load was used to monitor the response of the device during the disturbance. In the case of the ASD, the effects of magnitude and duration variations associated with various types of voltage dips (one-phase, two-phase and three-phase) and under different loading conditions were explored. When testing the voltage dip sensitivity of the devices, experimental setups were built for each device separately. After building the setup properly, the procedures for testing the sensitivity of the device under test are as follows:

(i) The DUT is supplied with nominal voltage before any disturbance is generated. The PQ analyzer connected to the input side of the DUT is used for checking the quality of the supply voltage supplying the DUT.
(ii) Setting the phase-shift constant and point-on-wave initiation to 0˚, voltage dips are generated in the MX 45 by varying the RMS voltage magnitude in one of the phases from 90% to 0% of the nominal voltage with steps of 2%. For each magnitude, the dip-duration is progressively increased from 10 ms up to few seconds till the device trips, or until 60 s if the device does not trip. The dip ride-through of the device is ascertained by three repeated trials and about 5 s recovery time is allocated before the next voltage dip is applied.
(iii) Step (ii) is repeated for voltage dips with 90˚ point-on-wave dip initiation.
(iv) Steps (ii-iii) are repeated for different loading conditions.
(v) Steps (ii-iv) are repeated for two-phase and three-phase dips.

4.3.2 Voltage-tolerance curves of tested devices

In this section, the results from the equipment dip immunity tests are given in terms of variations on the voltage-tolerance curves.

4.3.2.1 Effect of voltage dips on AC contactors

AC contactors are electromechanical devices widely used for switching and controlling purpose of machines and processes in several commercial and industrial facilities. These devices often have low voltage ride-through capability and they are determined as weak links in automated production lines [71] such that a trip of a contactor can disrupt the whole production line even if all other equipment are immune to voltage dips. Several studies [2, 59, 72-75] show that AC contactors are sensitive to the magnitude, duration and point-on-wave initiation of voltage dips.

During voltage dips, the tripping in the electrical contacts of the contactor depends on the amount of energy stored in the contactor coil which is energized from one phase of a three-phase supply. When the RMS voltage on the phase supplying the AC-coil is reduced below a certain value V_{hold}, the main flux ($\Phi_m \propto V_{hold}$) and hence the force ($f_{min} \propto \Phi^2_{min}$)[72] needed to keep the contacts closed becomes lower than the minimum value. As a result a one-phase dip on the AC-coil can be sufficient enough to disengage the electrical contacts of the contactor leading to a three-phase interruption of the load supply.

The voltage-tolerance curves of six contactors against voltage dips affecting the source supplying the contactor coils are shown in Figure 4.3. For dips below the voltage-tolerance curves, the contactors disengage and cause three-phase interruptions lasting for intervals of the dip-duration. When the voltage dip ends and the supply voltage on the AC-coil recovers, the electrical contacts reengage automatically. This is ascertained by the PQ analyzer with a nominal-zero-nominal (u_n-0-u_n) transition in the RMS voltage at the load terminals. When the dip is not on the phase supplying the contactor coil, a situation that may happen with one-phase and two-phase dips, the contacts do not disengage. During such cases, the load experiences the same disturbance as in the source, and the PQ analyzer measures the remaining voltage (u_r) generated in the source with voltage transition u_n-u_r-u_n.

As also described in earlier studies [2, 59, 72-77], the test results for 0˚ and 90˚ points-on-wave of dip initiations in Figure 4.3(a, b) show that point-on-wave of dip initiation affects the contactor performance significantly. For voltage dips with 0˚ point-on-wave initiations, the voltage-tolerance curves of the tested contactors varied between 50–73% of the nominal voltage, and the duration thresholds varied between 25–50 ms. For voltage dips having remaining voltages less than ~50% and with 0˚ point-on-wave initiation, it can be seen from Figure 4.3(a) that the contactor C_1, for instance, trips faster to shallower dips than to deeper dips (or interruptions). When u=0% (short-interruption), there is higher momentary current (thus, high magnetic energy stored in the coil) at the point of initiation and a minimum AC amplitude (i.e., AC flux) during the dip than when the dip is 50% of the nominal voltage. The alternating current flowing through the coil in the latter case decreases the flux more rapidly, and contactor becomes less tolerant, than in the former case [78].

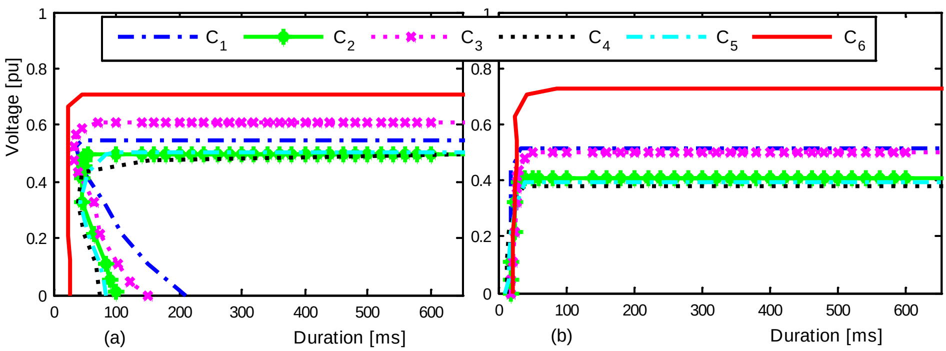


Figure 4.3: Voltage-tolerance curves (VTC) of six AC contactors (C_1, C_2, C_3, C_4, C_5, and C_6) for voltage dips with point-on-wave initiations of – (a) 0˚, and (b) 90˚.

For voltage dips with 90˚ point-on-wave initiations, the voltage-tolerance curves of the tested contactors varied between 38–70% of the nominal voltage, and the duration thresholds varied between 10–20 ms. Because of the inductive nature of the contactor coil, the coil current (or field strength) lags the voltage by ~90°. The coil current and thus the amount of magnetic energy is maximum at the zero-crossing and minimum at 90° of the coil voltage. For this reason, it can be seen from Figure 4.3(a, b) that each contactor trips faster to deeper dips and interruptions for 90˚ than for 0˚ point-on-wave initiations. When short dips take place at the zero-crossing, the flux is at its maximum which provides an energy buffer to maintain the contactor engaged for some time before it disconnects. If the voltage dip starts at 90°, the flux is at its minimum and there is no (very small) energy buffer to keep the contactor connected. Hence, short and deeper dips (or interruption) initiated at 90˚ are worse than those initiated at 0°. The horizontal parts of the voltage-tolerance curves for dips with 0° point-on-wave initiations are about ~2–12% higher than dips with 90° point-on-wave initiation, which indicates that the threshold voltage is not equal for different points-on-wave dip initiations.

For various types of contactors, results show that there is a slight variation in their sensitivity threshold (both magnitude and duration). For each contactor, the voltage-tolerance curves with 0° and 90° point-on-wave dip initiations are compared with the SEMI F47 power acceptability curve in *Appendix-C.1*. It can be observed that only three of the tested contactors (C_2, C_4 and C_5) comply with the SEMI F47 curve. It is also observed from Figure C.2 (in *Appendix-C.1*) that the impact of load change on the performance of the contactors to voltage dips is negligible. The improvements in the VTC of a contactor using the *phase-phase supply* and *Coil-Lock* mitigations can also be found in *Appendix-C.1*.

4.3.2.2 Effect of voltage dips on an AC adjustable speed drive

Adjustable speed drives (ASDs) are power electronic converters that have become integral parts of many industrial processes for improving process control by controlling the torque or speed of motors. The ASD controls the speed or torque of a motor by converting the fixed frequency supply voltage to a variable frequency and variable magnitude of voltage at the motor terminals. A schematic for a classical model of ASD is shown in Figure 4.4. The basic components of the ASD consist of a diode bridge rectifier, a DC-link and an IGBT inverter. The bridge rectifier converts the supply voltage into unregulated DC voltage and the DC-link filter, which acts as an energy buffer, smooths out the ripples allowing the DC component to go through. From the incoming DC voltage, the pulse-width modulated inverter creates AC voltage that is desired by the motor. A drive with active front end topology connected to the LV grid and coupled to the AC motor is emulated to represent the mechanical load.

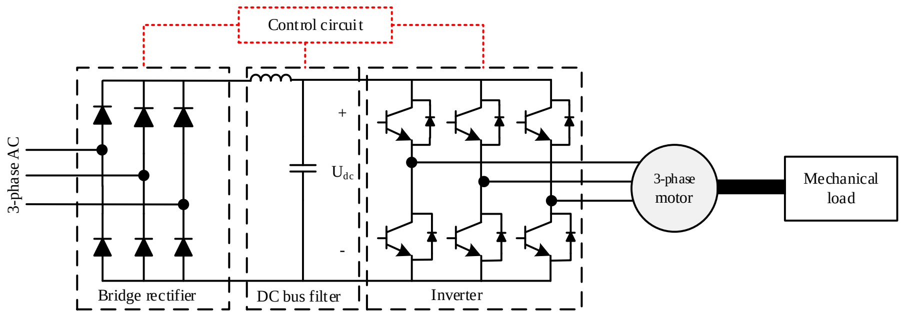


Figure 4.4: Basic components of an ASD connected to an emulated mechanical load.

Previous studies indicate that ASDs are sensitive to voltage dips [2, 60, 61]. Ignoring the voltage drops in the rectifier elements of the classical ASD model shown in Figure 4.4 and assuming no phase shift during different types of voltage dips, the DC bus voltage when the RMS voltage in the supply is dropped to v% of the nominal voltage (U_{rms}) can be calculated using (4.1)–(4.3).

$$One-phase\ dip: U_{dc} = \frac{\sqrt{3}(v+2)\sqrt{2}}{\pi} U_{rms} \quad (4.1)$$

$$Two-phase\ dip: U_{dc} = \frac{\left(3.598v+\sqrt{3}\right)\sqrt{2}}{\pi} U_{rms} \quad (4.2)$$

$$Three-phase\ dip: U_{dc} = \frac{\left(3\sqrt{3}\,v\right)\sqrt{2}}{\pi} U_{rms} \quad (4.3)$$

When the RMS voltage of the supply varies between 0–90% of the nominal voltage, the DC-link voltage during one-phase dips varies in the range of 67–97% relative to the pre-dip DC-link voltage. Similarly, the DC-link voltage varies between 33–96% and 0–90% of the pre-dip DC-link voltage for two-phase and three-phase dips respectively. This indicates that the DC bus voltage will be affected differently by various types of voltage dips.

The tripping of an ASD can happen due to the intervention of undervoltage protection when the DC-bus voltage is lower than the minimum limit (U_{dc-min}) or due to malfunction of the PWM controller of the inverter. With voltage dips, intervention of the undervoltage protection is the most common reason for the ASD trips [60]. As demonstrated in Figure 4.5, the time taken for the DC-bus voltage to reach below the minimum value can be calculated using (4.4) [2, 60].

$$t_{trip} = C\frac{U_{dc-pre}^2 - U_{dc-\min}^2}{2P} \quad (4.4)$$

where C is the DC-bus capacitance, P is the electric power required to drive the load, U_{dc-pre} is the pre-dip DC-bus voltage and U_{dc-min} is the DC-bus undervoltage protection value. As the load increases from no-load to full-load, the energy required by the motor to drive the load increases which makes the capacitor voltage decay and reach U_{dc-min} faster, and leading the device to enter the fail or disturbance region quickly. Thus, the immunity of the ASD worsens both vertically (when magnitude changes) and horizontally (when duration changes).

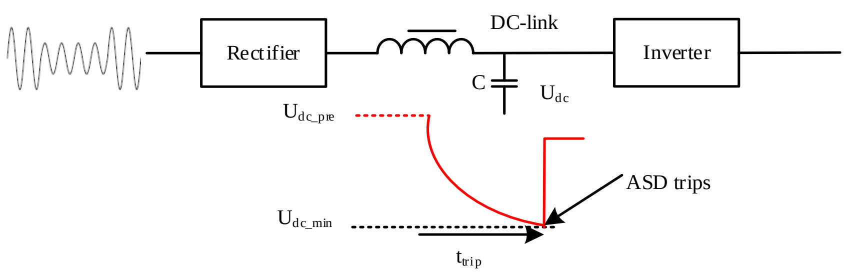


Figure 4.5: Tripping of an ASD on undervoltage.

For the ASD whose specification is given in Table 4.2, the behavior during different types of voltage dips and for various loading conditions is tested. A disconnection (or tripping) of the drive that requires a manual reset is considered as the malfunction criteria. The voltage-tolerance curves of the tested ASD against various types of voltage dips and under different loading conditions are presented in Figure 4.6.

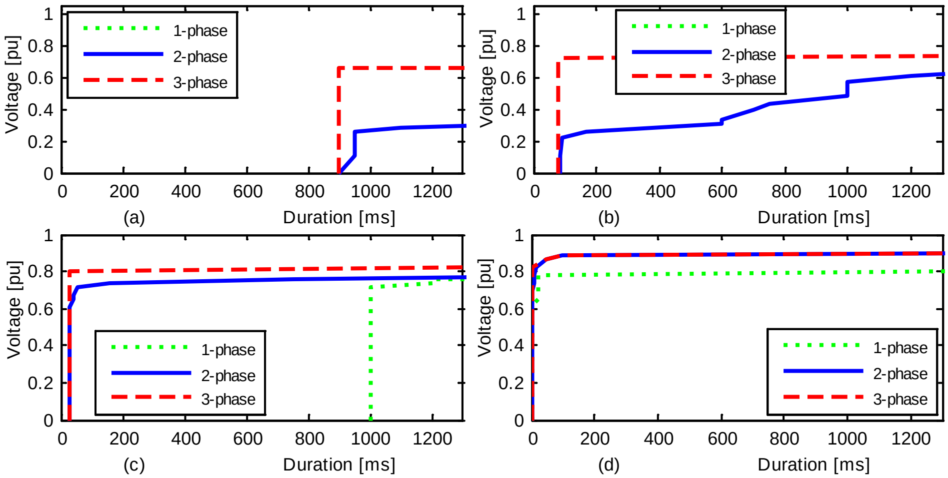


Figure 4.6: Voltage-tolerance curves (VTC) of an ASD against various types of dips and keeping the load constant at – (a) no-load, (b) 50% rated-load, (c) 75% rated-load, and (d) rated-load.

As can be seen from Figure 4.6, the sensitivity of the ASD to voltage dips is considerably influenced by the types of dips and by the loading conditions. At fixed and low loading conditions (up to 70% rated-load), the ASD is more susceptible to the variations in the magnitude of voltage dips (Figure 4.6(a, b)). It is also observed that the ASD loaded to below 70% rated-load is immune to one-phase dips (indicating that a minimum of 67% of the pre-dip DC-link voltage is sufficient enough to keep the ASD running) and thus VTCs are not visible for 0% and 50% rated-load. At 70% of rated-load or higher, one-phase dips started causing problems to the ASD (Figure 4.6(c, d)). Two-phase dips are less severe than three-phase dips and show similar patterns in that the tolerance curves move left and upwards when the loading condition increases.

The loading significantly influences the immunity of the ASD to various types of voltage dips. For example, three-phase dips caused tripping of the ASD at no-load (Figure 4.6(a)) when the supply voltage drops to less than ~65% of the nominal voltage for duration longer than 900 ms. When the load increases to full-load, the energy required to maintain the full-load is much higher than for low loading conditions and this leads the energy buffer of the DC-link to be drained quicker. Thus, the ASD became more vulnerable to shallow- and short-dips. The ASD at full-load, for instance, is found to be prone to almost all two-phase and three-phase dips lasting more than a cycle, and one-phase dips with magnitude of remaining voltage lower than 80% of nominal voltage lasting longer than a cycle. More results on the effect of loading during one-phase and two-phase dips can be found *Appendix-C.2*. It was also observed that the point-on-wave dip initiation is not significant to the performance of ASDs against voltage dips (see *Appendix-C.2*).

The tested ASD with diode bridge rectifier includes electronic controls (such as AC-side overcurrent protection, undervoltage protection of the DC-link voltage, and inverter-side overcurrent protection); and it can be seen from Figure 4.6 that the behavior in reality is more complicated than what can be described using (4.1)–(4.4). New drives with active front end (AFE) rectifiers have also come to the market mainly for loads requiring bidirectional drive. In ASDs with AFE converter, the diode bridge rectifier is replaced by a self-commutated pulsed rectifier with regenerative feedback facilities comprising IGBT modules and clean power filter. The dip ride-through of such drives depends on the rectifier devices' current ratings and loading conditions, and the thermal rating of an IGBT switch allows for overcurrent for certain duration [79]. At the switching frequency of the AFE, the ripple in the DC-bus voltage is small and the AFE rectifier has inherent boost function [79, 80]; and ASDs with AFE rectifier have better ride-through capabilities than classical drives. With an AFE rectifier, IGBTs with high overload factor can be used and the ASD can ride-through deeper dips in the supply voltages [80].

4.3.2.3 Effect of voltage dips on personal computers

Personal computers (PCs) comprise electronic devices that can be affected by the supply voltage variations. Figure 4.7 shows a simplified configuration of the power supply to personal computers and other low-power equipment. The power supply to a computer consists of a single-phase diode rectifier together with a capacitor and a DC-DC voltage regulator. The bridge rectifier coverts the AC signal into unregulated DC voltage, and a capacitor is often connected to the DC-link to reduce the voltage ripple at the input of the voltage regulator. The DC-DC converter transforms the unregulated DC voltage from the DC-link into regulated levels.

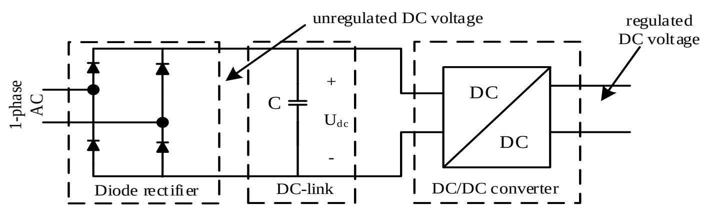


Figure 4.7: A simplified schematic of a computer power supply.

During normal operation, the capacitor is charged twice a cycle through the diodes. When the AC voltage drops suddenly during voltage dips, the capacitor starts to discharge and continues to discharge until the DC-bus voltage has dropped below the peak of the supply voltage, and a new operating point is reached at a lower DC-bus voltage. The duration of the discharge of the capacitor is dependent to the magnitude of the voltage dip, the size of the capacitor and the load current. The voltage regulator is often able to maintain the output voltage level for some variations in the input voltage. If the new steady state value is below the minimum operating voltage of the DC-DC converter or below a certain protection setting, the voltage dip can cause the equipment trip.

Voltage dips can cause computers to restart, and the effect for individual users may not be very significant unless they are used as servers or mainframe computers. However, in computer controlled systems and processes, mainly in commercial sectors like banks and telecommunications where they depend entirely on data processing through PCs in their network, the malfunction of PCs can result in the loss of data incurring substantial financial losses [63]. In the past, many works have been reported in [63, 81, 82] to understand the voltage immunity level of PCs. As an effort to understand the behavior of PCs against voltage dips, the sensitivity of four PCs (with specifications described in Table 4.2) are experimentally tested. During the tests, the PC power supplies and the monitors were supplied from different phases. On the phase supplying the PC power supply, voltage dips of various magnitude and duration are generated to study the ride-through capability of each PC while the monitor is supplied with a normal supply. An automatic restart/reboot is selected as the malfunction criterion for the PCs during voltage dips. After each shutdown due to a voltage dip, the PCs were allowed to restart the operating system properly before applying another dip.

The voltage-tolerance curves of the tested PCs along with the ITIC power acceptability curve are shown Figure 4.8. Similar to the previous research findings on the susceptibility of PCs against voltage dips, the obtained voltage-tolerance curves for the tested PCs include the same rectangular shape with a very sharp knee between two distinctive vertical and horizontal parts. The magnitude-duration pair of the knee points for the tested computers PC_1 to PC_4 are (56%, 118 ms), (62%, 150 ms), (42%, 290 ms) and (32%, 220 ms) respectively.

As can be seen from Figure 4.8, the magnitude thresholds of the tested PCs varied between 32%–62% of the nominal voltage while the duration thresholds varied between 118–290 ms. Comparing the sensitivity of the tested PCs, PC_2 is the most sensitive and PC4 is the least sensitive to the voltage dip magnitude. With regard to sensitivity of the PCs to dip durations, PC_1 malfunctions faster than the other PCs. It is also observed that all the tested PCs comply with the voltage dip immunity curve of the ITIC standard.

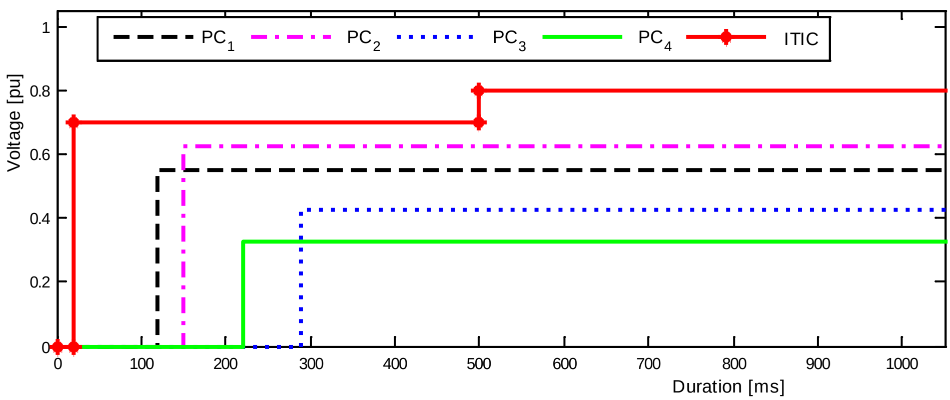


Figure 4.8: Voltage-tolerance curves of the tested PCs.

4.3.2.4 Effect of voltage dips on programmable logic controllers

Programmable logic controllers (PLCs) are another type of industrial devices sensitive to voltage dips. There are different types of PLCs for various methods of process control, but all controllers have the same basic elements. They all have a power supply module to supply the controller with an AC or DC voltage; CPU that is usually powered from an internal DC power supply through an AC or DC input; and I/O module which gives the CPU the means to interpret and manipulate electrical control signals.

The power supply module of the PLC provides DC power to all devices physically mounted in the PLC rack, including the CPU and I/O modules. When the power supply detects a serious disturbance, the CPU is notified to halt the execution and shutdown process operations. During voltage dips, the shutdown signal is generated when the voltage drops below the lower limit, and removes the shutdown signal when the voltage comes back to above the lower voltage limit.

When the power supply and I/O modules use AC voltages, voltage dips can affect the controller through the CPU power supply or I/O. For voltage dips with 0° point-on-wave initiation, the immunity of three PLCs described in Table 4.2 are tested against variations in magnitude and duration of voltage dips. Figure 4.9 shows the voltage-tolerance curves of the power supply modules for the three PLCs along with the SEMI F47 power acceptability curve. Voltage dips below the curves cause the internal DC voltages of the PLCs to fall below the lower limit and the relays/contacts to disengage the load. When the load trips due to a voltage dip and reconnects when the voltage recovers to a value above the lower limit, an *audible clicking sound* of the contact is heard, and this is ascertained by the PQ analyzer connected to the load terminal with a u%-0%-u% transition in the RMS voltage.

As can be seen from Figure 4.9, the three PLCs have different sensitivity curves against voltage dips. The magnitude thresholds for the tested PLCs varied between 18–35% of the nominal voltage and the duration thresholds varied between 20–380 ms. Also, it can be noticed that the tested PLCs satisfy the SEMI F47 power acceptability curve. However, it should be recalled that different types of PLCs with wide range of ride-through capabilities are available for various methods of process controls.

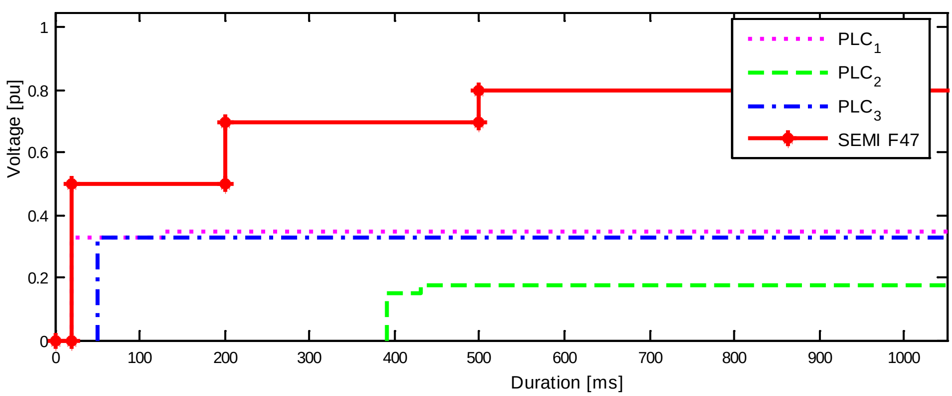


Figure 4.9: Voltage-tolerance curves of power supply modules for three PLCs from different manufacturers.

Regarding the sensitivity of the I/O modules, Figure 4.10 shows that the input modules for PLC_1 and PLC_3 are robust against voltage dips of any magnitude and duration as long as the source on the power supply module is free of voltage disturbance. The susceptibility of the I/O modules is, therefore, directly related to the immunity of the power supply module and the susceptibility of individual loads connected to the output module. On the other hand, the input module for PLC_2 is more sensitive than the power supply module. In this case, system shutdowns can happen before the PLC's power supply has not already led to the system trip and the susceptibility of the input module to voltage dips is very relevant.

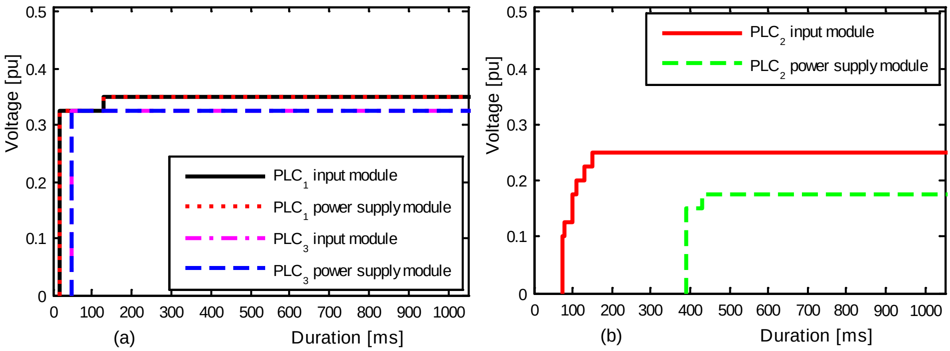


Figure 4.10: Dip susceptibility of the input module Vs power supply module for – (a) PLC_1 and PLC_3, and (b) PLC_2.

4.3.2.5 Effect of voltage dips on an Air conditioner

Air conditioner (A/C) is a low load appliance which is commonly used for regulating the air temperature into comfortable conditions with the objective of distributing the regulated air to the occupied space (e.g. building, or vehicle). With voltage dips, the motor current can increase and large currents during severe dips can activate the thermal protection to trip [83].

For the A/C specified in Table 4.2, the effect of variations of voltage dips parameters during cooling situations is experimentally tested. For this device, a temporary stoppage followed by self-rebooting is considered as a failure criteria during voltage dips. Normal operation is when the device performs well without any reboot. Figure 4.11 shows the sensitivity of the tested air conditioner against voltage dips for the intended temperatures of 22˚C and 18˚C while the outside temperature (temperature of the room) was 28˚C.

When the intended temperature is set to a value lower than the room temperature, the device (requires) consumes more energy (power) in order to reduce the heat from inside the room (building) and thus lowering the air temperature. When the supply voltage experiences voltage dips during such cases, the A/C can fail to operate properly. It can be seen from Figure 4.11 that the A/C is more vulnerable to voltage dips when it is intended to reduce the temperature of the room from 28˚C to 18˚C than from 28˚C to 22˚C, i.e., the A/C becomes vulnerable to relatively shallower and shorter voltage dips when the intended temperature is set to the lowest value and this is expected as more energy is required to reduce the surrounding temperature to the intended temperature. In this case, the A/C with intended temperature set to 22°C fails to voltage dips lower than 35% of the nominal voltage with duration longer than 550 ms, and the A/C malfunctions 10 cycles faster when the intended temperature is set to the lowest allowed value (18°C).

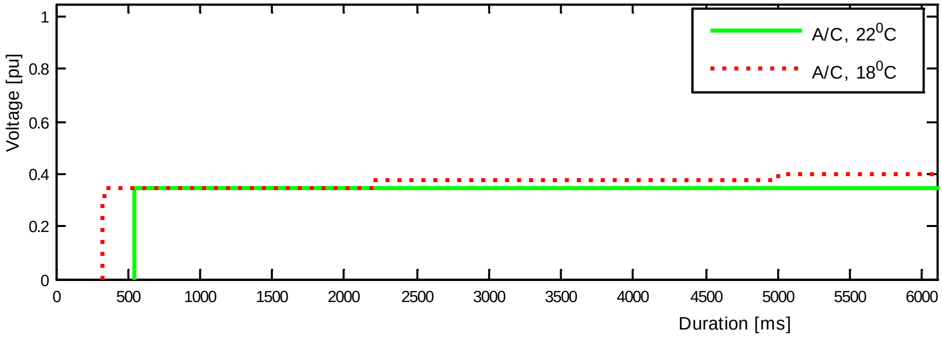


Figure 4.11: Voltage-tolerance curves for an Air conditioner based on experimental tests.

4.4 Process immunity to voltage dips

The sensitivity of an industrial process to voltage dips depends on the composition, interconnection and behavior of individual equipment that make up the process. The composition refers to the number and type of process equipment while the interconnection of process equipment deals with the series/parallel connections of equipment in the process. The behavior of individual equipment refers to the robustness of the device measured by the voltage ride-thorough capacity. The response of industrial processes to incoming voltage dips is directly influenced by the ride-through capability of equipment that make up the process. It is possible that a process may get disrupted due to the tripping of individual equipment or it may require the tripping of a group of equipment upon their interconnection.

One way to reduce the voltage dip problems of an industrial process is by making the process more robust against voltage dips. This can be attained by replacing the weak link equipment by an equipment with better ride-through capability or improving the immunity of the weak link of process equipment by installing power conditioning devices. To increase the immunity of the process to voltage dips, it is important to understand the response of individual equipment as well as the interaction among all equipment participating in the process.

4.4.1 Voltage dip sensitivity of a simple process

Figure 4.12 shows an experimental setup of a simple process that consists of the cascade of a contactor (C_1) and an ASD supplying a load. The sensitivity of the contactor and ASD to voltage dips are described earlier in this chapter. With this setup, the process is tested for voltage disturbances under which the equipment were tested in order to study the interaction between the devices and to identify the weak link of the process. The same procedures are followed as testing the immunity of the devices in evaluating the performance of the process against various dip types generated in the MX45 and under different loading conditions.

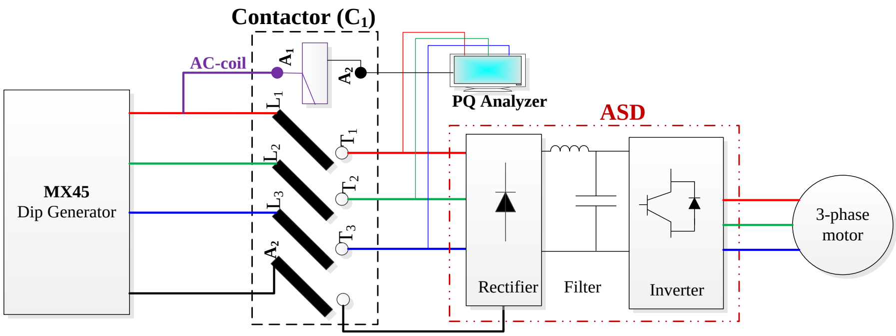


Figure 4.12: Experimental setup for testing the immunity of the process.

Figure 4.13 presents the effect of different types of dips on the voltage dips immunity of the process. For fixed loading situation, it can be seen that sensitivity of the process increases when the number of affected phases increases. The voltage-tolerance curves indicate that the process trips slightly faster to short- and shallow-dips of three-phase dips than two-phase and one-phase dips.

It can also be seen from Figure 4.13 that the process sensitivity against each type of dip increases when the load increases and more results can be found in *Appendix-C.3*. This is expected because the load draws more power from the supply that quickly drains the stored energy in the DC buffer of the ASD.

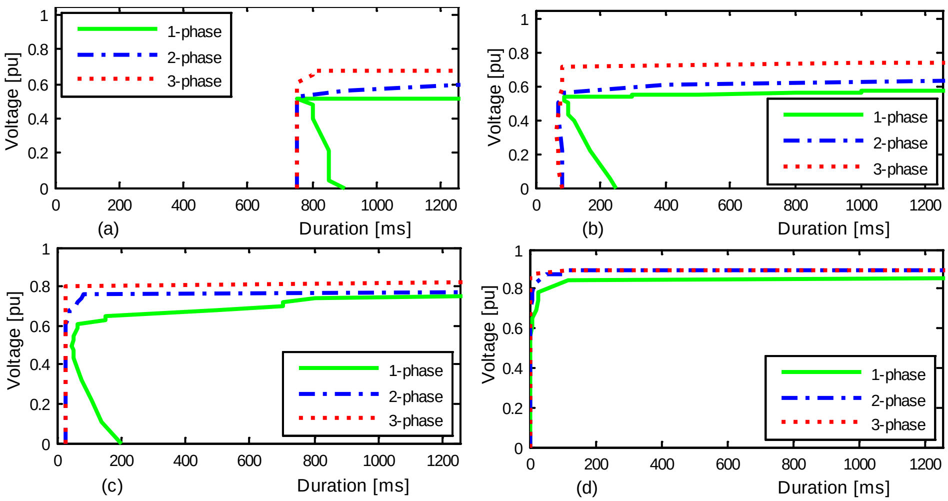


Figure 4.13: Impact of various types of voltage dips on the process immunity at loading conditions of – (a) 0% rated-load, (d) 50% rated-load, (c) 75% rated-load, and (d) 100% rated-load.

4.4.2 Weak link component of the process

Better insight into the weakest link of process equipment can be obtained by comparing the voltage-tolerance curve of the process with the tolerance curves of individual devices under similar conditions. For instance, Figure 4.14 shows a comparison on voltage dip immunity of the individual equipment and the process during three-phase dips and for various loading conditions.

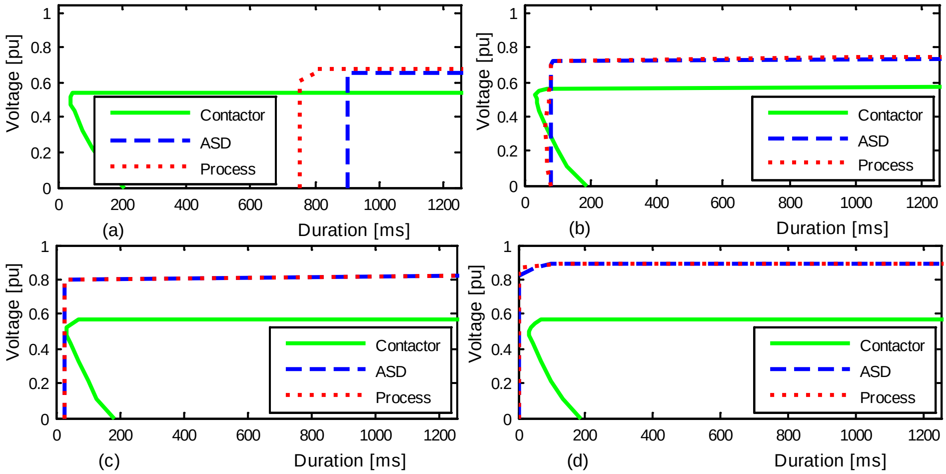


Figure 4.14: Comparison of immunity of a contactor C_1 and an ASD with the process against three-phase dips at loadings – (a) 0% rated-load, (b) 50% rated-load, (c) 75% rated-load, and (d) 100% rated-load.

At no-load, Figure 4.14(a) shows that the contactor tripped at least 700 ms faster than the ASD and 550 ms faster than the process for voltage dips below 54% of the nominal voltage. The process is, therefore, not affected by the contactor trip due to voltage dips shorter than 750 ms. Even if the ASD at no-load was not affected by three-phase voltage dips longer than 750 ms and shorter than 900 ms, the process tripped for these dips and the contactor is the weakest link of the process. On the other hand, the contactor was not affected by voltage dips shallower than 54% of the nominal voltage while the ASD tripped by three-phase voltage drops below 67% of the nominal voltage and longer than 900 ms. The ASD is, therefore, the weakest link of the process at no-load for dips with remaining voltage between 54–67% of the nominal voltage and longer than 900 ms. For 50% loading (Figure 4.14(b)), the ASD tripped for three-phase dips below 25% of the nominal voltage and longer than 80 ms before the contactor, and the voltage-tolerance curve of the process followed that of the ASD which indicates the ASD is the weakest link. For voltage dips with magnitude between 25–54% of the nominal voltage and shorter than 80 ms, the contactor tripped faster than the ASD but then the consequential interruption did not change the voltage-tolerance curve of the process. For high loads, it can be seen from Figure 4.14(c-d) that the ASD tripped before the contactor, and voltage-tolerance curves of the process followed that of the ASD. The ASD is, therefore, the weakest link of the process to three-phase dips during actual loading conditions.

Comparisons of equipment and process sensitivities curves for two-phase and one-phase dips under various loading conditions can be found in *Appendix-C.3*. For two-phase dips (Figure C.7), the performance of the contactor is the same as for one-phase dips and the ASD at no-load started tripping to dips with remaining voltage magnitudes below 25% of nominal voltage and longer than 900 ms dips. Three-phase interruptions caused by the contactor trip triggered the tripping of the process about 150 ms faster than the ASD and also for dips above 25%. As the loading increased to 50% rated-load, the ASD tripped before the contactor to dips below 25% of nominal voltage and duration longer than ~80 ms and this caused the process trip. For dips above 25% of nominal voltage, the disruptions caused by the contactor trip triggered the ASD to fail and hence the process at 50% rated-load to trip. Therefore, the contactor or ASD can be the weakest link depending on the magnitude of the remaining voltage. At high loads (75–100% rated), the ASD tripped before the contactor for two-phase dips and the tolerance curve of the process followed that of the ASD which indicates the ASD is the weakest link.

With one-phase dips, it is shown in Figure C.8 that the ASD at no-load and 50% rated-load was immune to all voltage dips. However, failure of the contactor due to one-phase dips on the AC-coil caused three-phase interruptions that tripped the ASD and hence the process. The shapes of the voltage-tolerance curves of the process and the contactor are similar except with some (700 ms–50 ms) delay in time and with a slightly lower horizontal part in the tolerance curve of the process. The contactor is, therefore, the weakest link of the process for one-phase dips at low loads. At 75% rated-load, the sensitivity curve of the process is shifted even closer to that of the contactor while the ASD tripped under these conditions for dips longer than 50 cycles. Thus, the contactor remains the weakest link for loading conditions up to 75% rated-load. At full-load, the voltage-tolerance curve of the process followed that of the ASD which implies that the ASD is the weakest link in the whole process.

Although the shape of voltage-tolerance curves of process components can give an indication for the weakest link component in the process, more information is still required. Table 4.3 gives a brief summary of the process components that triggered the tripping of the process depending on the remaining voltage and duration of various types of voltage dips and under different loading conditions. For one-phase dips at full-load and polyphase dips with realistic loading situations, the ASD is the weakest link of the process. During practical loading situations, the process becomes more susceptible to shallower dips when more number of phases are affected by the voltage dip. An increase in sensitivity towards shorter dips happens mainly when the weakest link in the process shifts from the contactor to the ASD which is highly load-dependent.

Table 4.3: Weak link of the process (component that triggers tripping of the process)

	Weak link component for various type of dips		
Loading	***One-phase dips***	***Two-phase dips***	***Three-phase dips***
0% rated	**Contactor** to dips with ($u<52\%$, $\Delta t\geq750$ ms)	**Contactor** to dips with ($u<57\%$, $\Delta t\geq750$ ms)	**Contactor** to ($u<54\%$, $\Delta t<900$ ms) **ASD** to ($u<67\%$, $\Delta t\geq900$ ms)
50% rated	**Contactor** to dips with ($u<54\%$, $\Delta t\geq100$ ms)	**Contactor** to ($u>25\%$, $\Delta t\geq80$ ms), **ASD** to dips ($u<25\%$, $\Delta t\geq80$ ms)	**ASD** to dips with ($u<72\%$, $\Delta t\geq80$ ms)
75% rated	**Contactor** to ($u<54\%$, $\Delta t\geq60$ ms), **ASD** to dips with $u>54\%$	**ASD** to dips of with ($u<76\%$, $\Delta t\geq30$ ms)	**ASD** to dips with ($u<80\%$, $\Delta t\geq30$ ms)
100% rated	**ASD** to dips with ($u<85\%$, $\Delta t\geq10$ms)	**ASD** to dips with ($u<89\%$, $\Delta t\geq10$ ms)	**ASD** to dips with ($u<90\%$, $\Delta t\geq10$ms)

In the CIGRE/CIRED/UIE JWG [2, 84], the concept of process immunity time (PIT) (defined in *Appendix-C.3*) is proposed for the assessment of process dip immunity based on the impact of a short-interruption of the supply for each equipment that make up the process. Applying this concept to the (tested) simple process, the PITs for the equipment and against different types of voltage disturbances and at various loading conditions are given in Table C.1 (in *Appendix-C.3*). The equipment with the shortest PIT receives higher priority and the criticalities of the process equipment are ranked. Based on the PIT values, the critical equipment ranked first can be considered as the weakest link component in the process. However, the PIT of the process can be different from that of the weakest link component in the process. The actual PIT values of the process can also be influenced by the types of disturbances and the loading conditions.

4.4.3 Estimated response of the process against field data

To assess the performance of end-user equipment and processes, information about the frequency and severity of voltage dips at the installation points, voltage-tolerance curves of process equipment and the connection of the equipment inside the process are needed. As discussed in *Chapter 3*, phase-phase dips evaluated from the phase-to-ground voltages which are monitored in the MV-networks propagate into phase-dips in the LV-network. Therefore, the magnitudes and durations of phase-phase dips in the MV-network are considered for analyzing the estimated equipment and process performance to various types of voltage dips from field measurements. The performance of the process that comprises of an AC contactor in series with an ASD against different types of dips monitored during four years of a substation is shown Figure 4.15. The voltage-tolerance curves of the contactor, ASD and the process are obtained from experiment tests described earlier in *Section-4.3* and *Section-4.4*. As it can be recalled, the voltage-tolerance curve the contactor is affected by the point-on-wave dip initiations while that of the ASD is significantly influenced by the loading conditions and type of dips. In this case, 0° point-on-wave dip initiations and 75% rated-load are considered for analysis purpose.

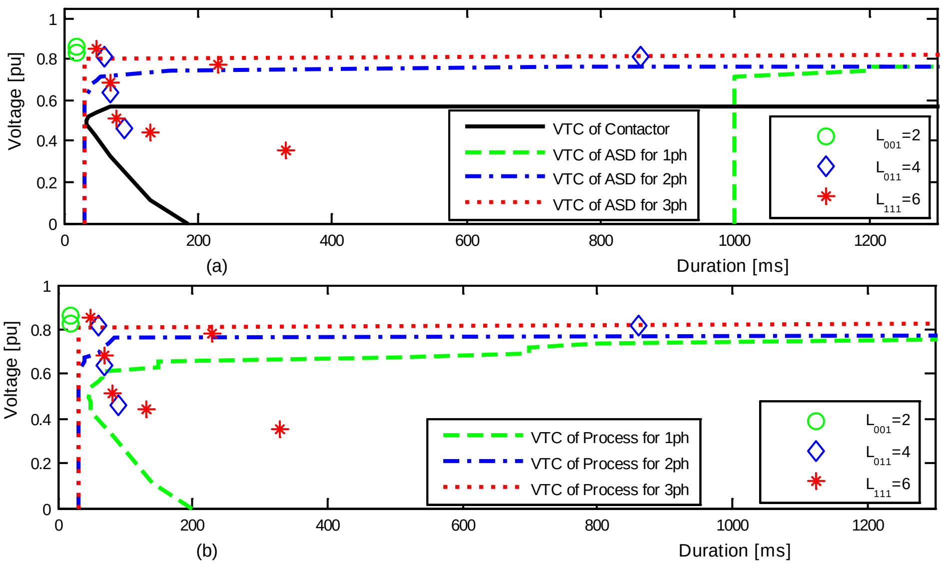


Figure 4.15. Estimated response against field measured one-phase (L_{001}), two-phase (L_{011}) and three-phase (L_{111}) dips for- (a) Contactor C_1 and ASD at 75% rated-load, (b) Process at 75% rated-load.

From the monitor installed in the MV-network, 12 dips of different type are transferring into the LV-network in 4 years. A summary on the performance of individual equipment and the process is given in Table 4.4. If the contactor coil is considered to experience all the dips in the LV-network (Table 4.4(a)), 4 dips would cause tripping of the contactor as wells as the ASD, and hence the process. Although the contactor can withstand the other dips, the ASD further trips to the other 3 dips that would also result in the tripping of the whole process.

In practice, the contactor coil may not be affected by one-phase or two-phase dips originating from the MV-network. In such cases, the contactor would have about 33% and 67% chance that its AC-coil would be exposed to one-phase and two-phase dips originating from the MV-network. Considering this probability may reduce the expected number of contactor trips, in this case from 4 to 3.67 trips in four years (Table 4.4(b)).

The frequency and severity of voltage dips caused by different types of dips may vary from site to site and this may affect the number of equipment and process trips. If the frequency and severity of one-phase and three-phase dips were interchanged (Table 4.4(c)), the contactor would trip to 4 dips; the ASD would trip to 2 dips while the process would trip to 5 dips. In this case, the 3 one-phase dips causing contactor trips would lead to three-phase interruptions that would initiate the process trip in addition to the 2 trips because of the ASD.

Table 4.4: Summary on the voltage dips performance of equipment and a process

Dip types in an MV-network	*Total number of dips in 4 yrs [#]*	*Dips below VTC of the Contactor C_1 [#]*	*Dips below VTC of the ASD [#]*	*Dips below VTC the Process [#]*
	(a) Assuming the contactor coil is always affected by any type of dip in the LV-network			
L_{001}	2	0	0	0
L_{011}	4	1	2	2
L_{111}	6	3	5	5
Total	***12***	***4***	***7***	***7***
Mean	***3.00***	***1.00***	***1.75***	***1.75***
	(b) Considering the chance for the contactor coil to be affected by different types of dips			
L_{001}	2	0	0	0
L_{011}	4	0.67	2	2
L_{111}	6	3	5	5
Total	***12***	***3.67***	***7***	***7***
Mean	***3.00***	***0.92***	***1.75***	***1.75***
	(c) Effect of variation in dip frequency and severity on equipment and process trip			
L_{001}	6	3	0	3
L_{011}	4	1	2	2
L_{111}	2	0	0	0
Total	***12***	***4***	***2***	***5***
Mean	***3.00***	***1.00***	***0.50***	***1.25***

In *Appendix-C.3*, the severity of voltage dips from field measurement are compared with the voltage-tolerance curves of the process at various loading conditions for various types of dips. At no-load, none of the dips would cause the process trip. Since the magnitudes of the L_{001} dips are above 80% of the nominal voltage, the process at any loading conditions would not be affected by the L_{001} dips. At 50% rated-load, 1/4 of L_{011} dips and 3/6 of L_{111} dips would cause process trips in four years. At 100% rated-load, all L_{011} and L_{111} dips would cause process trips.

4.5 Summary

There are many standards dealing with power quality. Some standards provide guidance on how to test the immunity of devices. Others are developed with the purpose to be used as requirements mainly focusing on single components and the surrounding (classes of) electromagnetic environment. The present standards consider only the magnitude and duration of voltage dips for testing the equipment dip immunity requirements. Besides, the test points are specified for single-phase supply but not for three-phase supply.

It is observed from the immunity tests that different devices can have different immunity against voltage dips. The magnitude and duration of voltage dips are not the only parameters that affect the behavior of devices against voltage dips. For instance, the sensitivity of ASDs can be significantly influenced by the type of dips and the loading conditions while the behavior of AC contactors can be affected by the point-on-wave dip initiations in addition to the effect of dip magnitude and duration. The behavior of devices against voltage dips can, therefore, be accurately described when a higher number of voltage dip characteristics are considered.

The weak link component of a process can be estimated by comparing the voltage-tolerance curves of the process and equipment at similar test conditions against the same disturbance parameters. However, experiment results on a simple process showed that the immunity of the actual process can significantly be affected by the types of voltage dips and the loading conditions of the process; and the process dip immunity can actually be different from the immunity of the weakest link component within the process.

5

Impact of voltage dips on aggregated customers

5.1 Introduction

The impact of voltage dips on process equipment depends on the performance of the supply system and the sensitivity of the equipment to voltage dips. The performance of the supply system is described by the frequency and severity of voltage dips whereas the equipment sensitivity is represented by the voltage-tolerance curves. A common problem is that voltage dips are considered as a single-phase instead of multi-phase phenomenon, and most standards consider the magnitude and duration of voltage dips in describing the severity of voltage dips [8-10] and for testing equipment dip immunity [38, 67, 68, 85]. However, the two-dimensions of voltage dips may not show direct correlation with the impact of voltage dips on end-user equipment and processes. Besides this, different types of equipment have a wide range of behavior against various types of voltage dips (detailed in *Chapter 4*).

The effect of voltage dips on an industrial process, which is usually composed of several equipment, is more complex than what is explained in the standards. Moreover, different customers are connected to the distribution networks and the effect of voltage dips on the combined customers becomes even more complicated. In this chapter, a methodology for estimating the impact of voltage dips on the combined customers is described. Taking into account the transfer of voltage dips from the MV-network to the LV-network, the correlation between the severity of voltage dips and their impact on the aggregated customers is analyzed. Based on field measurement data from several sites for several years, voltage dip severity weighting factors are calculated that may be useful for estimating the economic impact of voltage dips on the customers in the whole MV distribution network or on an industrial customer connected to the network. Moreover, the obtained system dip severity indices can be used for comparing the severity of voltage dips during aggregation of multiple-dips and for setting voltage dip limits for the regulatory purpose.

5.2 Single-event index of voltage dips

As discussed in *Chapter 3*, the characteristic of RMS voltage magnitude as a function of time can be obtained from the voltage waveform with high time resolution. From the event characteristic as a function of time, a number of indices describing the event can be determined. Several methods, leading to a single-index for each voltage event, have been considered in many literatures [39, 86-90] for evaluating the severity of voltage dip events.

A voltage dip severity evaluation approach based on the *lost voltage-time area* of dips is presented in [88]. According to this method, the product of the voltage drop and duration can be compared with the area that belongs to the corresponding "corner point" on the ITIC or SEMI F47 curve. RMS voltage with rectangular shape is considered along with a reference curve which is only applicable for single-phase phenomenon. For a polyphase voltage dip event with nonrectangular shapes, the lost voltage-time area (LVTA) of the event can be calculated as the line integrals of the voltage drops during the dips related to each phase expressed by (5.1),

$$LVTA = \int_{t_{1a}}^{t_{2a}} \left(1 - \frac{u_a}{u_n}\right) dt + \int_{t_{1b}}^{t_{2b}} \left(1 - \frac{u_b}{u_n}\right) dt + \int_{t_{1c}}^{t_{2c}} \left(1 - \frac{u_c}{u_n}\right) dt \tag{5.1}$$

where u_n is the nominal value for the RMS voltage, u_a, u_b and u_c are RMS values of the event below the dip start threshold, and between the moment of dip-start t_1 and moment of dip-end t_2. The larger the LVTA of the event the more severe it is considered to be. However, the method provides no direct indication between comparative single-event index values and the behavior of process equipment during the events.

As described in [39, 86, 87], severity index (S_e) of a voltage dip event can be calculated from the event magnitude and duration along with the reference curve. The value can be calculated using (5.2),

$$S_e = \frac{1-u}{1-u_{ref}(d)} \tag{5.2}$$

where u is the remaining voltage magnitude (in pu) and $u_{ref}(d)$ is the magnitude value of the reference curve during the same event duration (d). With this method, the severity of each event can be compared with the voltage-tolerance curves of equipment (such as SEMI F47, ITIC or other curves when available). In this case, the magnitude of the remaining voltage should be the value at the equipment terminals when voltage dips are monitored at other voltage levels.

Voltage sag energy index is another approach described in [39, 89, 90] for evaluating the severity of a dip event in terms of a single-index value. For a dip event involving multiple-phases, the voltage sag energy index (E_{vs}) proportional to the energy not delivered to a constant impedance load can be evaluated by (5.3) [39],

$$E_{vs} = \int_{t_{1a}}^{t_{2a}} \left(1 - \frac{u_a^2}{u_n^2}\right) dt + \int_{t_{1b}}^{t_{2b}} \left(1 - \frac{u_b^2}{u_n^2}\right) dt + \int_{t_{1c}}^{t_{2c}} \left(1 - \frac{u_c^2}{u_n^2}\right) dt \tag{5.3}$$

where u_a, u_b and u_c are RMS values of the event below the dip start threshold; t_1 and t_2 are the dip-start and dip-end moments of the event associated with each phase-to-ground or phase-phase voltages.

The aforementioned methods can simplify the comparison of severities of voltage events. However, the single-index representation of the event may lead to a high loss of information. Besides, the result of single-event index method is no longer directly related to equipment behavior. Another method of determining the impact of voltage dips on the customers is discussed more in detail in the next sections.

5.3 Voltage dip impact on aggregated customers

In this section, the impact of voltage dips on the aggregated customers are evaluated from the change of power as a result of voltage dips from field measurements. Figure 5.1 is the schematic of a generic network showing the monitoring point, aggregated customers connected to this monitoring point and end-users. Depending on the size of the substations, the MV-networks considered here consist of between 11 and 32 radially operating feeders connected to the primary substation. The feeders are numbered as F_1, F_2… F_n and all customers in each feeder are aggregated into a big customer connected to the point of common coupling (PCC) of the primary substation.

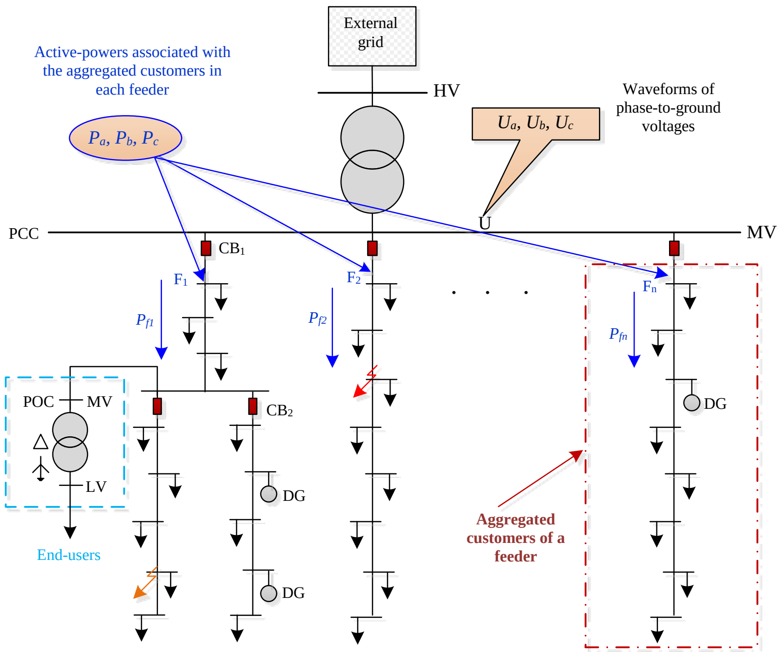


Figure 5.1: Schematic of a generic distribution network.

With regard to the monitoring tools installed at the PCC (Figure 5.1) of MV-networks, two groups of data recorded by the PQ monitor are used for analyzing voltage dip impacts. The first part includes waveforms of phase-to-ground voltages sampled at 4 kHz. The other group of data includes half-cycle RMS values of per-phase power for the aggregated customers in each feeder connected to the main substation (PCC).

The flowchart shown in Figure 5.2 gives an overview of procedures for evaluating the impact of voltage dips on the aggregated customers. For each voltage event monitored at the PCC of an MV substation that consists of n feeders, the evaluation procedure includes:

(i) Characterization of the voltage event and checking if it qualifies for a dip.
(ii) Evaluation of the active-power for the aggregated customers in each feeder before, during and after the event when (i) is satisfied.
(iii) Checking if the relative origin of the dip is in the upstream (HV or another feeder) with respect to the feeder under consideration.
(iv) Estimating the absolute loss of power for the aggregated customers in each feeder satisfying (iii) and categorizing it as loss of loads or loss of DGs.
(v) Evaluating the system loss of loads and loss of DGs by combining the losses in all feeders calculated in step (iv).
(vi) Estimating the relative loss of power for the customers in the entire substation.

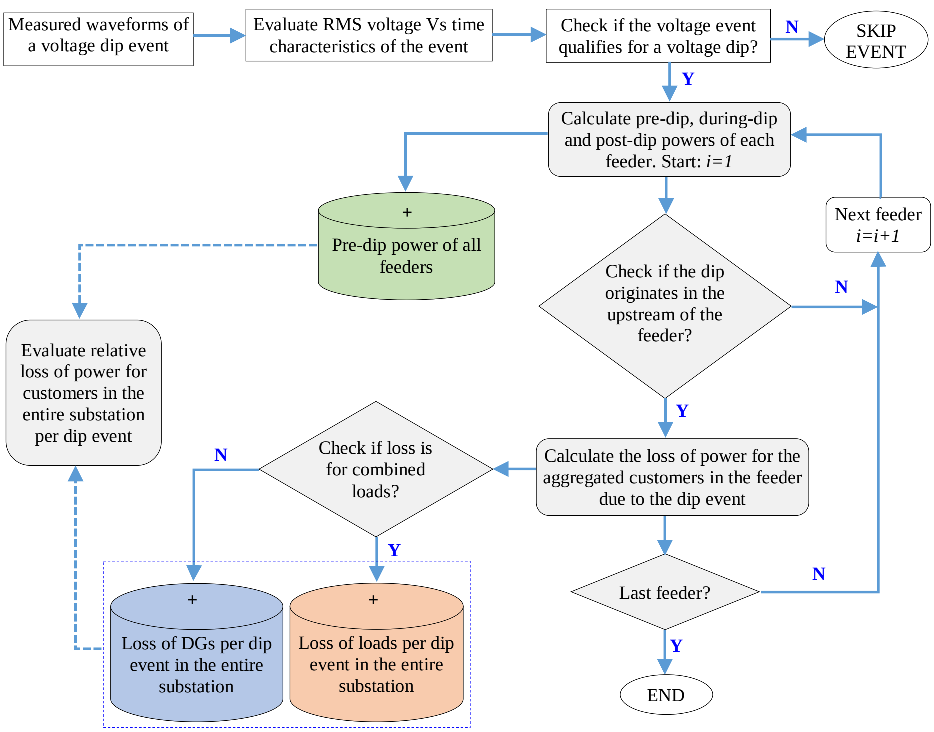


Figure 5.2: Flowchart for a voltage dip impact evaluation procedure.

5.3.1 Voltage dip severity assessment

As discussed more in detail in *Chapter 3*, RMS voltage characteristics as a function of time are evaluated from the measured waveforms of phase-to-ground voltages using the guidelines of the IEC 61000-4-30 [6]. Since end-users are mostly connected to the MV-networks through Dyn transformers, parameters of voltage dips propagating to the end-user terminals are determined from the characteristics of phase-to-phase voltages as a function of time that are evaluated from the waveforms of phase-to-ground voltages.

For analyzing the correlation between the variations of voltage dip parameters with their impact on the aggregated customers (discussed later in *Section 5.4*), the severities of voltage dips are characterized here in terms of the remaining voltage magnitude, duration and type. Depending on the number of phase-phase voltages in the MV-network being affected by the dip, voltage dips are categorized into three types- L_{001} (dips affecting only one of the phase-phase voltages), L_{011} (dips affecting two of the phase-phase voltages) and L_{111} (dips in all phase-phase voltages). The distribution of different types of voltage dips collected from PQ monitors installed at the MV side of six HV/MV substations during four years can be seen from the profile shown in Figure 5.3. It can be noticed that clusters of phase-phase dips with magnitudes varying from deeper (magnitudes lower than 50% of the nominal voltage) to shallow ($u \geq 50\%$) have certain intervals of times that have to do with the clearing time of protection devices used in the HV- and MV-networks. From this point of view, groups of voltage dips with short-durations ($\Delta t \leq 200$ ms), with medium-durations ($200 < \Delta t \leq 1000$ ms) and long-durations ($\Delta t > 1000$ ms) are considered. In order to take the cumulative impact of multiple-dips on the aggregated customers into account, the lowest-magnitude and total-duration method of aggregating multiple-dips is considered in the analysis.

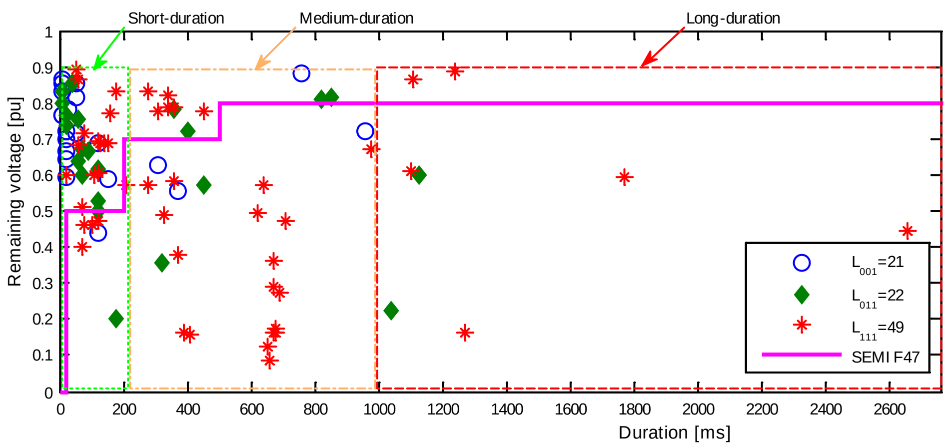


Figure 5.3: Scatter plot of phase-phase dips for various types of dips.

5.3.2 Relative origin of voltage dip events

The origin of a voltage dip measured in the MV-network can be the HV-or MV-network. Several techniques have been proposed in [91-95] by many researchers for locating the source of voltage dips. In [91], a method using the real current component is discussed to locate the source of voltage dips. Another method proposed in [92] uses the line-fitting parameters of the current and voltage during voltage sag for detecting sag direction. By detecting the seen impedance and its angle before the dip event, application of distance relay method is proposed in [93]. In [94], an approach based on the causes of events is considered to identify the source of voltage dips. A method based on the concurrent monitoring of an event by nearby primary substations connected to a common HV-network is discussed in [95]. However, these methods use information of multiple monitors, or require knowledge of HV-network topology or they are applied only to dips caused by short-circuit faults. In this thesis, a method based on the active-power for the aggregated customers of each feeder is used for detecting the relative origin of dips monitored at the main MV busbar.

Before and after the occurrence of a voltage dip event, a feeder may have large-positive, very small (negligible) or large-negative values of power. Depending on the net power before and after the dip event, the pre-dip and post-dip power in each feeder is considered positive (load-power) if the feeder draws power from the substation, and negative (generation-power) when the feeder generates power towards the main busbar. With regard to the pre-dip and post-dip powers of the combined customers in each feeder, the different situations related to the status of the feeder during the dip event at the PCC can be categorized as:

- *Interruption of customers* when the post-dip power of a feeder is reduced to a very low value due to a fault in the same feeder (for example, due to operation of secondary protection).
- *Partial loss of loads* when a feeder shows less load-power or more generation-power after the dip than before the dip event and the disturbance is not in the same feeder (for instance, due to a disturbance in the other feeders or HV).
- *Partial loss of distributed generations (DGs)* if the post-dip power of a feeder shows an increase in load-power or a decrease in generation-power relative to the pre-dip power, and when the dip is not caused by the connection of additional loads in the same feeder.
- *More loads (less DGs)* when the post-dip power of a feeder is larger than the pre-dip power and the dip is caused due to the switching of additional loads in the same feeder.
- *No (negligible) change of power* when the power of aggregated customers in a feeder is not affected by the dip event.

For the aggregated customers of a feeder, a voltage dip that is monitored at the PCC of the MV-network may originate in the downstream (within the same feeder) or upstream (in the HV-network or in any other neighboring feeders). Using the power characteristics of the aggregated customers in each feeder, the *upstream/downstream* criteria is used to detect the relative origin of the dip with respect to the feeder under consideration. According to this criteria, the dip event originates in the downstream of the feeder when the during-power is much higher than the pre-dip power whereas the post-dip power reduces to a very small value if the event is caused by a short-circuit fault or the post-dip power increases if the event is due to the switching of additional loads. This method is further explained in [96] and it is applied here to distinguish the change of power due to an interruption or due to the connection of additional loads from the losses related to a voltage dip impact. In this work, the difference between the pre-dip and post-dip powers of each feeder is considered for estimating the impact of voltage dips on the customers only if the dip event originates in the upstream of the feeder under consideration.

An example of voltage dip event caused by a short-circuit fault occurring in a feeder and its impact on the aggregated customers in different feeders is shown in Figure 5.4. As can be seen in Figure 5.4(a), the during-dip power is significantly larger than the pre-dip power and the power reduces to zero when the feeder is interrupted after the fault is cleared. In Figure 5.4(b-d), the during-dip power of the respective feeder is less than the pre-dip power and the resulting effect of the dip event on the aggregated customers of the feeders is in the loss loads (Figure 5.4(b)) and loss of DGs (Figure 5.4(c,d)). The loss of power due to the interrupted feeder is not included in the analysis for estimating the impact of voltage dips on the customers.

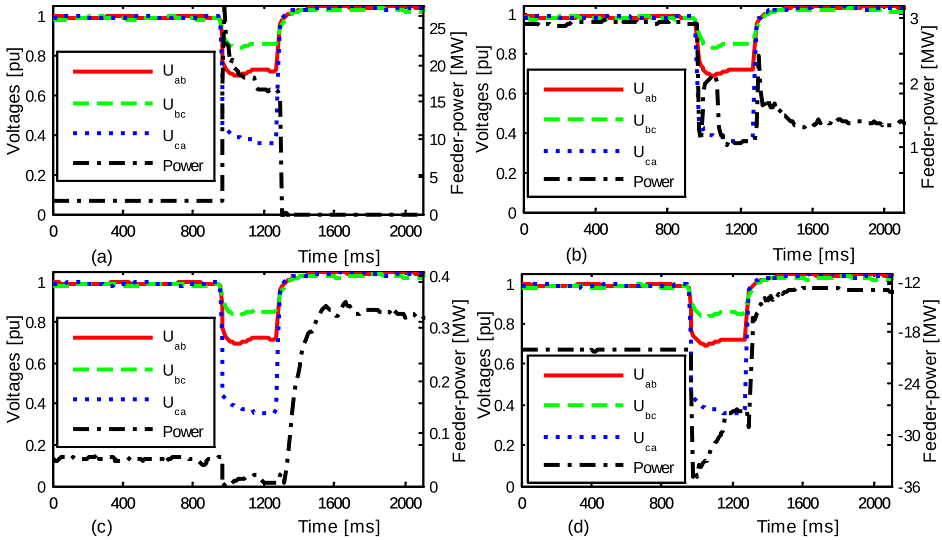


Figure 5.4: Voltage dip caused by short-circuit fault in a feeder leading to the – (a) complete interruption of customers in the same feeder, (b) 1.53 MW less load-power in another feeder, (c) 0.22 MW more load-power (0.22 MW less DG-power) in another feeder, and (d) 6.86 MW less DG-power in another feeder.

Another example of a voltage dip event caused by the switching of loads in a feeder and its impact on the aggregated customers in different feeders is shown in Figure 5.5. During the connection of loads (Figure 5.5(a)), the active-power suddenly increased due to the inrush current and settles down to steady state value after the dip. The consequences of this event on the customers in the other feeders are shown in Figure 5.5(b-d). The change of power between the pre-dip and post-dip powers shown in Figure 5.5(b) and Figure 5.5(c) are considered for the loss of loads when estimating the impact of dips on the aggregated customers.

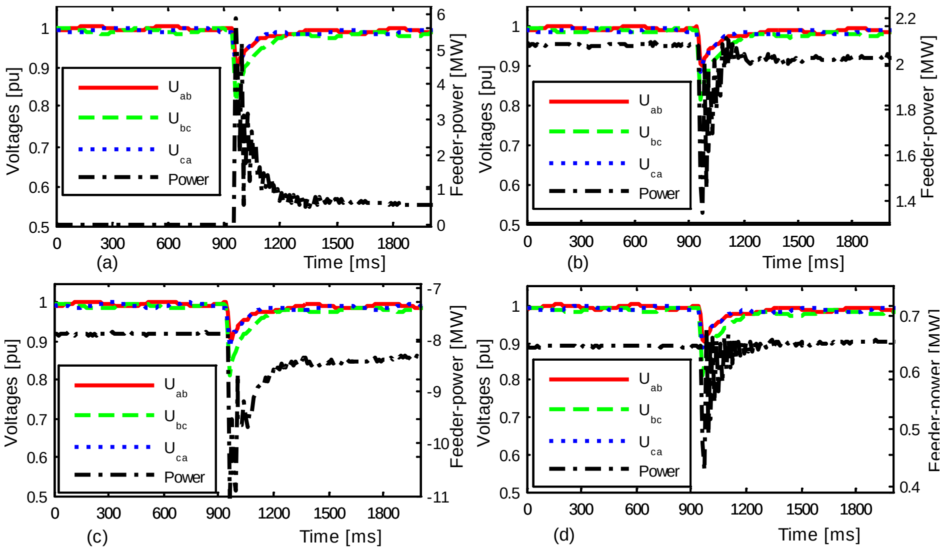


Figure 5.5: Voltage dip caused by the switching of loads in a feeder resulting in – (a) 0.55 MW more load-power in the same feeder, (b) 0.05 MW less load-power in another feeder, (c) 0.40 MW more DG-power (0.40 MW less load-power) in another feeder, and (d) negligible effect on customers in another feeder.

5.3.3 Dip-related loss of power estimation

The proposed method of assessing the impact of voltage dips makes use of active-powers of the aggregated customers, connected to the main substation, measured before and after the voltage-dip events. Although a feeder may include mixture of loads and DGs, it is difficult to know the exact amount of loads and DGs before and after the dip events from the available data. Taking this into account, the change of power for aggregated customers before and after the dip event is considered for estimating the absolute impact of voltage dips. The dip-related loss of power estimation procedure follows two steps– estimating the loss of power for the customers in each feeder of a substation and then evaluating the losses in the entire substation.

In the first step, the amount of loss of load-power or DG-power in a feeder *f* due to a voltage dip event *k* is estimated from the change in active-power (ΔP) of the feeder using the formula (5.4),

$$\begin{aligned} \overset{k}{\Delta P}_{f,load} &= \overset{k}{P}_{f,load_{pre}} - \overset{k}{P}_{f,load_{post}} \\ \overset{k}{\Delta P}_{f,\mathrm{gen}} &= \overset{k}{P}_{f,\mathrm{gen}_{post}} - \overset{k}{P}_{f,\mathrm{gen}_{pre}} \end{aligned} \qquad (5.4)$$

where $P_{f,pre}$ and $P_{f,post}$ are the pre-dip and post-dip powers for the aggregated loads or generations in the feeder following a voltage dip event. For each dip event that is monitored at the PCC of a substation consisting of *n* feeders and experienced by the end-users, the change of powers for the aggregated loads and generations are calculated separately. In the analysis, the change of power in a feeder is not considered for estimating the dip impact on customers if the event originates in the downstream of the same feeder while the changes of powers in the other feeders are considered as the loss of loads or loss of DGs. Examples of events and losses for the aggregated loads or DGs in different feeders are given in Figure 5.4 and Figure 5.5.

The second step deals with evaluating the amount of loss of power for the aggregated customers in the entire substation. After identifying the feeders affected by the dip event originating in the upstream, the loss of loads and loss of DGs in the whole substation only due to the voltage dip are treated separately. For an MV-network that consists of *n* fault-free feeders connected to the PCC of the primary substation, the absolute impact of each voltage dip event *k* on the loss of loads and DGs in the whole substation can be calculated using formula (5.5),

$$\begin{aligned} \overset{k}{\Delta P}_{sub,load} &= \sum_{i=1}^{n} \overset{k}{\Delta P}_{f_i,load} \\ \overset{k}{\Delta P}_{sub,gen} &= \sum_{i=1}^{n} \overset{k}{\Delta P}_{f_i,gen} \end{aligned} \qquad (5.5)$$

where ΔP_f and ΔP_{sub} refer to the change of powers in each feeder (*f*) and in the whole substation (*sub*) following the voltage dip event (*k*). Figure 5.6 illustrates the impact of a voltage dip on the aggregated customers in each feeder as compared to its impact on all customers in the MV distribution network. The voltage dip, characterized by remaining voltage magnitude of 0.36 pu and duration of 320 ms, is caused by a two phase-to-ground fault and the three phase-phase voltages in the MV-network experience unbalanced dips.

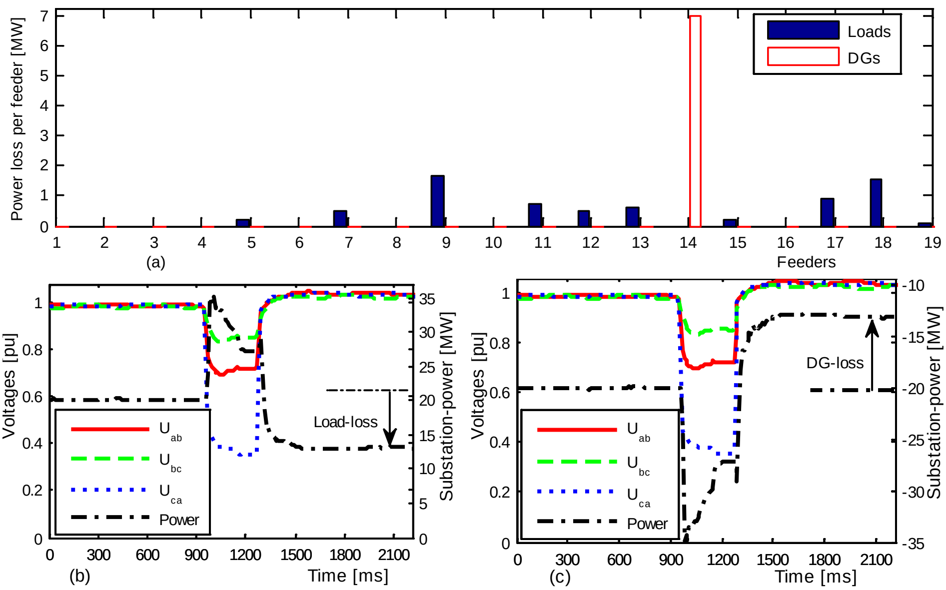


Figure 5.6: Effect of a voltage dip on the aggregated – (a) loads and DGs per feeder, (b) loads in the entire substation, and (c) DGs in the whole substation.

Figure 5.6(a) shows the loss of loads and DGs in each feeder. Taking all feeders into account, the combined effect of the dip is in the loss of 7.05 MW loads in the whole substation. This can also be seen from the power characteristics as a function of time shown in Figure 5.6(b) where the power is reduced from 20.13 MW before the dip to 13.08 MW after the dip event. Likewise, the plot in Figure 5.6(c) shows the impact of the dip event on the aggregated DGs in feeder 14, the same as the impact in the whole substation, leading to the loss of 6.92 MW.

5.3.4 Voltage dip severity and impact correlation

The absolute loss of power for the aggregated customers calculated using (5.5) can be affected by the size and type of customers as well as the occurrence time of faults. Losses even due to similar voltage dip parameters may significantly vary from place to place and time to time. The relative losses of power, estimated using (5.6), are therefore considered to compare the impact of voltage dips with their severities.

$$\begin{aligned} {}^{k}\Delta P_{sub,load}[\%] &= \frac{\sum_{i=1}^{n} {}^{k}\Delta P_{f_i,load}}{\sum_{i=1}^{n} {}^{k}P_{f_i,load_{pre}}} \times 100 \\ {}^{k}\Delta P_{sub,\text{gen}}[\%] &= \frac{\sum_{i=1}^{n} {}^{k}\Delta P_{f_i,\text{gen}}}{\sum_{i=1}^{n} \left| {}^{k}P_{f_i,\text{gen}_{pre}} \right|} \times 100 \end{aligned} \tag{5.6}$$

Figure 5.7 shows the relative loss of loads due to various types of phase-phase dips in the ZVH1 substation, which have a wide range of dip parameter variations. Depending on the magnitude of the remaining voltages, short-dips of L_{001}, L_{011} and L_{111} types resulted in the relative loss of 0–1%, 1–11% and 7–50% of the power for the aggregated loads respectively (Figure 5.7(a)). L_{111} dips with medium-durations caused to the losses of 26–68% of combined loads when the magnitudes vary in the range of 0.77–0.09 pu (Figure 5.7(b)); whereas long-duration of L_{011} and L_{111} dips showed 20–36% and 27–78% losses of power for the aggregated loads (Figure 5.7(c)).

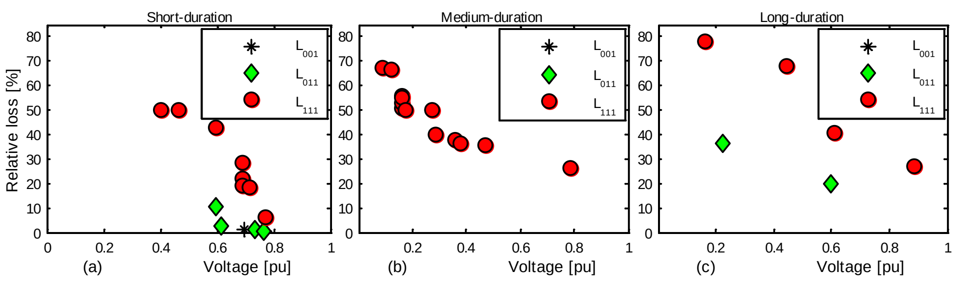


Figure 5.7: Relative loss of aggregated loads for different types of dips in the **ZVH1** MV-network with duration – (a) Δt≤200 ms, (b) 200<Δt≤1000 ms, and (c) Δt>1000 ms.

Within each dip-duration category (Figure 5.7), the more phase-phase voltages are affected by the dip the higher the relative loss of loads is. Moreover, the deeper the remaining voltage magnitude of each type of dip, the higher the relative loss of loads and hence the bigger the expected impact on the combined customers is. For the other substations, the effects of voltage dip parameters on the relative loss of loads for the aggregated customers can be found in *Appendix-D.1*. In each substation, it is observed that the relative loss of loads increase with the severity of dips, which depends on the type, magnitude and duration.

For the phase-phase dips from the monitors of all substations, variation in the relative loss of loads with the different dip parameters are shown in Figure 5.8. It is observed (Figure 5.8) that clusters of dips in each time-interval show higher losses of loads when more phase-phase voltages are affected by the dips and the impact due to each type of dip becomes worse when the dips get deeper and longer. The uneven trend in the relative loss of loads of few dips having similar properties might be because of variations in the size and sensitivity of customer, and the occurrence-time of faults in different substations (for instance, voltage dips are expected to have higher impact on big customers with more sensitive processes than customers with less sensitive processes; and more customers are likely to be affected during the day-time than during the night-time).

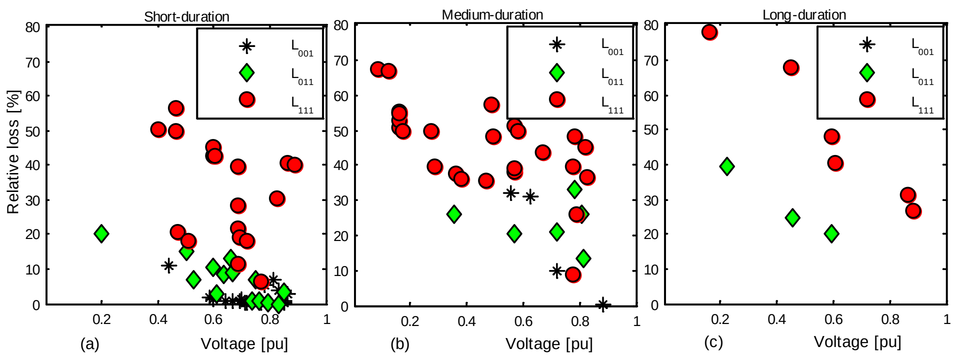


Figure 5.8: Relative loss of aggregated loads for various types of voltage dips from all substations with duration – (a) Δt≤200 ms, (b) 200<Δt≤1000 ms, and (c) Δt>1000 ms.

Table 5.1 summarizes the variations in the relative loss of power for the aggregated loads caused by the various types of dips with short-duration, medium-duration and long-duration. On average, the relative loss of loads due to short-duration L_{001}-L_{011}-L_{111} dips varies in the range 2%-8%-32% respectively, and the losses increase with medium- and long-duration dips to 18%-23%-45% and 28%-49% respectively.

Table 5.1: Effect of dip parameters as compared to their impact on the aggregated loads

	Variation of relative loss of loads [%]								
	Short-duration dips			*Medium-duration dips*			*Long-duration dips*		
	L_{001}	L_{011}	L_{111}	L_{001}	L_{011}	L_{111}	L_{001}	L_{011}	L_{111}
Minimum	0.04	0.07	6.22	0.20	13.39	8.95	-	19.99	26.71
Maximum	10.92	20.46	56.58	31.90	33.12	67.49	-	39.63	78.38
Mean	2.24	7.60	32.43	18.28	23.34	45.23	-	28.16	48.88

Depending on the fault-ride through capability of distributed generations (DGs) connected to the distribution network, voltage dips can cause the disconnection of generating units from the distribution network. The fault-ride through capabilities of DG-units of wind turbines or CHP-plants connected to the busbars of the MV networks depend on the phase-phase voltages at the point of connections (POCs) of the generation units [97]. In the new (draft) standards EN 50549-1/2 [32, 33], the low voltage ride-through requirements for the generating plants to be connected to the LV and MV distribution networks are described. However, due to the fact that the dip-profiles are available at the PCC of the substations while most of the DGs may be connected to the POCs, often far away from the PCCs, it is hard to exactly know whether the monitored dips disconnect the DGs or not. Figure 5.9 shows the relative loss of DGs for different types of dips in the ZHV1 MV-network.

Unlike the impact of voltage dips on the aggregated loads in the substation (shown in Figure 5.7), no general conclusion can be drawn from Figure 5.9 on the correlation between the severity of voltage dips and their relative impact on the aggregated DGs. At the times of voltage dip occurrences, the amount of power generated from the feeders with net generation-power significantly varies from time to time. Hence, voltage dips having similar properties do not always show similar impact on the loss of DGs.

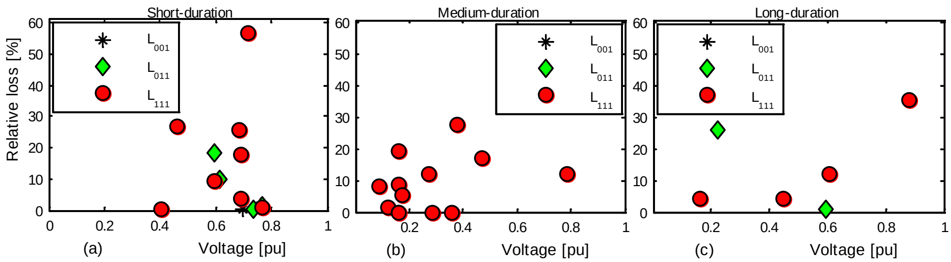


Figure 5.9: Relative loss of aggregated DGs for different types of dips in the **ZVH1** MV-network with duration – (a) Δt≤200 ms, (b) 200<Δt≤1000 ms, and (c) Δt>1000 ms.

5.4 Voltage dips severity weighting factors

The main concern of voltage dips is the economic impact on industrial and big commercial customers, and direct evaluation of the economic loss due to voltage dips is often difficult. The disrupting impact of a voltage in the interruption of an industrial process, or part of the process, may vary with different categories of customers. In [98-105], various values weighting factors (WFs) were applied for different magnitudes of voltage dips when estimating the relative impact of voltage dips. As discussed in this work earlier, the impact of voltage dips on customers not only depends on the magnitude of remaining voltage but also on the type and duration of voltage dips. Despite of their contributions to the severity of dips, the effects of dip types and dip durations were not considered in the previous researches.

In this section, the proposed approach for estimating the impact of voltage dips on the aggregated customers is extended to obtain system severity indices for various types of voltage dips using field data from six substations measured for several years.

5.4.1 Procedure of evaluating weighting factors

For each type of dip, values of WFs (in %) corresponding to various magnitude and duration ranges specified by the standard EN 50160 [8] are set as in Table 5.2.

Table 5.2: Weighting factors [%] for voltage dips according to the EN 50160 standard

Remaining voltage [%]	L_{001} dips (p=1)					L_{011} dips (p=2)					L_{111} dips (p=3)				
	Duration [s]					Duration [s]					Duration [s]				
	$\Delta t \leq 0.2$	$\Delta t \leq 0.5$	$\Delta t \leq 1$	$\Delta t \leq 5$	$\Delta t > 5$	$\Delta t \leq 0.2$	$\Delta t \leq 0.5$	$\Delta t \leq 1$	$\Delta t \leq 5$	$\Delta t > 5$	$\Delta t \leq 0.2$	$\Delta t \leq 0.5$	$\Delta t \leq 1$	$\Delta t \leq 5$	$\Delta t > 5$
$90>u\geq 80$	$WF_{1,1}$	$WF_{1,2}$	$WF_{1,3}$	$WF_{1,4}$	$WF_{1,5}$	$WF_{1,1}$	$WF_{1,2}$	$WF_{1,3}$	$WF_{1,4}$	$WF_{1,5}$	$WF_{1,1}$	$WF_{1,2}$	$WF_{1,3}$	$WF_{1,4}$	$WF_{1,5}$
$80>u\geq 70$	$WF_{2,1}$	$WF_{2,2}$	$WF_{2,3}$	$WF_{2,4}$	$WF_{2,5}$	$WF_{2,1}$	$WF_{2,2}$	$WF_{2,3}$	$WF_{2,4}$	$WF_{2,5}$	$WF_{2,1}$	$WF_{2,2}$	$WF_{2,3}$	$WF_{2,4}$	$WF_{2,5}$
$70>u\geq 40$	$WF_{3,1}$	$WF_{3,2}$	$WF_{3,3}$	$WF_{3,4}$	$WF_{3,5}$	$WF_{3,1}$	$WF_{3,2}$	$WF_{3,3}$	$WF_{3,4}$	$WF_{3,5}$	$WF_{3,1}$	$WF_{3,2}$	$WF_{3,3}$	$WF_{3,4}$	$WF_{3,5}$
$40>u\geq 5$	$WF_{4,1}$	$WF_{4,2}$	$WF_{4,3}$	$WF_{4,4}$	$WF_{4,5}$	$WF_{4,1}$	$WF_{4,2}$	$WF_{4,3}$	$WF_{4,4}$	$WF_{4,5}$	$WF_{4,1}$	$WF_{4,2}$	$WF_{4,3}$	$WF_{4,4}$	$WF_{4,5}$
$5>u$	$WF_{5,1}$	$WF_{5,2}$	$WF_{5,3}$	$WF_{5,4}$	$WF_{5,5}$	$WF_{5,1}$	$WF_{5,2}$	$WF_{5,3}$	$WF_{5,4}$	$WF_{5,5}$	$WF_{5,1}$	$WF_{5,2}$	$WF_{5,3}$	$WF_{5,4}$	$WF_{5,5}$

Considering the pre-dip power of n feeders of a substation and employing the absolute loss of loads and DGs evaluated using (5.5), the weighting factors representing the system average dip severity indices (SADSI) of dips can be obtained from the weighted average of the relative loss of power for the aggregated customers in the substations. For each type of dip p, the value of percentage WF in each cell of the voltage dip profile can be evaluated by the formula given in (5.7),

$$WF_{r,c}[\%] = \frac{1}{N_{r,c}} \sum_{k=1}^{N_{r,c}} \left(\frac{{}^{k}\Delta P_{sub,load} + {}^{k}\Delta P_{sub,\text{gen}}}{{}^{k}P_{sub,pre}} \right) \times 100 \tag{5.7}$$

where $N_{r,c}$ denotes the total number of voltage dips for the cell with the remaining voltage magnitude in the r^{th} row and duration in the c^{th} column, and $P_{sub,pre}$ represents the sum of absolute pre-dip powers of all feeders during each event (k) obtained by using (5.8).

$${}^{k}P_{sub,pre} = \sum_{i=1}^{n} \left| {}^{k}P_{f_i,pre} \right|. \tag{5.8}$$

From the relative loss of power related to the monitored dips, the preliminary values of WFs for the three types of dips with magnitudes varying in 10% range is shown in Table 5.3. From the assessment of available data, it is observed that some cells in the voltage dip density tables for each type of dip do not consist of any dip indices. As a result, no estimated losses and hence no WFs are obtained for such dips using the approach directly. For each type of dip, it can be noticed from Table 5.3 that the values of WFs obtained based on the average loss of power for the aggregated customers increase towards right of each row (with longer-dips) and downwards of each column (with deeper-dips) although the pattern of increment is not uniform. It is also presumed that the vacant cells would have some values of WFs if there were dips falling into these cells and affecting end-users.

Table 5.3: Preliminary values of weighting factors [%] for various types of voltage dips

Remaining voltage [%]	L_{001} dips (p=1)					L_{011} dips (p=2)					L_{111} dips (p=3)				
	Duration [s]					Duration [s]					Duration [s]				
	Δt≤0.2	Δt≤0.5	Δt≤1	Δt≤5	Δt>5	Δt≤0.2	Δt≤0.5	Δt≤1	Δt≤5	Δt>5	Δt≤0.2	Δt≤0.5	Δt≤1	Δt≤5	Δt>5
90>u≥80	0.20		2.80			1.65		19.69			12.30	29.14		37.83	
80>u≥70	0.91		9.93			2.10	19.99				27.30	30.73			
70>u≥60	1.28	11.07				8.36					35.46		40.43	44.34	
60>u≥50	1.57	20.75				26.01	26.95		31.10		36.06	41.10	42.09	44.70	
50>u≥40	10.92										37.17	42.41	43.55	67.80	
40>u≥30							31.90					48.37	53.17		
30>u≥20									36.32				56.17		
20>u≥10						31.10						51.31	57.52	78.38	
10>u													67.49		

5.4.2 Fitted weighting factors

From the available data, Mean-value or Mean-Max substitution approach is used to obtain the estimated values of WFs for filling the vacant cells. In a given column, a vacant cell between two completed cells is filled with the average of the two values, and the one in the lowermost of the column is filled from the mean and maximum values of WFs in that particular column. Estimated values of WF in the k^{th} row of a given column '*c*' can be obtained using (5.9).

$$WF_{k,c} = \begin{cases} \frac{1}{2}\left(WF_{k-1,c} + WF_{k+1,c}\right), & (middle) \\ \left(1 + \frac{1}{k-1}\sum_{i=1}^{k-1}\frac{WF_{i,c}}{100}\right)WF_{k-1,c}, & (lowermost) \end{cases} \tag{5.9}$$

Similarly, each vacant cell between two completed cells across a fixed row is filled with the average of the two values, and a vacant cell in the rightmost of the row is filled from the average and maximum values of WFs in that row. Estimated values of WF in the k^{th} column of a given row '*r*' can be found using (5.10).

$$WF_{r,k} = \begin{cases} \frac{1}{2}\left(WF_{r,k-1} + WF_{r,k+1}\right), & (middle) \\ \left(1 + \frac{1}{k-1}\sum_{j=1}^{k-1}\frac{WF_{r,j}}{100}\right)WF_{r,k-1}, & (rightmost) \end{cases} \tag{5.10}$$

During the estimation process, observation points are considered along the diagonal moving from the cell for $WF_{1,1}$. From each observation point, vacant cells at the observation point itself and/or to its left are estimated using (5.9) and (5.10), and a vacant cell between two completed cells is filled first with the average of the two. To yield the least biased estimate of the missing values of WFs, analytical strategy based on regression analysis is applied. In this case, curve fittings of Linear, Quadratic, Cubic, Exponential, Fourier and Gaussian models are compared to choose the best fit. For each type of dips within each duration range, the weighting factor is considered as dependent variable while the voltage dip magnitude is considered as independent variable. In order to apply the regression analysis, the same variance of the independent variable is achieved by varying the remaining voltage magnitudes in 10% variation (as in Table 5.3). For a set of *n* values of (estimated) WFs for each type of dip within certain duration-interval, marked as $\boldsymbol{y}_i$, each associated with a predicted value $\boldsymbol{f}_i$, the goodness of a curve fitting in predicting a value is measured by the coefficient of determination (R^2) expressed by (5.11) [106],

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(y_i - f_i)^2}{\sum_{i=1}^{n}(y_i - \bar{y})^2} \tag{5.11}$$

where $\bar{\mathbf{y}}$ is the mean of $\boldsymbol{y}_i$. The difference between the estimated values of WFs and the values predicted by the fitting model are residuals that represent the approximate independent errors. By minimizing the sum of the squares of the residuals, R^2 indicates how well the fit can predict the data and it falls between 0 and 1. The higher the value of R^2, the better the fitting curve is often at predicting the data.

For the various fitting models, comparative values of R^2 evaluated using (5.11) are shown in Table 5.4. In most cases, it is observed that the Quadratic, Cubic, Fourier and Gaussian fitting curves show higher values of R^2 than the Linear and Exponential fitting models. The Cubic fitting model gives the highest values of coefficient of determination for all types of dips, and values of R^2 vary between 0.91–0.99 corresponding to the shortest L_{001} and the longest L_{111} dips. For the best fitting curve (Cubic regression), comparisons between the observed (or estimated) and predicted values of WFs are shown in Figure 5.10.

Table 5.4: Values of R^2 (measure of goodness) for various types of dips using different fitting curve models

Curve fitting	L_{001} dips (p=1)					L_{011} dips (p=2)					L_{111} dips (p=3)				
	Duration [s]					Duration [s]					Duration [s]				
	$\Delta t \le 0.2$	$\Delta t \le 0.5$	$\Delta t \le 1$	$\Delta t \le 5$	$\Delta t > 5$	$\Delta t \le 0.2$	$\Delta t \le 0.5$	$\Delta t \le 1$	$\Delta t \le 5$	$\Delta t > 5$	$\Delta t \le 0.2$	$\Delta t \le 0.5$	$\Delta t \le 1$	$\Delta t \le 5$	$\Delta t > 5$
Linear	0.85	0.79	0.82	0.82	0.82	0.85	0.97	0.97	0.88	0.82	0.87	0.98	0.95	0.93	0.99
Quadratic	0.86	0.97	0.96	0.96	0.96	0.92	0.97	0.97	0.90	0.97	0.95	0.98	0.97	0.94	0.99
Cubic	0.91	0.97	0.97	0.96	0.96	0.92	0.99	0.99	0.92	0.96	0.95	0.98	0.97	0.94	0.99
Exponential	0.73	0.66	0.70	0.70	0.70	0.73	0.95	0.95	0.91	0.70	0.79	0.97	0.97	0.93	0.98
Fourier	0.87	0.95	0.95	0.94	0.94	0.87	0.98	0.98	0.85	0.94	0.91	0.96	0.96	0.91	0.99
Gaussian	0.87	0.90	0.92	0.92	0.92	0.84	0.97	0.97	0.87	0.92	0.90	0.97	0.96	0.92	0.99

As can be seen from Figure 5.10, the deeper the magnitude of the remaining voltages the larger the predicted values of WFs are. It can also be noticed that the values of WFs increase when the number of phase-phase voltages affected by the dip increases. Furthermore, the longer the duration of each type of dip the higher the value of WF is. Average values of WFs for the three types of voltage dips with the remaining voltage magnitudes varying in 10% are also given in Table 5.5.

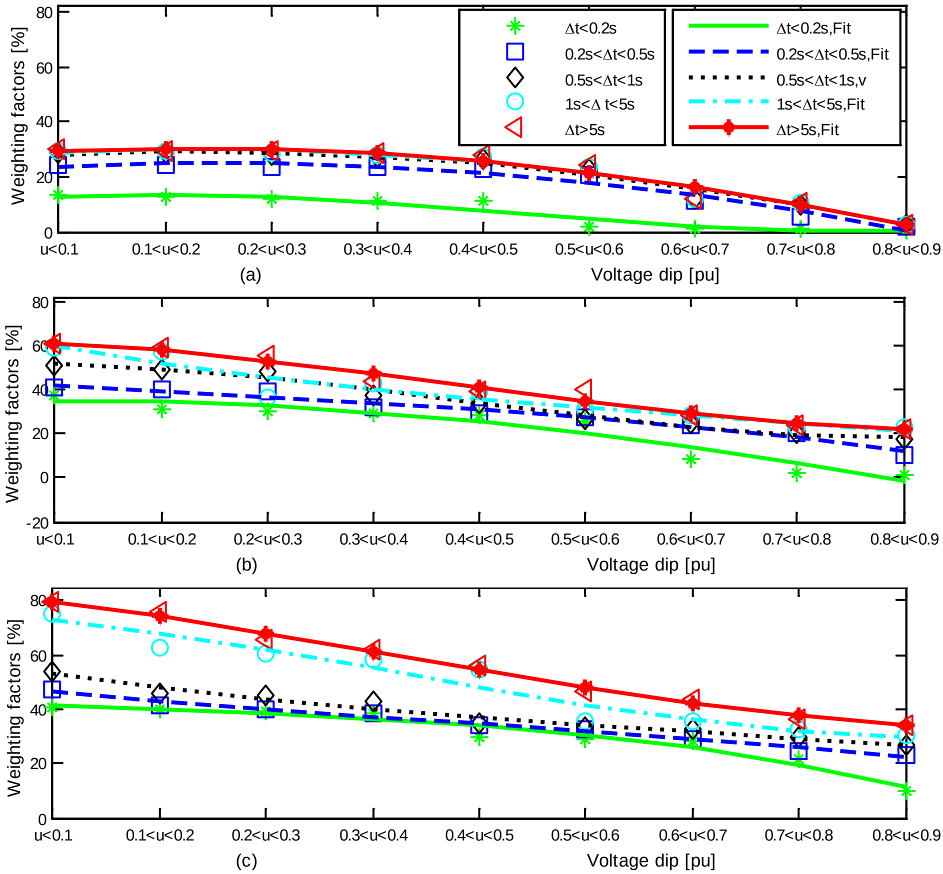


Figure 5.10: Comparison between observed and predicted WF values for – (a) L_{001} dips, (b) L_{011} dips, and (c) L_{111} dips.

Table 5.5: Average weighting factors [%] completed using the Cubic curve fitting model

Remaining voltage [%]	L_{001} dips (p=1)					L_{011} dips (p=2)					L_{111} dips (p=3)				
	Duration [s]					Duration [s]					Duration [s]				
	$\Delta t \leq 0.2$	$\Delta t \leq 0.5$	$\Delta t \leq 1$	$\Delta t \leq 5$	$\Delta t > 5$	$\Delta t \leq 0.2$	$\Delta t \leq 0.5$	$\Delta t \leq 1$	$\Delta t \leq 5$	$\Delta t > 5$	$\Delta t \leq 0.2$	$\Delta t \leq 0.5$	$\Delta t \leq 1$	$\Delta t \leq 5$	$\Delta t > 5$
$90>u\geq 80$	0.20	1.16	2.27	2.36	2.45	1.65	11.95	18.33	19.32	19.57	11.41	22.51	26.99	29.92	33.96
$80>u\geq 70$	0.95	7.29	9.44	9.77	9.89	6.40	17.92	19.42	22.52	22.42	19.74	25.96	29.30	32.08	37.44
$70>u\geq 60$	1.76	13.22	15.62	16.13	16.37	13.59	22.97	22.85	25.51	26.55	26.03	29.04	31.66	36.18	42.27
$60>u\geq 50$	4.44	17.93	20.73	21.38	21.71	19.90	27.24	27.87	28.57	31.55	30.65	31.85	34.19	41.72	48.09
$50>u\geq 40$	7.58	21.43	24.72	25.46	25.86	25.23	30.87	33.76	31.95	37.00	33.97	34.53	37.00	48.17	54.54
$40>u\geq 30$	10.55	23.40	27.50	28.29	28.74	29.47	34.00	39.78	35.91	42.49	36.35	37.20	40.20	55.01	61.29
$30>u\geq 20$	12.36	23.72	27.92	28.72	29.16	32.53	36.77	45.21	40.71	47.60	38.16	39.98	43.89	61.72	67.98
$20>u\geq 10$	12.75	24.70	29.01	29.82	30.30	34.31	39.31	49.31	46.61	51.91	39.76	42.99	48.21	67.78	74.25
$10>u$	13.56	24.81	29.17	29.99	30.46	34.70	41.77	51.36	53.89	55.02	41.53	46.36	53.25	72.67	78.76

5.4.3 Proposed weighting factor indices

The values WFs shown in Table 5.5 are used to obtain the average WFs for voltage dips with different magnitudes and durations according to the standard EN 50160 given in

Table 5.6. Multiplying these WFs (expressed in pu) by the corresponding frequency of voltage dips will give the average number of equivalent interruptions caused by the voltage dips in each cell.

Table 5.6: Fitted average weighting factors [%] for voltage dips classification according to the EN 50160 standard

Remaining voltage [%]	L_{001} dips (p=1)					L_{011} dips (p=2)					L_{111} dips (p=3)				
	Duration [s]					Duration [s]					Duration [s]				
	$\Delta t\leq 0.2$	$\Delta t\leq 0.5$	$\Delta t\leq 1$	$\Delta t\leq 5$	$\Delta t>5$	$\Delta t\leq 0.2$	$\Delta t\leq 0.5$	$\Delta t\leq 1$	$\Delta t\leq 5$	$\Delta t>5$	$\Delta t\leq 0.2$	$\Delta t\leq 0.5$	$\Delta t\leq 1$	$\Delta t\leq 5$	$\Delta t>5$
$90>u\geq 80$	0.20	1.16	2.27	2.36	2.45	1.65	11.95	18.33	19.32	19.57	11.41	22.51	26.99	29.92	33.96
$80>u\geq 70$	0.95	7.29	9.44	9.77	9.89	6.40	17.92	19.42	22.42	22.52	19.74	25.96	29.30	32.08	37.44
$70>u\geq 40$	4.60	17.52	20.36	20.99	21.31	19.58	27.02	28.16	28.68	31.70	30.21	31.81	34.28	42.02	48.30
$40>u\geq 5$	12.31	24.16	28.40	29.21	29.66	32.75	37.96	44.28	46.41	49.26	38.95	41.63	46.39	64.29	70.57
$5>u$	13.56	24.81	29.17	29.99	30.46	34.70	41.77	51.36	53.89	55.02	41.53	46.36	53.25	72.67	78.76

The mean values of WFs, obtained based on the weighted average of the relative loss of power for the aggregated customers, are between the two extreme (minimum and maximum) values. These values could be affected by few dips leading to extremely small or too big losses of power. The share of few dips leading to extremely big loss of sensitive customers, for instance, could be overshadowed by more dips leading to small losses and this may result in small values of WFs. Consequently, the obtained WFs may underestimate the expected equivalent process interruption caused by few but severe dips and thus can underestimate the expected cost of such dips to sensitive plants. To discriminate the effect of few dips leading to extremely small or very big portion of disconnected customers on the average WFs, the 95-percentile of WFs (shown in Table 5.7) can be used with big and sensitive industrial customers.

Table 5.7: 95-percentile of weighting factors [%] for various types of voltage dips according to the EN 50160 standard

Remaining voltage [%]	L_{001} dips (p=1)					L_{011} dips (p=2)					L_{111} dips (p=3)				
	Duration [s]					Duration [s]					Duration [s]				
	$\Delta t\leq 0.2$	$\Delta t\leq 0.5$	$\Delta t\leq 1$	$\Delta t\leq 5$	$\Delta t>5$	$\Delta t\leq 0.2$	$\Delta t\leq 0.5$	$\Delta t\leq 1$	$\Delta t\leq 5$	$\Delta t>5$	$\Delta t\leq 0.2$	$\Delta t\leq 0.5$	$\Delta t\leq 1$	$\Delta t\leq 5$	$\Delta t>5$
$90>u\geq 80$	1	3	5	5	5	4	18	26	27	27	17	31	36	39	44
$80>u\geq 70$	3	12	15	15	15	11	25	27	30	31	27	35	38	42	48
$70>u\geq 40$	8	25	28	29	29	27	36	37	38	41	40	41	44	53	60
$40>u\geq 5$	18	33	37	38	39	42	48	55	58	61	49	53	58	78	85
$5>u$	20	33	38	39	40	45	53	63	66	67	52	58	66	87	94

The ratio of the 95-percentile WFs to the average WFs is presented in Figure 5.11. It can be seen that the ratio of the 95-percentile to the average WFs is relatively high for short and very shallow L_{001} dips. These dips could be significant for industrial plants with sensitive processes, and it is a creditable indicator that the 95-percentile approach is reasonable for estimating the economic impact of voltage dips in industrial plants. From the ratio, it can be observed that the 95-percentile of WFs may result in about:

- 2–5 times more equivalent interruptions due to very shallow (u>0.8 pu) and long-duration to short-duration L_{001} dips than the average WFs.
- 1.4–2.4 times more equivalent interruptions due to very shallow and long-duration to short-duration L_{011} dips than the average WFs.
- 1.3–1.5 times more equivalent interruptions due to very shallow and long-duration to short-duration L_{111} dips than the average WFs.

- 20–50% more equivalent interruptions due to very deep (u<0.05 pu) longest L_{111} dips and shortest L_{001} dips than the average WFs.

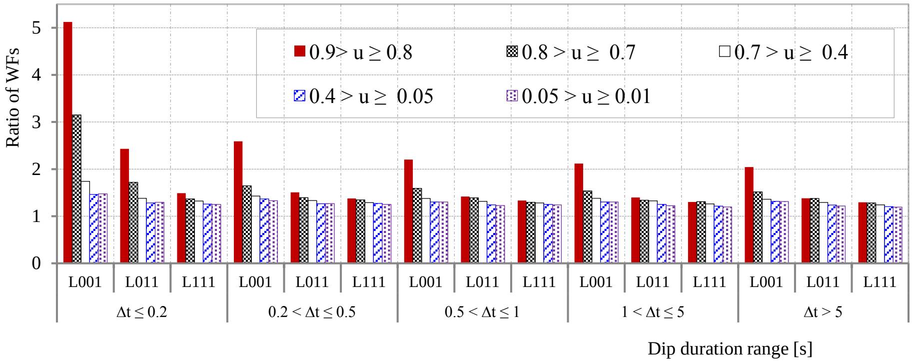


Figure 5.11: Ratio of the 95-perecentile WFs to the average WFs for different types of dips.

For estimating the economic impact of voltage dips in different industrial customer categories (ranging from the least sensitive to the most sensitive processes), 25-percentile of WFs, 50-percentile of WFs, 75-percentile of WFs and 99-percentile of WFs are given in *Appendix-D.2*.

5.5 Summary

This chapter proposes an approach for estimating the impact of voltage dips on the aggregated customers based on the ‘loss of power’ during a dip. The approach considers the change between the pre-dip and post-dip power of all customers in the distribution network during voltage dip events monitored at the PCC of the MV-networks.

For the various types of voltage dips monitored in six substations for four years, the relative losses are calculated and compared with the severity of voltage dips characterized by the remaining voltage magnitude, duration and type of dips. The method shows a strong correlation between the severity of voltage dips and their impact on aggregated customers. That is, the relative loss of power and thus the impact on the combined customers increases with longer and deeper dips; and even gets worse with more phase-phase voltages affected. Depending on the magnitude and duration of voltage dips, on average the measured dips in one, two and three phase-phase voltages resulted in the relative loss of power for aggregated customers connected to the MV-networks ranging between 0–21%, 2–36% and 12–78% respectively (Table 5.3).

Based on the weighted average of the relative loss of power for the aggregated customers, the estimation method is also extended to obtain system average dip severity indices (or weighting factors) for various types of voltage dips. This approach can be very helpful for estimating the economic loss of voltage dips and for setting voltage dip limits in the MV distribution networks for the regulatory purpose.

6

Economic loss due to voltage dips

6.1 Introduction

Voltage dips can lead to the disruption of manufacturing processes pertaining to either equipment malfunctioning or failure due to a reduced voltage level. Because of the propagation from one part of the network to another, the frequency of voltage dips occurrence is higher than interruptions and the annual economic impact on industrial customers can be significantly larger [1, 4, 17, 19, 98, 107-110]. In many manufacturing processes, a defect of only a few vital pieces of equipment may result in a complete or partial shutdown of production which in turn leads to huge financial losses. In some processes, in addition to the loss of production, the loss of material and the time taken to clean up and restart the process make the financial loss even worse [111].

Reliable information regarding to the economic loss incurred due to voltage dips is essential to both customers and network operators as it provides the very basis for cost-benefit analysis for all potential investments on the possible mitigation solutions. The assessment of economic loss due to voltage dips involves careful consideration of:

- voltage dip profiles at the customer terminals,
- customer load/process susceptibility, and
- calculation of the losses induced by the process interruption.

Voltage dip profile at the customer terminals provides the information regarding the frequency and characteristics of voltage dips. This information can be obtained from site monitoring over a longer period (discussed in *Chapter 3*), or can be predicted by computer simulations using fault positions method [16, 17, 19, 109] (discussed in *Chapter 2*). The sensitivity of process equipment to voltage dips directly influences the response of the industrial process to the incoming dips and thus has a direct impact on the resulting financial losses. The sensitivity of equipment can be found from the manufacturer specifications or commonly used standards or from experiments (more in *Chapter 4*).

By comparing the sensitivity of process equipment against voltage dips with the performance of the supply system, a compatibility analysis is generally required to evaluate the effects of voltage dips on an industrial plant. In this chapter, two methods of estimating the economic impact of voltage dips are discussed. The effectiveness of available alternative solutions in reducing the dip-related problems and associated cost of investment are described.

6.2 Overview of existing methodologies

There are many technical mitigation solutions available on the market to reduce the disruptive impact of voltage dips. Although there exist solutions to mitigate voltage dips, it is important that facilities evaluate the expected economic impact of voltage dips before making new investments for reducing the problems.

6.2.1 Cost estimation of voltage dips

Over the years, numerous attempts have been made to address the economic consequence of voltage dips. The IEEE 1346 standard [35] provides guidelines recommended for technical and financial evaluation of voltage dips based on compatibility analysis between process equipment and electric power systems. It is intended to be applied at the planning or design stage of a system where power supply and equipment choices are still flexible and incompatibilities can be resolved. The overall analysis consists of three steps– development of a coordination chart, cost estimation of process disruption per dip, and calculation of total financial losses. The coordination chart provides a comparison between voltage dip performance of the supply system (expressed in terms of magnitude and duration represented using contour lines) and the equipment voltage-tolerance curves to identify the number of disruptive events. All costs related to the process disruption will be determined from a survey that stipulates the participation of different actors of the process chain including frontline workers, suppliers, finance, accounting, sales and marketing staff. The total financial losses of the facility are obtained by multiplying the cost of process disruption with the number of disruptive events identified in the chart. Although the method proposed by this standard is simple, it often needs huge amount of data some of which are difficult to gather and others are dealing with confidentiality issues of the company. According to the standard, the sensitivity of the entire industrial process is represented by the most sensitive equipment in the process. However, tripping of the most sensitive equipment may not necessarily cause the process trip. Besides, the standard does not consider the interconnections between equipment and sub-processes that might have a significant impact on the process operation.

Some methods concentrating at network-level are proposed in [19, 109]. According to this method, the variables affecting the financial loss estimation were identified to be voltage dip frequency, number of customers and cost per dip. The average annual dip frequency (for dips less or equal to 50% of nominal voltage) were estimated using a probabilistic approach and network reliability data typically derived from permanent faults. The customers in the LV-networks were categorized into five different groups (domestic, agricultural, industrial, commercial services and public services) in order to assume similar behaviors to every component of a group. With regard to cost, the cost per dip was calculated for every one of the five groups of customers from the evaluation of direct and indirect economic consequences of voltage dips. From the combination of results on different surveys, approximate costs obtained per type of customer are shown in Table 6.1. The total annual economic cost of voltage dips for each customer category of the entire network was calculated by multiplying the cost per dip with the number of customers and annual frequency of dips in the network. In this method, a big sample of data originally prepared for other purposes was used to extrapolate the cost of voltage dips. In practice, customers in each category consist of heterogonous electricity users, and the size, annual energy and electrical behavior may considerably vary especially in the industrial customers.

Table 6.1: Cost for a single voltage dip in various customer category [19, 109]

	Customer category				
	Domestic	Agricultural	Industrial	Commercial	Public
Cost per dip [€]	1	1	1060	170	130

Another method of estimating the cost of voltage dips applied on plant-level losses is suggested in [112, 113]. Survey was conducted on more than 200 small industrial customers (up to 2–3 MW peak plants) of various sectors fed from the MV-networks. To avoid several risks from the direct cost estimation questions, this survey focused on other data concerning plant operation, structure of productive system, equipment sensitivity, restart procedures and other aspects related to the interruption consequences. The proposed method is a complete analysis of the target industry and costs contemplated in the economic damage due to each event include all components within equation (6.1),

$$Cost = C_{LP,D} + C_{LP,R} + C_{WM} + C_{IP} + C_{DE} + C_{EM} - S_M - S_E \qquad (6.1)$$

where $C_{LP,D}$ refers to the cost of lost production during the supply disturbance,
$C_{LP,R}$ is cost of lost production during the restart time,
C_{WM} denotes cost of wasted material,
C_{IP} refers to the cost of imperfect products,
C_{DE} is cost of damaged equipment,
C_{EM} represents cost of extra maintenance,
S_M denotes saving on raw materials, and
S_E refers to the saving on energy not consumed.

From the survey, all these costs and saves are estimated, and costs of voltage dips are presented in normalized costs per voltage dip per kW power to enable a comparison among different industrial sectors and sizes. It was found that most sensitive plants have normalized cost per dip in the range of 0.25–1.5 €/kW despite the many different production sectors and plant characteristics involved [112]. This method is claimed to provide accurate costs related to voltage dips and short-interruptions. However, it highly depends on the cost figures of every sub-process [114] in the plant related to all direct and indirect costs which are difficult to obtain, require time-consuming investigation, and often involve confidentiality issues. Besides, outages and severe dips are considered as having the same effect on the operation since no reference is considered to the dip magnitude and duration.

Other estimation approaches [98, 100-105, 115] consider weighting factors to account for different magnitudes of voltage dips when estimating the economic loss relative to the cost of a complete interruption. An example of weighting factors, adopted from [98, 105], is shown in Table 6.2. Interruption costs, which are categorized as product related losses, labor-related losses and ancillary costs, are evaluated by survey on the actors of the process. Nevertheless, the method provides no detailed documentation on how the weighting factors are obtained and no additional information about the effect of dip-duration and dip-type.

Table 6.2: Example of weighting factors for different voltage dip magnitudes [98, 105]

Event category	Weighting factor for economic analysis
Interruption	1
Sag with minimum voltage below 50%	0.8
Sag with minimum voltage between 50% and 70%	0.4
Sag with minimum voltage between 70% and 90%	0.1

6.2.2 Overview of mitigation solutions

Mitigation techniques refer to the measures taken to reduce the number and/or severity of voltage dips, and thus to reduce the financial damage to a process. Broadly speaking, the economic losses associated with voltage dips can be reduced by any of the following actions:

- *Improving the supply voltage performance of the electrical network*. This involves some design improvements in the electrical network that results in a change of voltage dip density (with fewer and/or less severe voltage dips).
- *Installing power-conditioning devices*. Mitigation devices can be used to improve the ride-through capability, thus reduce the vulnerability area, of equipment and processes against voltage dips. This will not affect the frequency of voltage dips in the electric network but the number of equipment and/or process trip will be reduced due to the enhanced withstanding capability.
- *Using robust equipment.* Replacing the weakest link device(s) by equipment with better ride-through capability can modify the equipment behavior and thus improve the performance of equipment and processes against voltage dips.

As depicted in Figure 6.1, various mitigation solutions can be applied at several levels to reduce the dip-related problems of a facility. Depending on the type and level of application, the mitigation methods can reduce the effective number of process interruptions to a certain extent. However, each solution comes at a cost and it can be costly. The solutions can be broadly classified as customer-level solutions or grid-level solutions [98, 115]. Mitigation of voltage dips at the grid-level, in general, can protect large part of a network but also incurs higher costs. Whereas solutions relatively at a cheaper cost can be achieved by modifying the robustness of the process equipment although this requires a detailed study of the process equipment and their susceptibility to voltage dips.

6.2.2.1 Customer-level solutions

As represented in Figure 6.1, voltage dip mitigation solutions that can be implemented within the periphery of the customer's facility may affect the performance of a single equipment (a), all equipment within a single process (b) or all processes within the entire facility (c). To mitigate the consequences associated with voltage dips, a wide range of alternative solutions, with varying degrees of cost and effectiveness, are available [105, 111, 115-122].

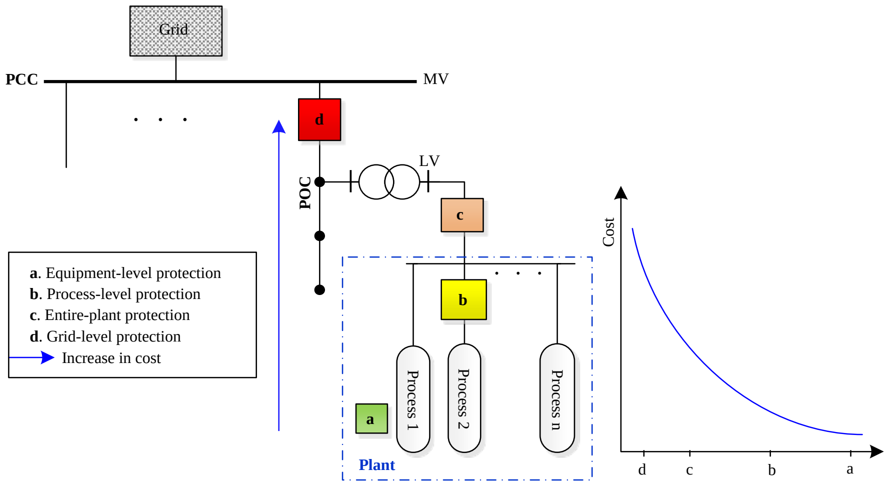


Figure 6.1: Position of mitigation options for improving the equipment and/or process voltage dip performance.

Solutions at equipment-level (often up to 10 kVA) are designed to support for critical elements of equipment, such as control systems, that may determine the overall response of the process. These solutions may involve modifications in the equipment specifications and design, or using power conditioning devices for reducing the voltage dip susceptibility curve of sensitive equipment. With AC relays, contactors, solenoids and motor starters, which are often diagnosed as weak links in automated production lines, Coil-Locks can provide the device controlled by an AC coil with a ride-through capability of voltage dips with remaining voltage up to 25% of the nominal voltage lasting for durations at least 3 sec [116]. Other options including dip proofing inverter (DPI), voltage dip compensators (VDC), constant voltage transformers (CVT) and uninterruptable power supply (UPS) can also be applied at the equipment-level.

The effect of voltage dips on *individual processes (or machines)* (usually ranging between 10–500 kVA) can be corrected using mitigation solutions that are applicable at machine-level protections. Machine-level solutions include UPS, dynamic sag correctors (DySC) and Flywheel (FW). In addition to UPS and Flywheel, other alternative options like dynamic voltage restorer (DVR) and active voltage conditioner (AVC) can be used at system-level to protect the *entire facility* against voltage dips. A wide-range of mitigation options applicable at various levels and their effectiveness in reducing the dip-related problems are summarized in Table 6.3.

6.2.2.2 Grid-level solutions

In the distribution network, supply system modifications and equipment that affect multiple customers can be integrated at location ‘d’ of Figure 6.1 to improve the quality of the supply and performance of customers. The frequency of faults and thus dips can be reduced by implementing tree trimming, insulator washing, adding arrestors and animal guards methods. Besides, insulated conductors for bare conductors and underground circuitry can reduce the interference of human and animal activities.

The operation of a power system can be improved by reducing the fault clearing time of protection devices which will reduce the severity of voltage dips. By using reactors usually mounted at the beginning of feeders in the MV-network, the fault-current due to downstream disturbance can be limited, and this can reduce the frequency and/or severity of voltage dips that other feeders will experience. Opening tie breakers and supplying far loads from other transformers is also a possible solution that requires modification in the system configuration to reduce the vulnerability area. Besides, installing generators close to sensitive loads can also support the voltage during distant dips.

Table 6.3: Effectiveness of various mitigation options

	Effectiveness	**Application**
Equipment-level solutions (up to 10 kVA)		
Coil-Lock [116]	Dips down to 25% and duration shorter than 3 sec	AC-relays, contactors, Solenoids, Motor starters
Dip proofing inverter (DPI) [117]	Dips and interruptions shorter than 3 sec	AC-relays, contactors, Solenoids, Motor starters
Voltage dip compensators (VDC) [118]	Dips down to 50% of nominal voltage for 4–22 sec	Contactors, Relays, Motor starters, PLC controls, Semiconductor equipment, and other control elements
Constant voltage transformers (CVT) [119]	Dips up to 30–40% of the nominal for any duration up on proper sizing	One-phase equipment controls
Uninterruptable power supply (UPS) [105]	Dips and interruptions for a significant duration depending on size of UPS	equipment controls and loads
Machine-level (10–500 kVA) and entire plant-level (0.5–50 MVA) solutions		
Uninterruptable Power Supply (UPS) [105]	Dips and interruptions for a significant duration depending on size	Single load or group of loads/ processes in a facility
Dynamic sag correctors (DySC) [115, 123]	Dips and interruptions up to 5 sec (sized full-boost)	Machine to facility-wide protection
Flywheel (FW) [111, 115]	Dips and interruptions for a significant period of time, depending on size of FW	Single load or loads in the entire plant
Dynamic voltage restorer (DVR) [115], [120]	Voltage drops as low as 40% for a period up to one second	Loads in the MV- and LV-networks
Omniverter-Active voltage conditioners (AVC) [121]	Voltage drops down to 50% and 30% of the nominal voltage with three-phase and one-phase dips for at least 30 sec	Three-phase loads in the entire manufacturing facility (25 kVA-1 MVA in LV- and 1-50 MVA in MV-networks)
Static transfer switch (STS) [122]	Voltage dips and interruptions	Customers in the entire feeder (or facility) with alternate feeder

6.2.3 Decision-making tools

Despite the availability of several types of voltage dip mitigation techniques, each solution comes at a cost. Besides, not every mitigation technique is effective to solve all dip-related problems, and the solution can be too expensive or cost-competitive relative to the expected number of reduction in system interruptions caused by voltage dips. Figure 6.2 presents a flow chart consisting of the basic elements during the economic evaluation of voltage dips and technical solutions. In the economic analysis for choosing the optimal mitigation solution, the expected annual cost of voltage dips before mitigation (referred to as the “do nothing” option) is compared with the cost of solution and cost of unmitigated dips after mitigation.

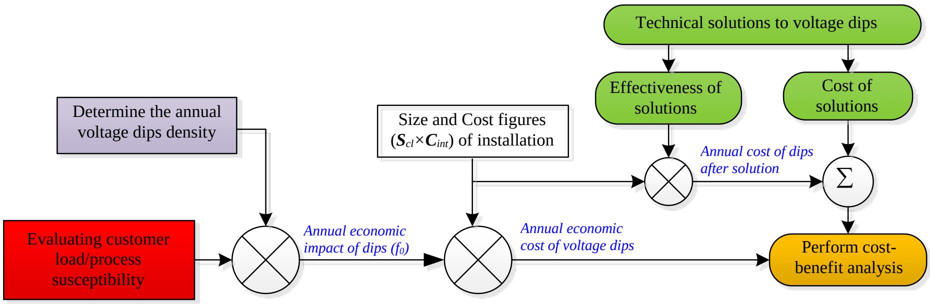


Figure 6.2: Flowchart for the economic evaluation of voltage dips and technical solutions.

Due to the fact that mitigation techniques can zbe costly, it is worth justifying the economic feasibility of preventive measures before making any investment. To analyze the economic feasibility of PQ solutions, different industries may consider one or a combination of the following decision-making criteria:

- Net present value (NPV)
- Payback time (PBT)
- Internal rate of return (IRR)
- Profitability index (PI)

6.2.3.1 Present worth analysis

To perform the economic feasibility of investments on mitigation options, the net present value (NPV) method is usually used. The NPV analysis considers any element that results in a cost or profit, revenue in-flow or out-flow, and it can be expressed by (6.2)[124-126],

$$NPV = \sum_{t=0}^{n} \frac{\left(f_r (C_{\text{int}} \times S_{cl}) - (C_0 + OMC_t) \right)(1+e)^t}{(1+r)^t (1+i)^t} \tag{6.2}$$

where NPV is the net present value of a series of cost, f_r refers to the expected number of avoided interruptions at the beginning of a year, C_{int} is cost of load interruption [€/kW/int.], S_{cl} is size of critical load in the system [in kW], C_0 denotes the cost of initial (capital) investment of solution [€], *OMC* is the expected annual operating and maintenance cost [€/yr], *e* is the escalation rate of costs (normally same value as inflation rate), *r* is discount (interest) rate adjusted for inflation, *i* is inflation rate, *t* refers the number of years, and *n* denotes the lifetime of the investment [yr].

In the NPV analysis, all future benefits (in-flows) and expenditures (out-flows) associated with the investment on the PQ solution are spread over the entire lifespan of the solution. There is also a time value associated with money, and "the present" is considered as the common point in time in order to make a decision on the feasibility of investments. For assumed values for rates of inflation, discount and escalation, it can be pointed out from (6.2) that the economic benefit ($f_r(C_{int}$×$S_{cl})$) and the operating and maintenance cost (*OMC*) of the solution are both zero at the time of investment (t=0), and the net return at the time of investment is –C_0.

The main target of investments on mitigation techniques is to reduce the expected cost of voltage dips, which is related to the reduction in the expected number of outages caused by voltage dips over a certain period of time. When identifying feasible solutions, the decision-making highly depends on maximizing the expected “avoided economic damages” which rely on the future benefits ($f_r(C_{int}\times S_{cl})$) and expenditures ($OMC_t$). The NPV method is typically used for large capital projects [124] and the NPV values can be compared for different mitigation options. In general, any solution can be considered as acceptable and is expected to increase the economic value of the company if the NPV value is positive within the lifetime of the project. If mutually exclusive investments yield positive NPV values, the mitigation option with the highest NPV would be the most preferable choice.

6.2.3.2 Payback time

The payback time (PBT) of an investment is the number of years of benefit required for the project to breakeven, and it is often defined as the ratio of the net investment to the net annual return [124]. When the net cash flow (net return) is negative in the year y_n and positive in the year y_{n+1}, then the breakeven point occurs sometime on the way into the year y_{n+1}. If it is assumed that the cash flows occur regularly over the course of the year, the PBT can be computed using the formula (6.3) [127],

$$PBT = y_n - \frac{NCF(\mathrm{y}_n)}{CF(\mathrm{y}_{n+1})} \tag{6.3}$$

where y_n is the last year with a negative net return or net cash flow (NCF), $NCF(y_n)$ refers to the net cash flow in that year, and $CF(y_{n+1})$ denotes the total cash flow (in-flow − out-flow) in the following year (y_{n+1}).

Based on the payback rule, an investment is acceptable if its calculated payback period is less than some pre-specified number of years called the cutoff period. Because of its simplicity, the payback period rule is often used as a rule of thumb to make relatively minor decisions, especially in small businesses biased towards short-term projects. Many industrial companies often look for investments on PQ projects with payback less than 1–2 years in order for them to be considered, equivalent to a 50–100% return rate [124, 127]. Despite its simplicity, the payback rule ignores all cash flows after the cutoff date and considers equal weight to all cash flows before the cutoff point (i.e., it ignores the time value of money). If the same cutoff date is used regardless of the project lifetime, the payback rule tends to accept many poor short-lived projects and reject many good long-term projects.

6.2.3.3 Internal rate of return

Internal rate of return (IRR) is a measure of the desirability of a project and it is defined as the discount rate at which the investment breaks even, i.e. the return which results in a zero NPV when it is used as the discount rate [124]. Assuming the same value for the escalation rate as inflation rate, the IRR can be evaluated by (6.4),

$$-C_0 + \sum_{t=1}^{n} \frac{CF_t}{(1+IRR)^t} = 0 \tag{6.4}$$

where CF_t $(=f_r(C_{int} \times S_{cl}) - OMC_t)$ is the annual cash flow, the difference between the revenue in-flows and out-flows. Based on the IRR rule, the IRR should be greater than the cost of capital (discount rate) for a project to be accepted. With mutually exclusive projects, the option with the highest IRR would be the most desirable choice as long as it also provides the highest profit (NPV).

6.2.3.4 Profitability index

The profitability index (PI), also called benefit-cost ratio, is defined as the ratio of the payoff (present value of the future cash flows) to the initial investment of a proposed project [124]. This is another tool used to evaluate the feasibility of projects by quantifying the amount of value created per unit investment, and it is often useful for selecting among various project combinations and alternatives when available investment funds are limited. Assuming the same value for the escalation rate as inflation rate, the PI can be evaluated by equation (6.5)

$$PI = \frac{1}{C_0} \sum_{t=1}^{n} \frac{f_r(C_{\text{int}} \times S_{cl}) - OMC_t}{(1+r)^t}. \tag{6.5}$$

More generally, if a project has a positive NPV, then the present value of the future cash flows must be bigger than the initial investment. The profitability index would thus be bigger than unity for a positive NPV investment and less than unity for a negative NPV investment. With mutually exclusive projects, the option with the highest profit (NPV) would be the most desirable choice even if the PIs are higher with the other options.

6.3 Proposed cost estimation methods of voltage dips

To consider a cost effective preventive measure for protecting installations and reduce the disruptive impact of voltage dips in a facility, the customer should know the approximate number of load outages, which also represent the economic impact, caused by voltage dips. However, direct evaluation of the economic loss of voltage dips is difficult and it is often expressed relative to that of a complete interruption of the entire plant.

As described in *Chapter 4* and *Chapter 5*, the impact of voltage dips on equipment and processes depends on the severity of dips and sensitivity of the installation. Thus, the different magnitudes and durations of various types of dips (L_{001}, L_{011}, and L_{111}) at the POC of the facility should be considered separately when analyzing the economic impact on customers. The annual load outage cost (ALOC) of an industrial facility caused by voltage dips depends on the number of interruption of loads, size of critical loads and cost of load interruption. The value of ALOC can be estimated using the formula (6.6),

$$ALOC = f_0 \times (S_{cl} \times C_{\text{int}}) \tag{6.6}$$

where f_0 is the frequency of annual interruptions due to voltage dips [#/yr], S_{cl} is the size of critical loads [in kW] and C_{int} is the cost of interruption per unit load [€/kW]. The number of interruptions caused by the dips may vary from facility to facility. The cost of interruption, which involve direct and indirect cost, is highly dependent on the types of processes and often varies among different customer categories even experiencing the same characteristics of voltage dips [4, 128].

In the following sections, two approaches of estimating the economic impact of voltage dips relative to that of a complete interruption of the entire plant are discussed. The first one derives plant-specific severity indices and the second one uses generalized weighting factor values.

6.3.1 Cost estimation based on equipment sensitivity analysis

The response of industrial processes to incoming voltage dips is directly influenced by the voltage dip ride-through capability of equipment that make up the process. The composition and sensitivity of process equipment to voltage dips often vary within different category of industries. In this section, an approach of estimating the economic impact of voltage dips based on equipment sensitivity analysis is demonstrated using an illustrative manufacturing facility.

Figure 6.3 shows the flow diagram for estimating the economic loss caused by voltage dips based on sensitivity analysis of process equipment within a facility. The annual economic loss of an industrial plant due to voltage dips depends on the annual frequency and severity (characterized by magnitude, duration and type) of voltage dips at the POC of the plant, on the composition, behavior and interaction of process equipment against voltage dips, and on the size of load and cost of load interruption.

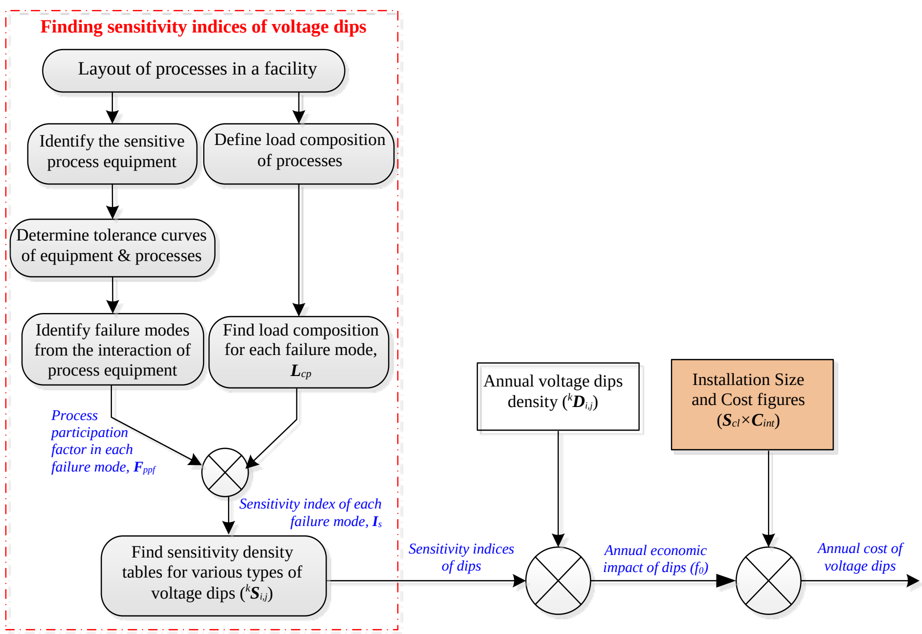


Figure 6.3: Flowchart for estimating economic impact of voltage dips based on sensitivity analysis.

6.3.1.1 Process layout in the illustrative facility

Depending on the size and complexity of the plant, the production of the manufacturing facility will rely on one or more processes each composed of equipment that might be susceptible to voltage dips. The composition of equipment and processes can vary from facility to facility, and so does the economic impact due to voltage dips. To illustrate the cost estimation approach, the electrical layout of a manufacturing facility comprising four independent processes and supplied from a 10/0.4 kV transformer is described in Figure 6.4. In this facility, 1000 kW of the total load is assumed to be critical load that is sensitive to voltage dips.

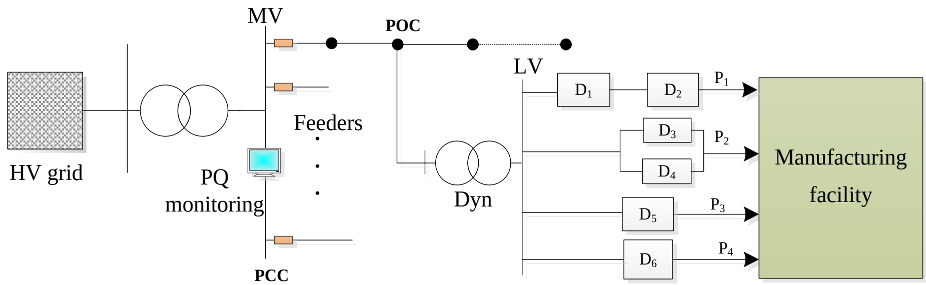


Figure 6.4: Layout of a manufacturing facility for illustration.

The complete production of the manufacturing facility shown in Figure 6.4 depends on the performance of the four processes during voltage dips; and the performance of each process is determined by the ride-through capability of the equipment that make up the process. In this case, process P_1 depends on the sensitivity of device D_1 connected in series with device D_2, while process P_2 depends on the sensitivity of two devices D_3 and D_4 connected in parallel. The voltage dip performance of process P_3 and P_4 are governed by the ride-through capability of single devices D_5 and D_6 respectively.

In a large number of industrial plants, AC contactors, adjustable speed drives (ASDs), programmable logic controllers (PLCs) and computers (PCs) are commonly used devices sensitive to voltage dips [35, 59-65]. In the illustrative facility, an AC contactor and adjustable speed drive (ASD) will be used in process P_1 for D_1 and D_2. In process P_2, two computers PC_1 and PC_2 that comply with the ITIC power acceptability curve are considered in parallel performing the same task. The PCs are supplied from two different phase-voltages in order to enhance the reliability of the process P_2 in the facility. PLC is used for D_5 to control the performance of process P_3 and the performance of process P_4 is controlled by device D_6 which complies with the SEMI F47 power acceptability curve. It is also considered that the processes P_1, P_2, P_3 and P_4 have load compositions of 30%, 20%, 10% and 40% of the total load in the facility.

6.3.1.2 Voltage-tolerance curves of equipment

For the illustrative facility, the sensitivities of the AC contactor, ASD, and PLC are obtained from laboratory tests (descried in *Chapter 4*), while the general ITIC and SEMI

F47 power acceptability curves are considered for the PCs and SEMI F47 device. The sensitivity of the devices can be summarized as:

- AC contactor C_1 that trips for voltage dips with $u_r \leq 54\%$ and $\Delta t > 20$ms (considering characteristics of both 0° and 90° point-on-wave dip initiations),
- ASD at 75% rated-load which trips during voltage dips with $u_r \leq 70\%$ and $\Delta t \geq 1000$ ms, $u_r \leq 70\%$ and $\Delta t \geq 30$ ms, and $u_r \leq 80\%$ and $\Delta t \geq 30$ ms for one-phase, two-phase and three-phase dips respectively,
- Programmable logic controller PLC_1 that trips the process during voltage dips with $u_r \leq 32\%$ and $\Delta t \geq 30$ ms, and dips with $u_r \leq 35\%$ and $\Delta t \geq 130$ ms,
- PCs and SEMI device that comply with the ITIC and SEMI F47 curves.

Figure 6.5 shows the voltage-tolerance curves of the sensitive devices plotted together against the three types of voltage dips. The susceptibility area of the ASD increases with polyphase dips while that of contactor, PCs and PLC are the same with all types of dips assuming the control voltage is affected by the dip.

6.3.1.3 Failure modes of load process

The performance of each process depends on the behavior and interaction of individual equipment that make of the process. From this perspective, it is presumed here that:

- Process P_1 trips if the contactor and/or ASD fails,
- Process P_2 trips if both PCs fail,
- Process P_3 trips if the PLC fails, and
- Process P_4 trips if the SEMI F47 device fails.

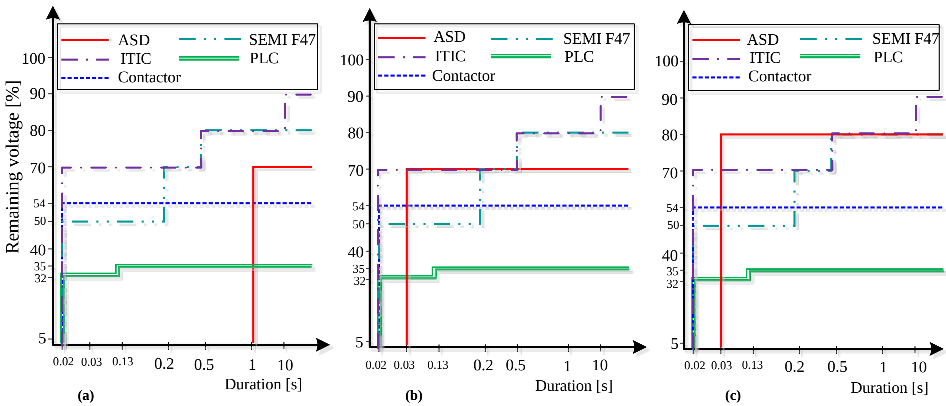


Figure 6.5: Voltage-tolerance curves of equipment subjected to dips in – (a) one-phase, (b) two-phases, and (c) three-phases.

Based on the sensitivity and interaction of process equipment in the facility under consideration, voltage-tolerance curves of each process in the facility are plotted in Figure 6.6 for the three types of dips. From the equipment behavior subjected to different types of voltage dips, it can be observed that:

- Process P_3, which is controlled by the PLC, is the most robust process as no other process can fail ahead of it.

- SEMI F47 curve is fully enclosed by the ITIC curve and thus process P_2 trips whenever P_4 trips,
- Process P_2 will withstand one-phase dips as its performance is governed by two PCs connected in parallel and supplied from different phase supply voltages. With two-phase dips, the ITIC power acceptability curve fully encloses other process equipment and P_2 fails whenever any other process fails for such dips.
- Voltage-tolerance curve of the ASD tightens with polyphase dips and a possibility that only P_1 fails with larger susceptibility area can happen for three-phase dips.

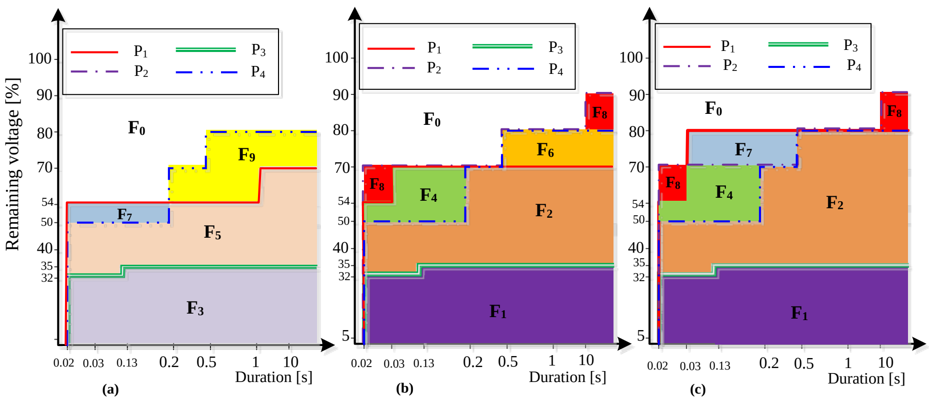


Figure 6.6: Process immunity curves and various failure modes of the load process subjected to – (a) one-phase dips, (b) two-phase dips, and (c) three-phase dips.

Taking into account that '*r*' processes fail at the same time during each type of voltage dip, the maximum possible number of failure modes (N_{fm}) in a facility that comprises 'n' independent processes can be found using formula (6.7).

$$N_{fm} = \sum_{r=1}^{n} \left(\frac{n!}{r!(n-r)!} \right) \tag{6.7}$$

The actual number of failure modes (m) in the facility, however, depends on the sensitivity and interaction of each process, which again depends on the ride-through capability and interaction of process equipment, against various types of voltage dips. Examining the behavior and interaction of processes subjected to different types of voltage dips (shown in Figure 6.6), the facility under consideration actually resulted in nine failure modes (F_1–F_9) summarized in Table 6.4. In the first failure mode (F_1), all processes fail at the same time for two-phase and three-phase dips while F_7, F_8 and F_9 are failure modes in which only a single process fails at a time during various types of dips. It can also be observed that the vulnerability area of each failure mode can vary with different types of dips.

6.3.1.4 Sensitivity values of failure modes

The severity values of the failure modes depend on the number of processes failing at the same time, the load composition of processes, and the type of voltage dip affecting each failure mode. Suppose L_1, L_2…L_n are the load compositions of the respective processes such that a particular voltage dip causes a disruption which can be expressed as percentage loss relative to a complete shutdown of the entire load process, the sensitivity index ($\boldsymbol{I_s}$) matrix of the 'm' failure modes can be obtained using (6.8),

$$I_s = F_{ppf} \frac{L_{cp}}{100} \tag{6.8}$$

where $\boldsymbol{F_{ppf}}$ is the matrix of process participation factor expressed by (6.9) in which each element 'a' is represented by '1' or '0' to indicate the participation of processes in the respective failure modes, and $\boldsymbol{L_{cp}}$ is the percentage of load composition matrix of processes, articulated by (6.10).

$$F_{ppf} = \begin{pmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{m1} & \cdots & a_{mn} \end{pmatrix} \tag{6.9}$$

$$L_{cp} = \begin{pmatrix} L_1 & L_2 & \cdots & L_n \end{pmatrix}^T \tag{6.10}$$

Considering the assumed values of load compositions of processes in the facility, the sensitivity indices of the failure mode are given in Table 6.4. The values range from 20% for the failure mode F_8 to 100% when all processes are affected in F_1.

Table 6.4: Participation of processes, type of involving dips and sensitivity index for each failure mode

	Failure modes								
	F_1	F_2	F_3	F_4	F_5	F_6	F_7	F_8	F_9
Process failing per failure mode	$P_1P_2P_3P_4$	$P_1P_2P_4$	$P_1P_3P_4$	P_1P_2	P_1P_4	P_2P_4	P_1	P_2	P_4
Dip types involved per failure mode	2/3-ph	2/3-ph	1-ph	2/3-ph	1-ph	2-ph	1/3-ph	2/3-ph	1-ph
Process participation factor (F_{ppf})	1111	1101	1011	1100	1001	0101	1000	0100	0001
Sensitivity index (I_s) of failure modes	1.00	0.90	0.80	0.50	0.70	0.60	0.30	0.20	0.40

By replacing each failure mode with its corresponding value of sensitivity index (I_s), tables of sensitivity density ($\boldsymbol{S}_{i,j} \propto s(u_i, \Delta t_j)$) obtained for the three types of dips (one-phase, two-phase and three-phase) having 'u' magnitude of remaining voltage and 'Δt' duration are shown in Table 6.5. It can be observed that different values of sensitivity density can be obtained for voltage dips even represented within the same range of magnitude and/or duration in the standards (e.g. dips having magnitude between 40-70% of nominal voltage and duration in the range between 10-200 ms). This indicates that sensitivity indices with higher resolution can be obtained with this methodology that can help for estimating the equivalent number of interruptions of the facility caused by voltage dips.

Table 6.5: Sensitivity density for various types of voltage dips in the facility

Remaining voltage [%]		Duration [s]: $0.01 < \Delta t \leq 0.2$ $\Delta t \leq 0.02$	$\Delta t < 0.03$	$\Delta t < 0.13$	$\Delta t \leq 0.2$	$0.2 < \Delta t \leq 0.5$	$0.5 < \Delta t \leq 1$	$1 < \Delta t \leq 5$	$5 < \Delta t \leq 60$ $\Delta t \leq 10$	$\Delta t > 10$
(a) One-phase dips										
$90 > u \geq 80$		0	0	0	0	0	0	0	0	0
$80 > u \geq 70$		0	0	0	0	0	0.4	0.4	0.4	0.4
$70 > u \geq 40$	$u<70$	0	0	0	0	0.4	0.7	0.7	0.7	0.7
	$u<54$	0	0.3	0.3	0.3	0.7	0.7	0.7	0.7	0.7
	$u<50$	0	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
$40 > u \geq 5$	$u<40$	0	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
	$u<35$	0	0.7	0.7	0.8	0.8	0.8	0.8	0.8	0.8
	$u<32$	0	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
$5 > u$		0	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
(b) two-phase dips										
$90 > u \geq 80$		0	0	0	0	0	0	0	0	0.2
$80 > u \geq 70$		0	0	0	0	0	0.6	0.6	0.6	0.6
$70 > u \geq 40$	$u<70$	0	0.2	0.5	0.5	0.9	0.9	0.9	0.9	0.9
	$u<54$	0	0.5	0.5	0.5	0.9	0.9	0.9	0.9	0.9
	$u<50$	0	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
$40 > u \geq 5$	$u<40$	0	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
	$u<35$	0	0.9	0.9	1	1	1	1	1	1
	$u<32$	0	1	1	1	1	1	1	1	1
$5 > u$		0	1	1	1	1	1	1	1	1
(c) three-phase dips										
$90 > u \geq 80$		0	0	0	0	0	0	0	0	0.2
$80 > u \geq 70$		0	0	0.3	0.3	0.3	0.9	0.9	0.9	0.9
$70 > u \geq 40$	$u<70$	0	0.2	0.5	0.5	0.9	0.9	0.9	0.9	0.9
	$u<54$	0	0.5	0.5	0.5	0.9	0.9	0.9	0.9	0.9
	$u<50$	0	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
$40 > u \geq 5$	$u<40$	0	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
	$u<35$	0	0.9	0.9	1	1	1	1	1	1
	$u<32$	0	1	1	1	1	1	1	1	1
$5 > u$		0	1	1	1	1	1	1	1	1

6.3.1.5 Assessment of the economic impact

To consider the most cost-effective investment on mitigation techniques, customers should take into account the variations in the frequency and severity of voltage dips at their points of connections over several years when evaluating the expected annual economic loss. From this perspective, the average annual voltage dip density ($\boldsymbol{D}_{i,j} \propto d(u_i, \Delta t_j)$) corresponding to the sensitivity density ($\boldsymbol{S}_{i,j} \propto s(u_i, \Delta t_j)$) need to be considered for each type of voltage dip at the end-user's terminal. An example of voltage dips density corresponding to the sensitivity density for various types of dips is shown in Table 6.6 to demonstrate the application of the methodology for estimating the economic loss of voltage dips.

By combining the voltage dip density with the respective sensitivity density, the total number of annual equivalent interruptions (f_0) caused by the voltage dips at the POC of the facility can be estimated using (6.11),

$$f_0 = \sum_k \sum_j \sum_i \left(\overset{k}{d}(u_i, \Delta t_j) \right) \left(\overset{k}{s}(u_i, \Delta t_j) \right) \quad (6.11)$$

where ${}^{k}d$ and ${}^{k}s$ are the annual voltage dip density and sensitivity density functions for each type of dip (k). On average, the facility considered here for illustration would experience 9.25 dips per year leading to the economic loss of ~5.78 times that of the complete interruption of the entire load in the facility.

Table 6.6: An example of average annual voltage dip density at the connection point of the facility

Remaining voltage [%]		Duration [s]: *0.01 < Δt ≤ 0.2* Δt≤0.02	*0.01 < Δt ≤ 0.2* Δt<0.03	*0.01 < Δt ≤ 0.2* Δt<0.13	*0.01 < Δt ≤ 0.2* Δt≤0.2	*0.2 < Δt ≤ 0.5*	*0.5 < Δt ≤ 1*	*1 < Δt ≤ 5*	*5 < Δt ≤ 60* Δt≤10	*5 < Δt ≤ 60* Δt>10
		(a) One-phase dips								
90 > u ≥ 80		0	0	0	0	0	0	0	0	0
80 > u ≥ 70		0.5	0	0	0	0	0	0	0	0
70 >u≥ 40	*u<70*	0.25	0	0	0	0	0	0	0	0
	u<54	0	0	0	0	0	0	0	0	0
	u<50	0	0	0	0	0	0	0	0	0
40 >u≥ 5	*u<40*	0	0	0	0	0	0	0	0	0
	u<35	0	0	0	0	0	0	0	0	0
	u<32	0	0	0	0	0	0	0	0	0
5 > u		0	0	0	0	0	0	0	0	0
		(b) two-phase dips								
90 > u ≥ 80		0	0	0	0	0	0	0	0	0
80 > u ≥ 70		0.5	0	0	0	0	0	0	0	0
70 >u≥ 40	*u<70*	0	0	0.5	0.25	0	0	0.25	0	0
	u<54	0	0	0	0	0	0	0	0	0
	u<50	0	0	0	0	0	0	0	0	0
40 >u≥ 5	*u<40*	0	0	0	0	0	0	0	0	0
	u<35	0	0	0	0	0	0	0	0	0
	u<32	0	0	0	0	0	0	0.25	0	0
5 > u		0	0	0	0	0	0	0	0	0
		(c) three-phase dips								
90 > u ≥ 80		0	0	0	0	0	0	0.25	0	0
80 > u ≥ 70		0	0	0.25	0.25	0.25	0	0	0	0
70 >u≥ 40	*u<70*	0.25	0	0.5	0.75	0	0.25	0	0	0
	u<54	0	0	0	0	0	0	0	0	0
	u<50	0	0	0.5	0	0	0	0.5	0	0
40 >u≥ 5	*u<40*	0	0	0	0	0.25	0.25	0	0	0
	u<35	0	0	0	0	0	0	0	0	0
	u<32	0	0	0	0	0.5	2	0	0	0
5 > u		0	0	0	0	0	0	0	0	0

A good aspect of this approach is that the contribution of different failure modes, where different processes participate, can be compared and this would help customers to compare various mitigation solutions that could be applied at different levels (such as equipment-level, process-level, or entire-plant level). For the illustrative facility, the contribution of the failure modes to the expected number of annual equivalent interruptions is shown in Table 6.7. About 97% of the equivalent interruptions are due to the tripping of processes in F_1, F_2 and F_4 while other failure modes contribute little or nothing. It should be recalled, however, that variations in the frequency and/or severity of voltage dips, or the load composition of process can alter the total equivalent interruptions and contributions made by each failure mode.

Table 6.7: Contribution of failure modes to the annual equivalent interruptions due to voltage dips

	Failure modes										
	F_1	F_2	F_3	F_4	F_5	F_6	F_7	F_8	F_9	F_0	Total
Number of dips per year	2.75	2.00	0.00	2.00	0.00	0.00	0.75	0.00	0.00	1.75	9.25
Dips per failure-mode [%]	29.73	21.62	0.00	21.62	0.00	0.00	8.11	0.00	0.00	18.92	100
Number of interruption/yr	2.75	1.80	0.00	1.00	0.00	0.00	0.23	0.00	0.00	0.00	5.78
Interruptions/failure-mode [%]	47.62	31.17	0.00	17.32	0.00	0.00	3.90	0.00	0.00	0.00	100

6.3.1.6 Significance of equipment and processes

An interesting feature of this methodology is that it can help the customer to evaluate and compare the economic importance of equipment and processes in the facility. By knowing the expected contribution of equipment and processes to the total equivalent interruptions, the customer can rank the economic values of equipment and processes paving the way for comparing more alternative solutions before making any investment for reducing the voltage dip problems. Evaluating the economic importance of equipment and processes involves the following steps:

(i) Consider that a particular equipment is completely immune to voltage dips.
(ii) Formulate the failure modes and their sensitivity values (as described earlier).
(iii) Evaluate the equivalent interruptions due to any other equipment and processes.
(iv) Compute the reduction in the economic impact after the equipment under consideration is assumed to be fully immune.

For each equipment, process or group of processes, the above steps can be repeated to determine the respective economic values. In each case, the reduction in the equivalent interruption (f_r) can be calculated using (6.12),

$$f_r = f_o - \sum_k \sum_j \sum_i \left(\overset{k}{d}(u_i, \Delta t_j) \right) \left(\overset{k}{s^*}(u_i, \Delta t_j) \right) \qquad (6.12)$$

where f_o represents the equivalent interruption before any mitigation is considered in the facility and s^* denotes the new severity density function after an equipment or a process (or a group of processes) is mitigated. The value of f_r indicates the maximum contribution of the equipment, process or group of processes to the total equivalent interruptions of the facility under consideration.

For the facility considered for illustration, the economic significance of individual equipment, individual processes and combined processes during the most optimistic situation are shown in Table 6.8. At equipment and process level, a maximum economic gain of 40% can be attained when the ASD is considered completely immune to voltage dips. The economic gains would increase up to 73% when a combination of two processes are fully protected and up to 96% when a combination of three processes are made completely immune to voltage dips.

Table 6.8: Economic significance of equipment and processes during the most optimistic situation

Protected device or process		Reduction in interruption/yr			
		f_r *[#]*	f_r *[%]*	*Rank*	
	Nothing	0.00	0.00	-	
Equipment-level	Only contactor of P_1	0.00	0.00	19	
	Only ASD of P_1	2.33	40.22	10	
	Only PC_1 or PC_2 of P_2	1.33	22.92	16	
	Only PLC of P_3	0.28	4.84	18	
	Only SEMI device of P_4	1.90	32.87	13	
Process-level	Only process P_1	2.33	40.22	9	
	Only process P_2	1.33	22.92	15	
	Only process P_3	0.28	4.84	17	
	Only process P_4	1.90	32.87	12	
Group of processes	Both processes P_1, P_2	3.65	63.15	5	**A_1**
	Both processes P_1, P_3	2.61	45.07	8	
	Both processes P_1, P_4	4.23	73.10	3	**A_2**
	Both processes P_2, P_3	1.61	27.77	14	
	Both processes P_2, P_4	3.23	55.80	7	**A_3**
	Both processes P_3, P_4	2.18	37.72	11	
	Processes P_1, P_2, P_3	3.93	67.95	4	**B_1**
	Processes P_1, P_2, P_4	5.55	96.02	2	**B_2**
	Processes P_2, P_3, P_4	3.50	60.55	6	**B_3**
Entire plant	All processes	5.78	100.00	1	**C**

6.3.1.7 Cost-benefit analysis with technical solutions

Although the maximum economic values of equipment or processes are evaluated by considering the equipment or processes being fully protected against voltage dips, not every mitigation technique is effective to completely solve all dip-related problems in practice. If a minimum reduction of interruption by 50% during the most optimistic situation is aimed in the facility under consideration, seven conditions all involving group of processes (ranked 1–7 in Table 6.8) can be considered for comparing the appropriateness of more alternative solutions. As depicted in Figure 6.7, a combination of two processes, three processes and all processes protected by solutions at ‘A’, ‘B’ and ‘C’ can be considered for further cost-benefit analysis. Again, it must be recalled that the composition and robustness of equipment and processes can vary in different facilities. As a result, the economic importance of equipment and processes and thus positions of feasible solutions can also alter.

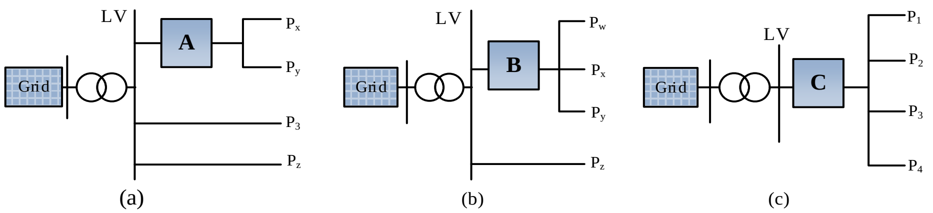


Figure 6.7: Position of alternative solutions protecting – (a) two processes (A_1=P_1P_2, A_2=P_1P_4, or A_3=P_2P_4) at ‘A’, (b) three processes (B_1=$P_1P_2P_3$, B_2=$P_1P_2P_4$, or B_3=$P_2P_3P_4$) at ‘B’, and (c) all processes ($P_1P_2P_3P_4$) at ‘C’.

In this section, active voltage conditioner (AVC), dynamic voltage restorer (DVR), dynamic sag corrector (DySC), Flywheel (FW) and uninterruptable power supply (UPS) are considered to examine their cost-benefit analysis for protecting group of processes at different positions shown in Figure 6.7. Taking the effectiveness of each solution (Table 6.3) into account, the reduction in the annual equivalent interruptions are evaluated and presented in Table 6.9. It can be noticed that AVC and DVR would reduce the number of annual shutdown of the manufacturing facility by less than 30% and this is due to the fact that most of the dips are deeper which could not be mitigated by these devices. On the other hand, DySC, UPS and FW can effectively reduce the number of equivalent interruptions by ~56–100% depending on the position of solutions application.

Table 6.9: Annual reduction in the number of load halts (in the study case) with various mitigation options at several poistions

Position		**Protected processes**	**Reduction of interruption [#/yr]**					**Reduction of interruption/yr [%]**				
			AVC	***DVR***	***DySC***	***UPS***	***FW***	***AVC***	***DVR***	***DySC***	***UPS***	***FW***
A	A_1	P_1, P_2	1.53	1.53	3.65	3.65	3.65	26.4	26.4	63.1	63.1	63.1
	A_2	P_1, P_4	1.25	1.25	4.23	4.23	4.23	21.6	21.6	73.1	73.1	73.1
	A_3	P_2, P_4	0.68	0.68	3.23	3.23	3.23	11.7	11.7	55.8	55.8	55.8
B	B_1	P_1, P_2, P_3	1.53	1.53	3.93	3.93	3.93	26.4	26.4	67.9	67.9	67.9
	B_2	P_1, P_2, P_4	1.73	1.73	5.55	5.55	5.55	29.8	29.8	96.0	96.0	96.0
	B_3	P_2, P_3, P_4	0.68	0.68	3.50	3.50	3.50	11.7	11.7	60.6	60.6	60.6
C		P_1, P_2, P_3, P_4	1.73	1.73	5.78	5.78	5.78	29.8	29.8	100	100	100

As described earlier, the facility under consideration experiences about 5.78 equivalent interruptions per year due to the expected annual dips. For several types of industrial customers, a range of momentary interruption costs per kW demand of process, adopted from [4, 128], and cost voltage dips are given in Table 6.10. The expected annual costs of voltage dips for the typical industries are calculated using the average costs of process interruption.

Table 6.10: Cost of momentary interruption and annualized cost of voltage dips before mitigation for typical industries [4, 128]

Category of industrial company (IC)	Cost per interruption [€/kW]		Average annual cost [€/year]
	Minimum	Maximum	
IC_1: Automobile manufacturing	5	8	36,125
IC_2: Textile, Metal fabrication, Mining	2	4	17,340
IC_3: Petrochemical, Rubber& plastics, Food processing	3	5	23,120
IC_4: Electronics	8	12	57,800
IC_5: Pharmaceutical	5	50	158,950
IC_6: Semiconductor manufacturing	20	60	231,200

To analyze the feasibility of the solutions at different positions, the cost of mitigation options should be compared with the economic benefits gained in reducing the dip-related losses. The initial investment and running costs associated with the alternative solutions under consideration, adopted from [4, 115], are summarized in Table 6.11.

Table 6.11: Costs of different alternative solutions at machine or group of machines level [4, 115]

	Alternative PQ solutions				
	AVC	DVR	DySC	UPS	FW
Initial investment cost, C_0 [€/kVA]	250	300	200	500	500
Operating & maintenance cost, OMC [%C_0/yr]	2	5	5	15	7

Considering a 10-year lifespan of investments on the various solutions and 10% discount rate, and using the average cost of interruptions for the aforementioned six categories of industrial customers, the annualized costs after mitigation in IC_1, IC_2 and IC_3 industries (Table 6.10) are much higher, for all mitigation options considered at various positions, than cost of voltage dips before mitigation. This implies none of the mitigation options considered here would be acceptable in these groups of industries. It should be noted, however, that an illustrative facility with a generic load composition is considered here and the results may not be applicable directly to these companies. Figure 6.8 shows a comparison on the annualized costs of voltage dips in the other categories (Pharmaceutical, Electronics and Semiconductor industries) before and after mitigation.

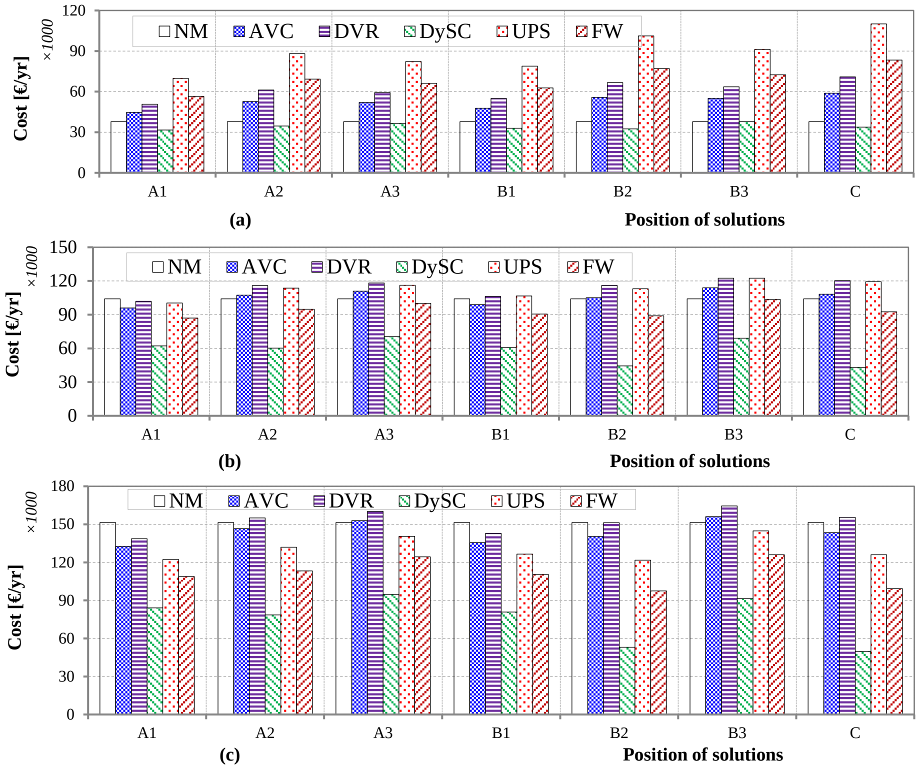


Figure 6.8: Comparison of annualized cost voltage dips without mitigation (NM) and with various mitigations at different positions for – (a) Electronics industry, (b) Pharmaceutical industry, and (c) Semiconductor manufacturing.

It can be seen from Figure 6.8 that the effectiveness of the mitigation options to be applied at different positions in reducing the number of annual interruptions and hence the economic gains vary. For the Electronics plant (Figure 6.8(a)), only the DySC at all positions showed lower annualized costs after mitigation than before mitigation and it would be the only acceptable option for the layout under consideration. In the Pharmaceutical industry, Figure 6.8(b) depicts that AVC at A_1 and B_1; DVR and UPS at A_1; DySC and FW at all positions would give net positive annualized costs and would be considered as acceptable options. Since the interruption cost is high in the Semiconductor manufacturing industries, Figure 6.8(c) shows that DVR at A_1 and B_1, and the other mitigation options in almost all positions would deliver lower annual costs after mitigation than before mitigation, and they can be considered as acceptable solutions over the lifetime of the investments. However, the profitability of the acceptable solution considered at several positions may again vary significantly and customers can use decision making tools to choose the most optimal solution.

For the Electronics, Pharmaceutical and Semiconductor industries, the desirability of the mitigation options to protect two processes at A_1, three processes at B_1 and all the four processes at C are compared in Table 6.12 based on NPV, PI, IRR and PBT decision-making criteria. In the Electronics industry, only investments on DySC at the different positions would give positive NPV, PI values greater than unity, IRR values greater than the discount rate, and PBTs less than the lifetime of the investments. In the Pharmaceutical and Semiconductor industries, most of the solutions under consideration are acceptable at the various positions. At each position (in this case A_1, B_1 or C), the DySC would be more preferable than any other options based on any of the decision making criteria.

Table 6.12: Comparing the desirablity of several mitigation options at three positions for three indusries

Industry	Solution	A_1				B_1				C			
		NPV	*PI*	*IRR*	*PBT*	*NPV*	*PI*	*IRR*	*PBT*	*NPV*	*PI*	*IRR*	*PBT*
IC_4 Electronics	***AVC***	-74,729	0.5	-4%	19.9	-108,416	0.4	-7%	25.1	-273,669	0.2	-14%	41.7
	DVR	-141,596	0.2	-16%	46.9	-188,657	0.1	-22%	79.0	-364,608	0.0	INV	INV
	DySC	67,409	1.6	22%	5.3	52,933	1.4	18%	6.3	44,186	1.2	14%	7.7
	UPS	-112,591	0.6	0%	16.0	-163,067	0.5	-2%	18.3	-315,814	0.5	-4%	21.1
	FW	-204,759	0.3	-10%	31.5	-273,669	0.2	-14%	41.7	-500,151	0.2	-25%	60.1
IC_5 Pharmaceutical	***AVC***	89,254	1.6	23%	6.3	55,567	1.3	17%	7.6	-45,385	0.8	6%	11.8
	DVR	22,387	1.1	13%	8.9	-24,674	0.9	7%	11.3	-179,119	0.5	-4%	19.9
	DySC	459,894	4.8	78%	1.4	474,988	4.3	70%	1.7	670,548	3.8	61%	1.9
	UPS	279,894	1.9	29%	5.2	258,988	1.7	25%	5.8	310,548	1.5	21%	6.6
	FW	187,725	1.6	23%	6.2	148,386	1.4	19%	7.1	126,211	1.2	10%	8.3
IC_6 Semiconductor	***AVC***	206,385	2.4	37%	4.2	172,698	2.0	29%	5.1	87,108	1.3	16%	7.7
	DVR	139,517	1.8	26%	5.6	92,457	1.4	19%	7.0	-46,627	0.9	7%	11.5
	DySC	740,239	7.2	117%	0.9	776,456	6.4	104%	1.1	1,117,949	5.7	92%	1.2
	UPS	560,239	2.9	46%	3.5	560,456	2.6	40%	3.9	757,949	2.3	35%	4.4
	FW	468,071	2.6	40%	3.9	449,854	2.2	35%	4.4	573,612	2.0	24%	5.1

To compare the desirability of the DySC in the Electronics, Pharmaceutical and Semiconductor industries, the variations of NPVs projected along the lifetime of the investments are shown in Figure 6.9. For the three types of industries, comparative values based on four decision-making tools are summarized in Table 6.13. In the Electronics industry, using the DySC at A_1 would be more cost-effective and also returns the investment faster than other positions. In case of the Pharmaceutical and Semiconductor industries, the use DySC is more profitable based on the NPV rule when it is used to mitigate the entire facility at C while the investment's payback time is shorter when the DySC is used to protect two processes at $A_{1.}$

Table 6.13: Comparing the desirablity of the DySC at several positions for three types industries based on the decision tools

Position		Protected process	**Electronics**				**Pharmaceutical**				**Semiconductor**			
			NPV	*PI*	*IRR*	*PBT*	*NPV*	*PI*	*IRR*	*PBT*	*NPV*	*PI*	*IRR*	*PBT*
A	A_1	P_1P_2	67,409	1.6	22%	5.3	459,894	4.8	78%	1.4	740,239	7.2	117%	0.9
	A_2	P_1P_4	35,385	1.2	15%	7.4	481,634	3.9	62%	1.8	800,384	5.8	94%	1.2
	A_3	P_2P_4	14,530	1.1	12%	8.6	369,379	3.6	57%	2.0	622,842	5.3	86%	1.3
B	B_1	$P_1P_2P_3$	52,933	1.4	18%	6.3	474,988	4.3	70%	1.6	776,456	6.4	104%	1.1
	B_2	$P_1P_2P_4$	58,662	1.3	16%	6.9	655,453	4.0	65%	1.7	1,081,733	6.0	98%	1.1
	B_3	$P_2P_3P_4$	54	1.0	10%	10.0	384,473	3.3	53%	2.2	659,059	4.9	80%	1.4
C		$P_1P_2P_3P_4$	44,186	1.2	14%	7.7	670,548	3.8	61%	1.9	1,117,949	5.7	92%	1.2

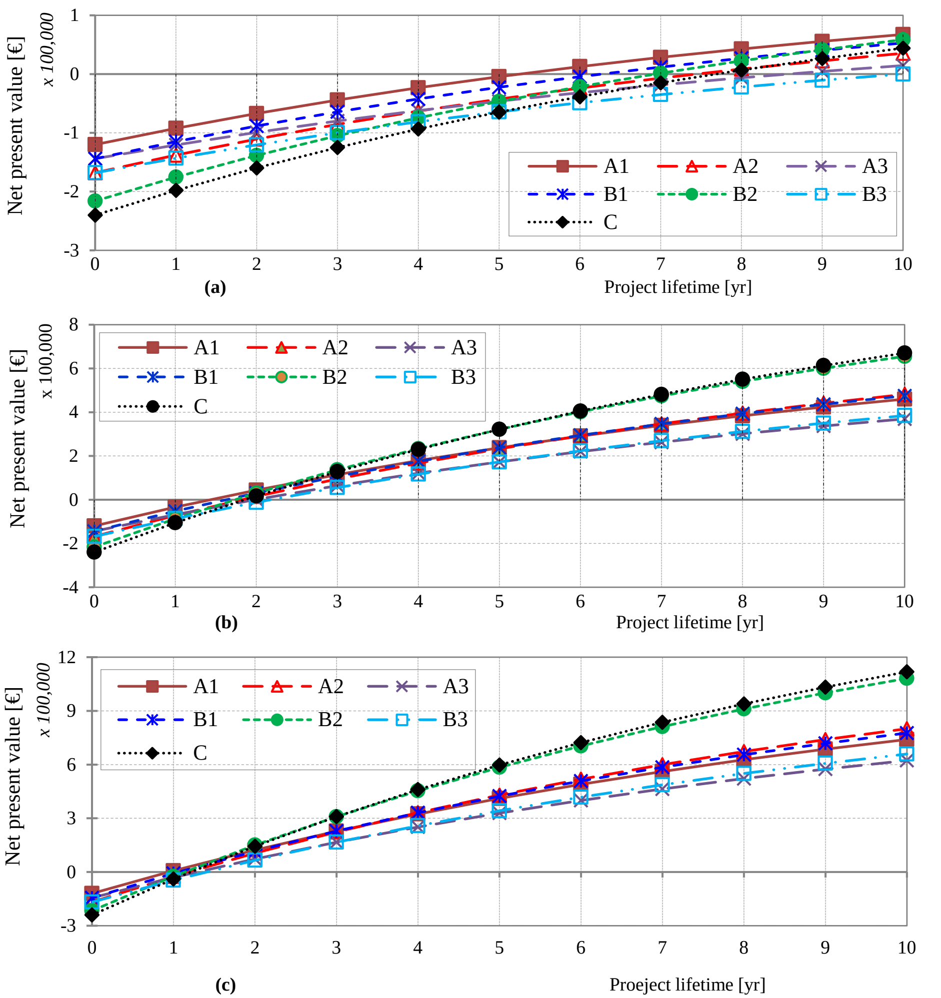


Figure 6.9: Present values of investments on DySC at different positions in the – (a) Electronics industry, (b) Pharmaceutical industry, and (c) Semiconductor manufacturing.

6.3.2 Cost estimation based on weighting factors

6.3.2.1 Estimating methodology

Figure 6.10 shows a general flow diagram for estimating the economic loss of voltage dips based on weighting factors (WFs) method. As described in detail in *Chapter 5*, system average values of weighting factors (WF) are evaluated for the three types of dips based on the weighted average of the relative loss of power for the aggregated customers in the entire MV-networks. The number of equivalent interruptions caused by voltage dips having a certain magnitude of remaining voltage and duration, distributed according to the standard EN 50160 shown in Table 5.2, is obtained by multiplying the frequency of voltage dips with the respective value of WF.

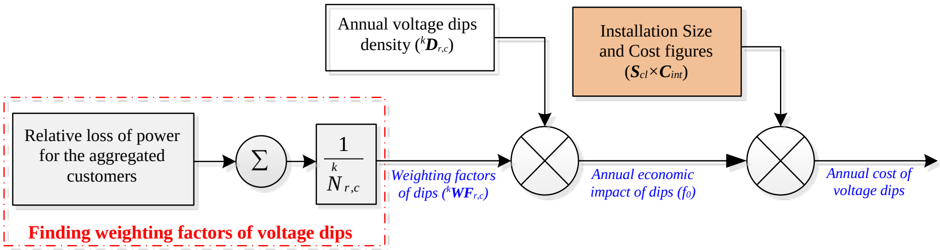


Figure 6.10: Flowchart for estimating the economic cost of voltage dips using weighting factor severity indices.

For each type of dips, the distribution densities for the annual frequency of voltage dips and the weighting factor can be represented by the matrices (6.13) and (6.14),

$$ {}^{k}D_{r,c} = \begin{pmatrix} {}^{k}d_{11} & \dots & {}^{k}d_{1n} \\ \vdots & \ddots & \vdots \\ {}^{k}d_{m1} & \dots & {}^{k}d_{mn} \end{pmatrix} \tag{6.13} $$

$$ {}^{k}WF_{r,c} = \begin{pmatrix} {}^{k}wf_{11} & \dots & {}^{k}wf_{1n} \\ \vdots & \ddots & \vdots \\ {}^{k}wf_{m1} & \dots & {}^{k}wf_{mn} \end{pmatrix} \tag{6.14} $$

where ${}^{k}d$ and ${}^{k}wf$ represent for the annual voltage dips density and the corresponding percentage of weighting factor density with remaining voltage (u) in *r*'s row and duration (Δt) in *c*'s column for each type of dips (*k*). Taking the magnitude, duration and type of dips into consideration, the total equivalent interruptions (f_0) caused by the corresponding voltage dip densities at the PCC of the MV-network can be evaluated using (6.15).

$$ f_0 = \frac{1}{100} \sum_{k} \sum_{r} \sum_{c} \left({}^{k}d\left(u_r, \Delta t_c\right) \right) \left({}^{k}wf\left(u_r, \Delta t_c\right) \right) \tag{6.15} $$

As is in (6.15), the total number of equivalent interruptions due to voltage dips is dependent upon the frequency of voltage dips, which also depend on the location of the process in the system network, and the severity (characterized by magnitude, duration and type) of voltage dips at the customer‘s terminal. Even though a voltage dip with a large drop in magnitude and/or lasting for a considerable period of time can cause wide-ranging disruptions, its overall annual economic impact may still be minimal if it rarely occurs.

Using the WFs represented in Table 5.2, which are obtained based on the average amount of reduction in power for the aggregated customers in the entire MV-networks, the annual equivalent interruptions due to voltage dips can be estimated. However, the values of average WFs can be affected by few dips leading to extremely small or too big losses and this again can influence the application of the WFs for estimating the economic impact of voltage dips on the operation of various types of customer installations. Depending on the type of customer categories and sensitivity of processes, customers may use other values of WFs (like 25, 50, 75, and 95 percentiles) instead of the average WFs. As depicted in Figure 6.10, the annual cost of voltage dips in an industrial plant can be estimated by multiplying the total equivalent interruptions with the cost of process interruption using (6.6).

If all customers in the MV-network that are affected by voltage dips are classified into 'n' categories, the corresponding annual economic impact of voltage dips in the same network ($f_1, f_2, \ldots, f_n$) may be estimated using the WFs that can be derived from the average WFs. Considering the size of load ('S' in kW) and the cost of interruption per unit load ('C_{int}' in €/kW) for each customer category, the total annual economic cost of voltage dips in the entire MV-network can be estimated using (6.16)

$$Total\ \cos t = \sum_{i=1}^{n} f_i \left(S_i \times C_{\text{int,i}} \right) \tag{6.16}$$

6.3.2.2 Illustrative example

The main application of the weighting factors (WFs) method is to estimate the expected cost of voltage dips in the MV distribution network. To illustrate the application of WFs for estimating the cost of voltage dips in the distribution network, an MV-network with a mean power of 60 MW is considered. In this network, the customers are categorized into domestic, agricultural, industrial, commercial and public. Based on a four-year data, the distribution for different type of dips shown in Table 6.6 is considered. It can be recalled that on average 9.25 dips per year are expected in the network under consideration.

The annual cost of voltage dips in the different group of customers is shown in Table 6.14. For each group, the size of customers is estimated based on their share to the final energy consumption (FEC) in the year 2012. Different weighting factors (WFs) ranging from 25-percentile to 95-percentile of the average WFs are considered for estimating the annual equivalent interruptions (IEs) of the various customer categories. Costs of outages for sudden interruption in each customer category are adopted from [129].

Table 6.14: Application of WFs for estimating the cost of voltage dips in various customer categories in the MV-network.

Sector	Share of FEC[7] [%]	Mean power (kW)	WF[8] used per sector	EI/yr [int/yr]	Outage cost [€/kW/int]	Annual cost [€/yr]	Share to annual cost [%]
Industrial	27	16,200	95-percentile	4.16	2.90	195,202	62.6
Commercial	17	10,200	75-percentile	3.25	2.10	69,615	22.3
Transport	29	17,400	50-percentile	2.90	0.73	36,804	11.8
Agricultural	7	4,200	25-percentile	2.58	0.70	7,593	2.4
Domestic	20	12,000	25-percentile	2.58	0.09	2,727	0.9
Total	100	60,000	-	-	-	311,941	100

In this particular example, the customers in each category are assumed to have similar characteristics even though they consist of heterogonous electricity users in practice.

[7] Source: Eurostat
[8] Values of the 95%, 75%, 50% and 25% of average WFs can be referred to Chapter 5

Despite the considerable energy consumption by the agricultural and domestic customers, the economic impact of voltage dips is negligible in these groups. For this particular case, the industrial customers share about 63% the annual cost of voltage dips in the in the entire network.

6.4 Summary

Due to the difficulty with direct assessment of the economic loss of voltage dips, two approaches for evaluating the economic impact of voltage dips relative to that of a momentary interruption are discussed. The first approach deals with finding the plant-specific sensitivity indices based on the composition of process equipment, and their behavior and interaction against different types of voltage dips. This approach can be easily applied in small industries and it is suggested that the effects of voltage dip parameters including magnitude, duration and type are considered when obtaining the process sensitivity indices for the industrial facility.

In the second approach, voltage dips severity weighting factors are obtained to express the economic impact of voltage dips relative to that of a complete interruption. In this case, the system severity weighting factors of voltage dips are evaluated based on the relative loss of power for the aggregated customers connected to the MV-networks. This approach is more applicable for making rough estimations about the economic impact of voltage dips at a network-level and the effects of dip magnitude, duration and type are also considered when obtaining the weighting factors.

7

Regulation of voltage dips in the MV distribution network

7.1 Introduction

Based on measurement results from different countries in the world, examples of statistical indices on voltage dips and short interruptions are reported in the IEC 610002-8 [9]. It is stated in the document that the frequency and probability of the occurrence of voltage dips is highly unpredictable both in time and place as it varies depending on the type of network and the point of observation. The standard EN 50160 [8] provides a voltage dip classification table (Table 3.2) allowing for a more harmonized way of presenting dip data throughout Europe. For a regulatory purpose, the classification is useful in evaluating the frequency of voltage dip occurrences over a certain period of time. It also gives the opportunity to apply the concept of "responsibility-sharing" between customers, equipment manufacturers and network operators. However, the regulation within the EN 5160 is not detailed as the cells within the table are not filled with the expected number of voltage dips; and customers usually face challenges to make the economic analyses on the possible mitigation techniques.

Many countries in the world are currently discussing voltage quality regulation and trying to set up a regulatory framework where also voltage dips are included in the national grid codes [41, 49, 130-134]. The Dutch regulator also wants to include limits regarding voltage dips in the national grid code and network operators have been requested to prepare a proposal for a regulatory framework. In this chapter, an approach based on severity weighting factors (WFs) is presented for classifying voltage dips into different clusters and setting limits on the number of dips for the regulatory purpose. A second method, based on equipment dip immunity curves, is discussed to compare the feasibility of the proposed method for developing the regulatory framework. Datasets of voltage dips monitored from several MV-networks over long period are used for setting the limits on the number of dips with both clustering approaches. The voltage dip regulation proposal can help both the network operators and the customers in evaluating the quality of supply voltage and estimating the related costs.

7.2 Voltage dip responsibility-sharing practices

An integral part of voltage quality regulation is defining the responsibilities to be shared among different parties involving in the delivery and usage of power. Voltage dip responsibility-sharing curves define the voltage quality requirements of the network in coordination with the performance of equipment or installations. These curves set up a boundary between the voltage dips for which customer equipment or installation should be immune and the number of events that should be limited by the network operators for the regulatory purpose. The responsibility-sharing curves could be defined based on:

- Test levels recommended by some standards (e.g. IEC 61000-4-11/34), or
- Immunity requirements for industrial equipment (such as SEMI F47, ITIC).

When responsibility-sharing curves exist as national standards, customers may make a contractual agreement with the network operators to deal with voltage dip-related inconveniences. In France, voltage dip duration of 600 ms and remaining voltage of 70% of the nominal voltage are adopted in the Emerald Contract (EdF) [133, 134] as threshold values that are applicable to medium- and high-voltage customers under contract. According to the contract, customers are responsible for dealing with voltage dips shorter than 600 ms and for dips with magnitude of remaining voltage above 70% of the nominal voltage (see Figure 7.1). The network operators are responsible for limiting the number of voltage dips longer than 600 ms and deeper than 70% of the nominal voltage. As in [132, 135], the limit on the number of voltage dips per year for MV customers is set based on the local circumstances; whereas for HV customers the objective is set based on historical performance of the networks.

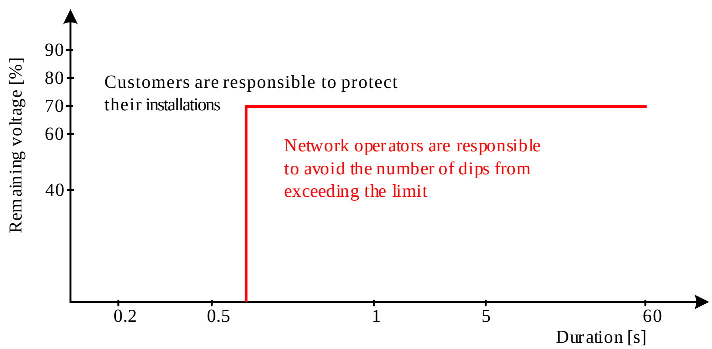


Figure 7.1: Voltage dip responsibility-sharing curve according to the contract with MV customers in France [134].

To apply the concept of sharing the responsibilities between different parties, the Swedish national regulatory authority[9] has also introduced voltage-quality regulation [130]. Regarding voltage dips, the responsibility-sharing curves[10] (Figure 7.2) divide the dip table into three areas based on remaining voltage and duration. As discussed in several reports [130, 136-138], voltage dips in Area A are expected to have little impact on end-

[9] *Energy Markets Inspectorate*

[10] *Different curves are provided for networks above 45 kV, and networks with 45 kV or less.*

user installations and it is the responsibility of the customers to make their equipment or installations immune against these dips; and no limit is set on the number of voltage dips in this area. In Area B, the impact of voltage dips is limited and the network operator has the responsibility to mitigate the voltage dips to the extent that the mitigation measures are reasonable. With regard to Area C, the quality of supply voltage is considered to be insufficient and voltage dips in this area are unacceptable. With this approach, equipment manufacturers must assure that their equipment is immune to voltage dips in Area A and must assure that different classes of equipment immunity are able to cover Area B.

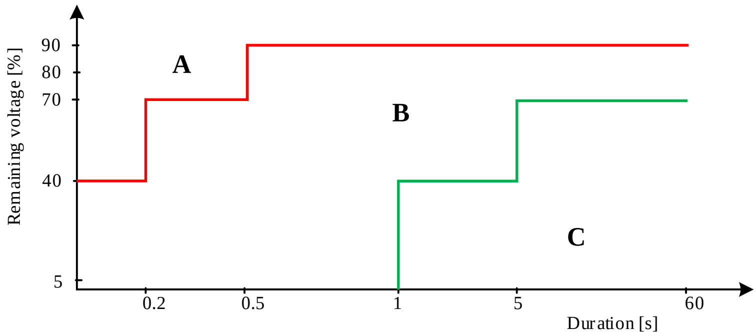


Figure 7.2: Voltage dip regulation in Sweden for networks up to and including 45 kV [130].

For the distribution networks in Italy [49, 131], immunity curves defined by Class 2 and Class 3 testing levels in IEC 61000-4-11/34 [37, 38] shown in Figure 7.3 are used as reference curves by the Italian regulator to distinguish between “minor dips” and “major dips” where the latter are often the most problematic for the customers. From measurement campaigns, the EN50160 standard table is used to classify dips when estimating the numbers of voltage dips, process immunity and related costs for customers. The “regulated dip-frequency index” is the average of voltage dips below the two curves (for Class 2 and Class 3).

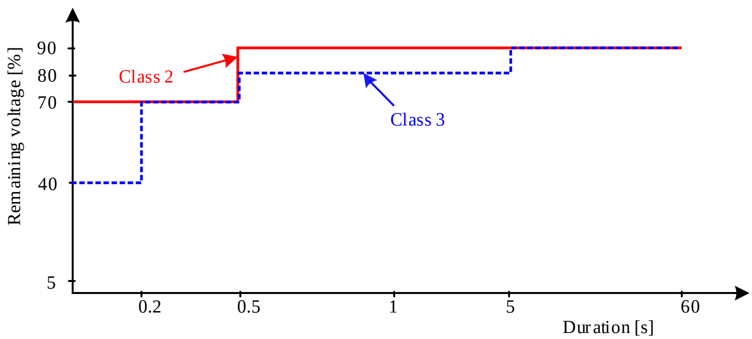


Figure 7.3: Voltage dip classification and responsibility-sharing proposed by the Italian regulator [49, 131].

Responsibility-sharing curves for undervoltages also exist outside of Europe (e.g. South Africa). A South African user specification standard [41] classifies voltage dips into Y, X, S, T and Z categories, shown in Table 7.1, based on a combination of network protection characteristics and customer load compatibility. This PQ standard places the responsibility with the customer for voltage dips in area Y that are expected to occur frequently in typical HV and MV systems. The number of dips is limited for all other dips. The X-areas (X1 and X2) reflect voltage dips with normal clearance times and hence a significant number of events in this area. Customers should attempt to protect their plant against at least X1-type dips. The T-type area reflects voltage dips due to close-up faults, which are not expected to happen too regularly and which the network operator should specifically address if excessive. S-type dips, which may occur with impedance protection schemes or with delayed voltage recovery, are not as common as X- and Y-type. Z-type dips are very uncommon in HV systems as this generally reflects problematic protection operation [139]. The allowed number of X-type dips is more than S-type dips, and the sum of X-and S-type dips is more than T-type dips.

Table 7.1: Voltage dip classification and responsibility-sharing according to the South African standard [41]

<table>
<tr><th rowspan="2">Remaining voltage [%]</th><th colspan="3">Duration [ms]</th></tr>
<tr><th>$20 < \Delta t \leq 150$</th><th>$150 < \Delta t \leq 600$</th><th>$600 < \Delta t \leq 3000$</th></tr>
<tr><td>$90 > u \geq 85$</td><td rowspan="3">Y</td><td rowspan="2"></td><td></td></tr>
<tr><td>$85 > u \geq 80$</td><td rowspan="2">Z1</td></tr>
<tr><td>$80 > u \geq 70$</td><td rowspan="3">S</td></tr>
<tr><td>$70 > u \geq 60$</td><td>X1</td><td rowspan="3">Z2</td></tr>
<tr><td>$60 > u \geq 40$</td><td>X2</td></tr>
<tr><td>$40 > u \geq 0$</td><td colspan="2">T</td></tr>
</table>

At present, most of the proposals are based on immunity curves of certain equipment only specified for test levels against Type I and Type II voltage dips. Although the same test levels and immunity curves are considered for equipment against one-phase and two-phase dips, the performances of equipment are different in practice. Moreover, the dip immunity test levels and voltage-tolerance curves in the existing standards are not applicable for three-phase equipment or installations.

7.3 Voltage dip regulation in the Netherlands

Voltage dips are monitored in the Dutch HV- and MV-networks and there has been a growing interest from the regulatory body to set up a regulatory framework regarding voltage dips to be included in the national grid code. This chapter discusses a proposal on voltage dip regulation for the Dutch MV distribution networks.

7.3.1 Building the dip regulation proposal

When building the proposal regarding voltage dips for the regulatory framework, different aspects are considered including:

- Monitoring voltage events,
- Assessing the monitored data,
- Presenting voltage dips, and
- Impact of voltage dips on customers connected to the MV-networks.

7.3.1.1 Monitoring data

As described in *Chapter 3*, voltage events monitored from 6 substations during 4 years and from 47 substations during one year are used.

7.3.1.2 Assessing monitored data

Regarding the data used, phase-to-ground voltages are monitored in the MV-networks while the end-users are essentially influenced by voltage dips associated to the phase-phase voltages [140, 141]. In this proposal, the following considerations are made:

- The characteristics of phase-phase voltages as a function of time are obtained for each event from the waveforms of phase-to-ground voltages. In this way, the effect of propagation on the number and severity of voltage dips at the customer terminals will be taken into account.
- An event, in a polyphase system, is considered as a voltage dip when the remaining voltage at least in one of the phase-phase voltages is below 90% of the nominal and at least in one of the phase-phase voltages is above 5% of the nominal voltage for a duration ranging between ½ cycle to 1 minute.
- When an event consists of multiple-dips occurring within a short interval, the principle of aggregation is applied. In this case, the aggregation interval is chosen based on the definition of a voltage dip as having the maximum duration. All dips occurring within 1-minute are, therefore, aggregated and counted as a single dip which is represented by the parameters of the most severe dip. To determine the most severe dip, the method of voltage sag energy index [39] is applied.
- Depending on the number of (one, two, or three) affected phase-phase voltages, voltage dips are classified as L_{001}, L_{011} and L_{111} dips. In this way, the effect of different types of disturbances can be related to their impact on single-phase and three-phase equipment or installations.

7.3.1.3 Presenting voltage dips

Taking into account the propagation of voltage dips and aggregating multiple-dips into a single event, single-event indices of each substation are combined into annual site indices. The general voltage dip table of the EN 50160 standard (Table 3.2) is used for presenting the annual frequency of voltage dips. For this proposal, the following points are considered:

- For each monitoring location, classification of voltage dips is considered and annual voltage dip profile for each type of dips is treated separately.
- For each dip type, a voltage dip profile representing system indices is obtained based on the average number of dips per year over all monitoring locations.

7.3.1.4 Impact of voltage dips on customers

As discussed in *Chapter 5*, industrial processes are usually composed of several equipment and many customers of different category are connected to the MV distribution networks. The effect of voltage dips on the combined customers is, therefore, more complicated in practice than the equipment dip immunity requirements specified by some industrial and national/ international standards. Besides, the effect of different types of (balanced and unbalanced) voltage dips is not well considered in the standards. With this proposal, the effect of voltage dips on the aggregated customers connected to the MV-distribution networks is considered to determine voltage dips severity weighting factors (WFs) and the obtained severity WFs are used for building the framework on voltage dip regulation for the Dutch MV-networks. With regard to the WFs, the following points are considered in this proposal (more detail can be found in *Chapter 5* and [142]):

- For each phase-phase dip at the MV side of the HV/MV substations, the absolute loss of power for the aggregated customers in each feeder is estimated based on the change of power before and after the dip event. The losses of power in all feeders are combined to evaluate the impact of the dip on the aggregated customers in the entire network.
- The size and type of customers as well as the occurrence time of disturbances can vary from location to location, and this may significantly affect the amount of absolute loss of power due to voltage dips that even have similar characteristics. To obtain a strong correlation between the severity of voltage dips (characterized by magnitude, duration and type) and their impact on the aggregated customers, the relative loss of power is considered for all phase-phase dips.
- WFs representing the severity for various types of voltage dips are obtained from the weighted average of the relative loss of power for the aggregated customers due to voltage dips (in the same cell) over all monitoring locations. When completing values of WFs that correspond to voltage dips in each cell of the EN 50160 dip table, missing values are interpolated and the 95-percentile values of the average WFs is proposed as voltage dips severity indices for industrial customers.

7.3.2 Clustering and defining limit based on WFs: method-1

Based on the system severity indices obtained from the relative impact of voltage dips on the aggregated customers connected to the MV-networks, the method of weighting factors is applied here for building a voltage dip regulation proposal. Using the severity WFs shown in Table 5.7, the effect of different types of voltage dips are classified as BIG, MEDIUM or SMALL. This divides the voltage dip table into three clusters described as follows:

- Voltage dips with WFs above 50% (i.e. leading to the loss of more than 50% of the pre-dip power of customers) are considered as BIG effect and they are clustered as C;
- Voltage dips with WFs in the range of 30%–50% are regarded as MEDIUM effect and they are clustered as B; and
- Voltage dips with WFs below 30% are considered as SMALL effect and they are clustered as A.

Based on these criteria, three clusters (A_p, B_p, C_p), which also define the responsibility-sharing areas of different parties involved in the delivery and usage of power, are made for each type of dip '*p*' as shown in Table 7.2. According to this approach, a total of 8 clusters are made out of the three types of voltage dips. Because of the small effect they have on end-users, L_{001} dips are not included in cluster C. On the other hand, cluster A covers very small area for L_{111} dips due to the fact that these dips have very significant effect on the aggregated customers. It can also be seen from Table 7.2 that areas of similar clusters considerably vary from one dip type to another and this indicates the variation in the severity of various types of voltage dips which are even characterized by the same magnitude and duration.

Table 7.2: Clusters for various types of voltage dips based on weighting factors (WFs)

Remaining voltage [%]	**(a) Clusters for L_{001} dips** Duration [s]					**(b) Clusters for L_{011} dips** Duration [s]					**(c) Clusters for L_{111} dips** Duration [s]				
	$\Delta t \leq 0.2$	$\Delta t \leq 0.5$	$\Delta t \leq 1$	$\Delta t \leq 5$	$\Delta t > 5$	$\Delta t \leq 0.2$	$\Delta t \leq 0.5$	$\Delta t \leq 1$	$\Delta t \leq 5$	$\Delta t > 5$	$\Delta t \leq 0.2$	$\Delta t \leq 0.5$	$\Delta t \leq 1$	$\Delta t \leq 5$	$\Delta t > 5$
$90 > u \geq 80$	A_1	A_1	A_1	A_1	A_1	A_2	A_2	A_2	A_2	A_2	A_3	B_3	B_3	B_3	B_3
$80 > u \geq 70$	A_1	A_1	A_1	A_1	A_1	A_2	A_2	A_2	B_2	B_2	A_3	B_3	B_3	B_3	B_3
$70 > u \geq 40$	A_1	A_1	A_1	A_1	A_1	A_2	B_2	B_2	B_2	B_2	B_3	B_3	B_3	C_3	C_3
$40 > u \geq 5$	A_1	B_1	B_1	B_1	B_1	B_2	B_2	C_2	C_2	C_2	B_3	C_3	C_3	C_3	C_3
$5 > u$	A_1	B_1	B_1	B_1	B_1	B_2	C_2	C_2	C_2	C_2	C_3	C_3	C_3	C_3	C_3

With this clustering approach, the number of voltage dips in each cluster of the L_{001}, L_{011}, and L_{111} dips can be calculated from the respective dip profiles shown in Table 3.8. The different types of voltage dips belonging to similar clusters (e.g. A_1, A_2, and A_3) have similar effect on end-user installations. Due to this, such clusters can be combined to reduce the number of clusters into three general categories (A, B and C) for setting limits on the amount of voltage dips for the regulatory purpose. The number of voltage dips from all type of voltage dips belonging to similar cluster can be added together using (7.1),

$$\begin{aligned} A &= A_1 + A_2 + A_3 \\ B &= B_1 + B_2 + B_3 \\ C &= C_1 + C_2 + C_3 \end{aligned} \tag{7.1}$$

where the subscripts 1, 2 and 3 represent for the dip types L_{001}, L_{011} and L_{111} respectively. For the various types of dips, the average occurrence of voltage dips within the different clusters over all monitoring locations is summarized in Table 7.3. Considering the data from all monitoring locations, clusters A, B and C contribute about 52%, 43% and 5% to the average occurrence of 8.48 dips per year. It can also be seen from Table 7.3 that the majority of the L_{001} (~98%) and L_{011} (~67%) dips have small impact on the customers while more than 80% of the L_{111} dips have medium to big impacts on end-user installations.

Table 7.3: Average yearly occurrence of voltage dips within different clusters defined based on weighting factors

Dip type	**Culster per dip type**			Total	Share
	A	**B**	**C**		
L_{001}	2.61	0.06	0.00	2.67	31%
L_{011}	1.27	0.44	0.19	1.91	22%
L_{111}	0.56	3.13	0.22	3.90	46%
Total	**4.44**	**3.63**	**0.41**	**8.48**	**100%**

For both network operators and customers, the frequency and probability of voltage dips occurring every year is useful for estimating the quality of supply voltage and costs incurred due to this level of voltage quality. As it is noticed in *Chapter 3*, the frequency and severity of voltage dips vary from location to location and time to time. Using the average number of dips for regulatory purposes may underestimate the expected occurrence of voltage dips to some locations and it can also overestimate the expected occurrence of dips in other locations. Assuming the occurrence of voltage dip events is random and consecutive events are independent of each other, the probability of the occurrence of events occurring in a fixed period of time, with a known average rate, can be predicted using the Poisson's distribution function [4]. The probability mass function in the Poisson's distribution is given by (7.2),

$$P(X = k) = \frac{\lambda^k}{k!} e^{-\lambda} \tag{7.2}$$

where *P(X=k)* is the probability that exactly *k* dips occur in a fixed period of time,
k is the amount of voltage dips occurring in that particular period of time,
λ refers to the average voltage dips per the specified period, and
e is base of natural logarithm.

The number of dips within a particular cluster can be all from any of the dip types or they can be shared among all types. However, the total occurrence of events per cluster is important when setting limits on the number of voltage dips for the regulatory purpose. Because of the limited amount of voltage dips in cluster C (i.e. 0.41 dips/year), direct application of the Poisson's distribution function can lead to unrealistic values when setting the limits. To improve the practical application of the Poisson's distribution function, two possible options can be considered:

- Setting limits based on historical data;
- Setting limits by combining clusters B and C in one cluster (BC).

7.3.2.1 Setting limits based on historical data

It is possible that a high number of dips can occur in one year and few (or no) dips occur in the next year. Because of changes in the network, the regulator may consider to update the limits based on the number of voltage dip occurrences in the previous years (e.g. during the last 4-years). Using the prescribed clustering approach and considering the occurrence of voltage dips in the last four-years, the number of dips within the clusters A, B and C are about 18, 15 and 2 respectively. Using the Poisson's distribution function, it can be seen from Figure 7.4 that the number of dips in each cluster for the 95% time of the last four-years can be limited to 25, 21 and 4 dips respectively. From this point of view, a maximum of 21 and 4 dips for cluster B and C in the previous four-years can be considered as indicative limits for the network operator beyond which the quality of supply voltage at present is insufficient. From this, it can be said:

- voltage dips in cluster A have very little impact on customers' equipment or installations, and end-users are expected to choose equipment that ride-through these dips. Therefore, there is no need for setting a limit on the number of dips in this group.
- voltage dips in cluster B and C can affect customer installations significantly. The network operators should take measures to reduce these dips where possible, and they should take responsibility to avoid the dips from exceeding the

maximum limits. During periods when the numbers of voltage dips exceed the objective reference values, there is an indication of alarming power quality problems and the network operators should investigate the problem.

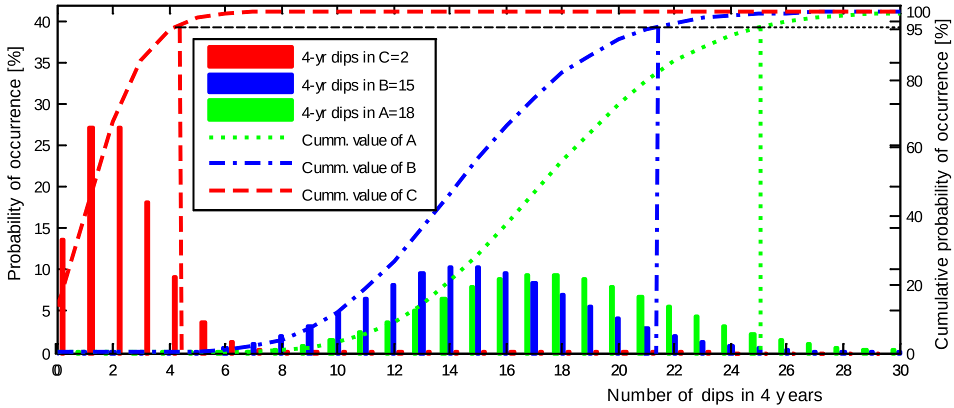


Figure 7.4: Probability distribution and cumulative function for the three clusters of voltage dips based on severity weighting factors and considering a four-year occurrence of dips.

7.3.2.2 Setting limits by combining B and C in one cluster

As described earlier, voltage dips within cluster B and C have significant effect on end-users and they should be regulated. By combining clusters B and C in one cluster, the number of clusters for each type of dips can be reduced to two (A and BC) as shown in Table 7.4. Similar to the previous case, the number of dips from the three types of voltage dips having similar effect can be aggregated. In this case, the average number of dips in clusters A and BC become 4.44 and 4.04 dips per year.

Table 7.4: Grouping for reduced clsuters with various types of voltage dips

Remaining voltage [%]	**(a) Clusters for L_{001} dips**					**(b) Clusters for L_{011} dips**					**(c) Clusters for L_{111} dips**				
	Duration [s]					Duration [s]					Duration [s]				
	$\Delta t \leq 0.2$	$\Delta t \leq 0.5$	$\Delta t \leq 1$	$\Delta t \leq 5$	$\Delta t > 5$	$\Delta t \leq 0.2$	$\Delta t \leq 0.5$	$\Delta t \leq 1$	$\Delta t \leq 5$	$\Delta t > 5$	$\Delta t \leq 0.2$	$\Delta t \leq 0.5$	$\Delta t \leq 1$	$\Delta t \leq 5$	$\Delta t > 5$
$90>u\geq80$															
$80>u\geq70$			**A_1**			**A_2**					**A_3**				
$70>u\geq40$													**BC_3**		
$40>u\geq5$			**BC_1**					**BC_2**							
$5>u$															

Applying the Poisson's distribution function, it can be seen from Figure 7.5 that the average number of dips in cluster A (~5 dip/year) and BC (~4 dips/year) have occurrence probabilities of 18% and 19% respectively. For the 95% of the time in a year, the number of dips can be restricted to 8 and 7 dips respectively; and a maximum of 7 dips per year in cluster BC can be considered as a limit beyond which the quality of the supply is unacceptable.

Comparing the two options to improve the application of the Poisson's distribution function for setting limits on the number of voltage dips, it can be deduced that:

- The number of clusters per each type of dip is reduced in the second case with the number of dips per year set for the combined cluster CB being close to the number of dip in the clusters $(B+C)/4$ in the first case.
- Voltage dips with BIG impact are treated together with dips having an average (MEDIUM) impact in the second case option while these are treated separately in the first option.

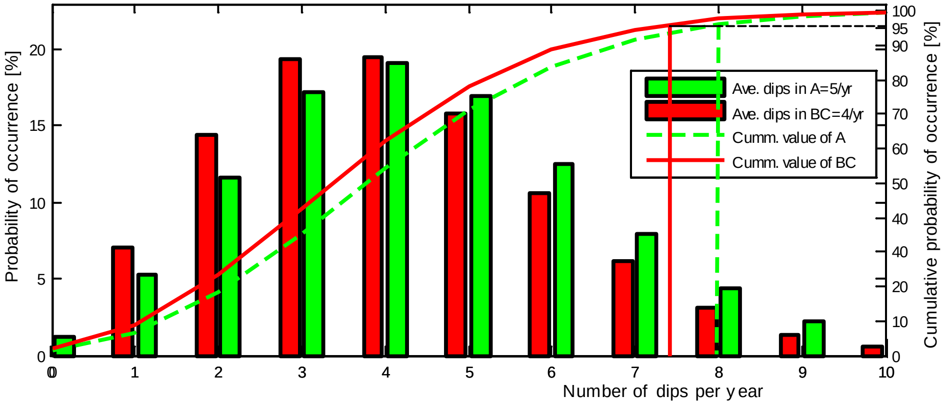


Figure 7.5: Probability distribution and cumulative function of the average dip occurrences for the reduced (two) clusters of voltage dips.

7.3.3 Clustering and defining limit based on immunity: method-2

Based on the equipment immunity specifications against unbalanced and balanced dips, five equipment immunity classes are proposed by the CIGRE/CIRED/UIE JWG C4.110 [2]. According to this document, voltage dip immunity Class A provides the highest level of equipment immunity to voltage dips and Class D specifies a basic level of equipment dip immunity. Voltage dip immunity Class B and Class C are in between the two while Class E is for equipment falling into none of the other classes.

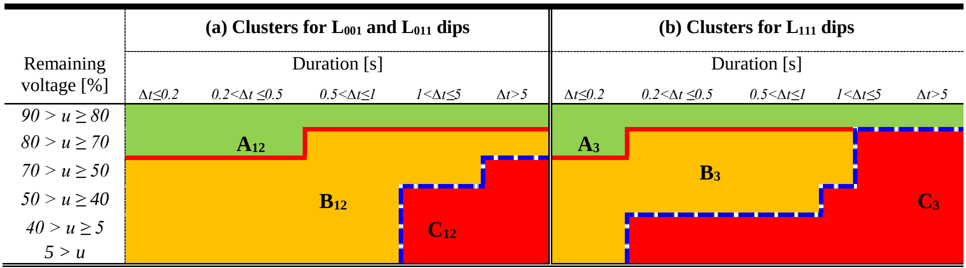
Considering the voltage-tolerance curves for equipment with the highest (Class A) and basic (Class D) dip immunity levels, three clusters can be made for balanced and unbalanced voltage dips as shown in Table 7.5. The three clusters and the responsibilities of different parties to voltage dips in the different clusters can be briefly described as follows:

- Cluster A (A_{12} for unbalanced and A_3 for balanced dips) covers areas above the curves for the basic level of dip immunity (Class D). Voltage dips in in this cluster (A_{12}=A_1+A_2, and A_3) have little impact on end-users and the customers should make their equipment or installations tolerate the dips in this area. Equipment manufacturers should also ensure that their equipment are immune to these dips.
- Cluster C (C_{12} for unbalanced and C_3 for balanced dips) covers areas below the curve for the highest level of dip immunity (Class A). Voltage dips in this cluster (C_{12}=C_1+C_2, and C_3) are the most severe dips indicating the supply voltage is inadequate. Voltage dips in this area may not be acceptable and the network

operators should work to prevent the number of dips from exceeding the limit set based on previous years.

- Cluster B (B_{12} for unbalanced and B_3 for balanced dips) covers areas between the curves for the basic and highest level of dip immunity. Due to the various level of immunity classes covered within this cluster, a certain number of dips in this area (B_{12}=B_1+B_2, and B_3) may be accepted and voltage dips in this area can be limited. The network operators have the responsibility to reduce dips in this area to the extent that the mitigation options are feasible. Equipment manufacturers should also make sure that different classes of products are available to cover this area.

Table 7.5: Responsibility-sharing curves based on dip immunity levels for Class A and Class D equipment against unbalanced and balanced dips.



For setting the limits on the number of voltage dips in the clusters B and C, the same procedure as for the previous method can be followed. The number of voltage dips in each cluster of the L_{001}, L_{011}, and L_{111} dips can be calculated from the respective dip profiles shown in Table 3.8. Due to the similar effect presumed to have on end-user installations, the different types of voltage dips belonging to similar clusters (e.g. A_1, A_2, and A_3) can be combined and this reduces the number of clusters into general A, B and C groups. Adding up all dips belonging to similar cluster using (7.1), the average occurrence of voltage dips within the different clusters over all monitoring locations is summarized in Table 7.6. On average, the number of measured voltage dips in cluster A, B and C is 3.98, 4.25 and 0.25 dips per year respectively. It can also be seen from Table 7.6 that equipment with minimum immunity level of Class D would negligibly be affected by the majority (~84%) of the L_{001} dips while the same equipment would trip to more than 58% and 76% of the monitored L_{011} and L_{111} dips respectively.

Table 7.6: Average yearly occurrence of voltage dips within clusters defined based equipment dip immunity

Dip type	Culster per dip type			Total	Share
	A	**B**	**C**		
L_{001}	2.24	0.43	0.00	2.67	31%
L_{011}	0.79	1.08	0.03	1.91	22%
L_{111}	0.95	2.73	0.22	3.90	46%
Total	**3.98**	**4.25**	**0.25**	**8.48**	**100%**

Due to the limited amount of voltage dips especially in cluster C (i.e., 0.25 dips/year), the historic performance of the networks is again considered with this approach to apply the Poisson's distribution function for setting the limits. Considering the occurrence of events in the previous four years, the numbers of dips in cluster A, B and C are about 16, 17 and 1 respectively. Using the Poisson's distribution function, it is shown in Figure 7.6 that the number of dips in cluster A, B and C for the 95% of the time in the last four years can be limited to 23, 24 and 3 dips respectively. According to this approach, 24 and 3 dips in the previous four years can be considered as the maximum limits beyond which the quality of supply voltage is insufficient.

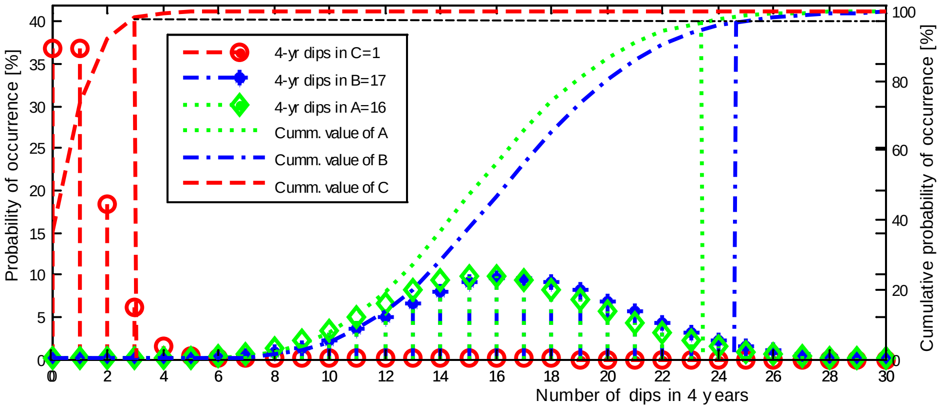


Figure 7.6: Probability distribution and cumulative function for the three clusters of voltage dips based on equipment dip immunity levels and considering a four-year occurrence of dips.

Comparing the two methods described in this chapter for setting limits on voltage dips for the regulatory purpose, the following points can be noted:

- In this thesis, the limits on the number of voltage dips is proposed to be set and updated over a four-year historical performance of the networks. According to this, the number of voltage dips set as a maximum limit for the combined clusters B and C using method-1 (system dip severity weighting factors) is close to the value obtained using method-2 (equipment dip immunity level). Method-2 led to one dip lower in cluster C and three dips higher in cluster B over four-years than the corresponding values in method-1. This is because the equipment with the basic and highest dip immunity levels, which are considered to define the responsibility-sharing curves in method-2, have the effect of increasing the area for cluster B and reducing the area for cluster C.
- Even though the same voltage-tolerance curves are considered in method-2 for equipment against unbalanced (Type I (L_{001}) and Type II (L_{011})) dips, the equipment sensitivities can vary in practice [143]. Besides, the sensitivity of processes and installations against voltage dips can be different from the equipment dip immunity requirements. Method-1, on the other hand, considers the effect of L_{001} and L_{011} dips on the customers separately, and this approach is more realistic for making different voltage dip clusters in developing the regulation proposal than method-2.

7.4 Summary

For building a proposal to set up a regulatory framework regarding voltage dips in the MV-networks, two approaches are described in this chapter. Different aspects including the frequency and severity of voltage dips occurring in the networks, the propagation of voltage dips, the classification of voltage dips, the aggregation of multiple-dips, and the effect of voltage dips are considered with each approach. Because of the limited number of voltage dips occurring yearly, the limits on the number of voltage dips are proposed to be set and updated based on historical performance of the networks over several years. With this, the variation of voltage dips due to the possible network modifications can also be considered in regulation.

In the first approach, three clusters are defined for each type of dips based on the severity weighting factors which are obtained from the relative loss of power for the aggregated customers connected to the Dutch MV-networks. The second approach considers the highest level and the basic level of equipment dip immunity classes for defining three clusters for the balanced and unbalanced voltage dips.

Considering the variation of voltage dips over four years, the results obtained from the two methods are close to each other. However, the first approach (based on WFs) considers the sensitivity of several equipment and installations connected to the MV-distribution networks and takes the impact of three types of dips separately. This approach is, therefore, chosen over the second method (based on equipment dip immunity) for building the proposal on voltage dip regulation for the Dutch MV-networks. For the network operators, this proposal can be important for evaluating the quality of the supply voltage in the grid, and for investigating the source of the disturbance and improving the supply voltage when the value is below the indicative minimum requirement. For the customers, this is useful to make economic analysis on the required mitigation measures for reducing the expected economic damages due to voltage dips.

8

Conclusions, contributions and recommendations

8.1 Conclusions

This chapter describes an overview of conclusions and main contributions which are covered in detail in the previous chapters.

8.1.1 Voltage dips monitoring and assessment

Even though monitors at the customer connection points in the MV-networks can give better information about the quality of supply, installing PQ-meters at all points is financially too expensive. It is beneficial that PQ-meters are installed at the optimal locations. Using a stochastic voltage dip estimation approach, comparative studies are performed on a generic MV-network. Simulation results showed that a meter at the main busbar (MV side of the HV/MV substation) can see relatively a higher number of voltage dips (in this case, up to 8% and 6% more phase-dips and phase-phase dips) than if it is installed at another POC downstream a feeder. The main busbar can, therefore, be considered as the most optimal monitoring location for the grid operator to get better insight into voltage dips at all customers POCs connected to the same main busbar.

There is considerable knowledge about the detection and characterization of voltage dips from the measured voltage waveforms. In most literatures and standards, the severity of voltage dips is commonly represented by the remaining voltage magnitude and duration. This can lead to the loss of information as dips having different impact may be represented in the same way. In addition to the two dimensions, the severity can be significantly affected by the type of voltage dips. Counting multiple-dips occurring within short-time intervals separately can have a significant effect on regulation while the impact is very similar to a single event. The counting of the number and characteristics of voltage dips which can affect the end-users, therefore, depends on the type and location of monitor connection and type of aggregation technique with multiple-dip events. Throughout the thesis, the remaining voltage magnitude, duration and type of dips are considered to characterize the severity of voltage dips.

8.1.2 Voltage dips impact

Present standards consider the remaining voltage magnitude and duration for the equipment dip immunity tests. However, the behavior of devices can also be influenced by other parameters in addition to the magnitude and duration of voltage dips. For instance, it is observed from the experimental tests that the sensitivity of AC contactors can also be affected by the point-on-wave dip initiation while the behavior of the adjustable speed drive is highly influenced by the type of dip and the loading condition. The sensitivity of processes and installations against voltage dips can also be different from the specified requirements of the equipment dip immunity limits.

Based on experimental tests on a simple process, the equipment with the shortest process immunity time (PIT) is in most cases found the weakest link component within the (tested) process. The obtained results demonstrate that the PIT and voltage dip immunity of the process can significantly be affected by the type of dip and loading condition. Besides, the PIT and voltage dip immunity of the process can actually be different from the PIT and voltage dip immunity of the weakest link component within the process.

Even though many efforts have been made on characterization and classification of voltage dips, and recommendations for testing and classifying the equipment dip immunity, there is no standard or guideline regarding the impact of voltage dips on the total customers connected to the MV distribution networks. An approach for estimating the impact of voltage dips on the aggregated customers is proposed in this thesis. The estimation approach is based on the loss of power for the aggregated customers connected to the MV-networks. The results indicate that the impact of various types of voltage dips on the combined customers are different. The approach shows a strong correlation between the severity of voltage dips (characterized by magnitude, duration and type) and their impact on the aggregated customers. From the measured data, voltage dips in one, two and three phase-phase voltages resulted in the average relative loss of power for aggregated customers connected to the MV-networks ranging between 0–21%, 2–36% and 12–78% respectively.

Despite the huge economic impact they have on (industrial) customers, the direct assessment of the economic loss of voltage dips is difficult. In this thesis, plant-specific and general system based approaches for estimating the economic impact of voltage dips relative to that of an interruption are proposed. The overall accuracy of the analysis depends on the accurate information about the appropriate number and severity of voltage dips, the performance of customers' installations against the dips, and the unit cost of disturbance and mitigation technique.

8.1.3 Voltage dips regulation

Two approaches introduced for building a proposal on voltage dip regulation are described in this thesis. The first approach uses the weighting factor (WF) method for classifying voltage dips into three clusters based on the relative loss of power for the aggregated customers connected to the Dutch MV-networks. In the second approach, the highest level and the basic level of equipment dip immunity classes are considered to define three clusters for balanced and unbalanced dips. Due to the limited amount of events occurring yearly, the limits on the number of voltage dips in the clusters are set and updated based on the historical performance of the MV-networks.

Considering the variation of voltage dips over four years, the indicative values set as the maximum acceptable limit in cluster B and C using the two methods are 21//24 and 4//3 dips in the last four years respectively. The first approach (based on WFs) considers the sensitivity of several equipment and installations connected to the MV-distribution networks and takes the impact of three types of dips separately. This approach is, therefore, chosen over the second method (based on equipment dip immunity) for building the proposal on voltage dip regulation for the Dutch MV-networks. For the network operators, this proposal can be important for evaluating the voltage quality in the grid, and for investigating the source of the disturbance and improving the supply voltage, where possible, if the value is below the indicative minimum requirement. For the customers, this is useful to make economic analysis on the required mitigation measures for reducing the expected economic damages due to voltage dips.

8.2 Thesis contributions

The main contributions of the thesis research can be summarized as follows:

Optimal monitor placement in the MV-networks: It is showed in this thesis that a PQ-meter at the main busbar of radial MV-network gives the best representation of dips at all POCs than any other POC downstream the feeder. From this point of view, the main busbar can be considered as the most optimal PQ-meter placement for monitoring voltage dips in the MV-networks with radial operation. Depending on the length of cables and the use of secondary protections, this monitor can miss recording some events occurring at locations farther away from the critical distances. Results show that the choice of optimal PQ-meter placement is not affected by the possible network modifications– such as change of protection schemes, and applications of coils and distributed generators.

Factors to be considered when assessing monitored voltage dip data: Because of the different impacts they have on end-users, various types of voltage dips are counted and treated separately throughout this thesis. Besides to this, various aggregation techniques are described to prevent multiple-dip events and short-time repetitive dip-events from being counted several times. The method of voltage sag energy index is applied for aggregating multiple-dips when building the proposal on voltage dip regulation for the regulatory purpose.

Impact of voltage dips on customers: An approach for estimating the impact of voltage dips on all customers connected to the MV distribution networks is proposed in this thesis. The proposed method considers the loss of power for the aggregated customers evaluated from the change between the pre-dip and post-dip powers during the events. The approach is applied to obtain system severity weighting factors for various types of voltage dips.

Economic impact estimation of voltage dips: Approaches of process sensitivity indices and system severity weighting factors are described in this thesis for estimating the equivalent number of interruptions caused by voltage dips. In the first approach, the source of coefficients for the indices are plant-specific which can be obtained based on the composition of process equipment, and their behavior and interaction against various types of voltage dips. In the second approach, general values of indices for the MV system are obtained based on the weighted average of the relative loss of power for the aggregated customers due to voltage dips monitored in several MV-networks. In both cases, the effects of voltage dip magnitudes, durations and types are considered. Using these approaches, the economic loss of voltage dips can be expressed relative to the economic impact of interruptions.

Voltage dip regulation for MV-networks: Based on voltage dip severity weighting factors and equipment dip immunity levels with various types of voltage dips, clustering approaches are proposed in this thesis for building a voltage dip regulation proposal and for setting the limits on the number of voltage dips in the Dutch MV-networks for the regulatory purpose.

8.3 Recommendations for future work

Severity of voltage dips: For customer reports or regulatory purpose, the use of aggregation techniques with multiple-dips can reduce the number of events into a reasonable amount. The actual effect of multiple-dips on process equipment or installations can be influenced by the gap between successive dips. However, the time-interval between successive dips is not limited with the aggregation methods described in this thesis. Future work can investigate the effect of multiple-dips and influence of the gap between multiple-dips on sensitive devices commonly used in industries.

Monitoring for impact evaluation: Most PQ meters for voltage dip monitoring commonly measure voltage waveforms. It is recommended that PQ-meters in the MV-networks also measure the current and/or power characteristics before, during and after the dip events. This can help for estimating the impact of dips on customers, and for determining the relative origin of the disturbances. However, further studies may be required regarding their techno-economic benefits.

Dip impact on combined customers: The proposed approach for estimating the impact of voltage dips on customers is based on the loss of power for the aggregated customers in six Dutch MV-networks. To enhance the applicability of the proposed approach globally, further investigations may be required in different countries by considering different aspects such as different networks (Rural/Urban, Overhead lines/underground cables).

Voltage dip regulation: The number of years over which the voltage dips regulation should be updated is still a discussion for the grid operators. The proposed voltage dip regulation may require simplifications and further discussion may be needed among different stakeholders before it is adapted in the national grid code. Further studies on the economic aspect will be required if any network modification to be made by the network operator can reduce the expected number of dips with a feasible investment.

A

Symmetrical components method

A.1 Symmetrical components for unbalanced faults

In a three-phase system, unbalanced faults result in asymmetrical voltages. With the help of symmetrical components, each phase voltage can be decomposed and represented by three symmetrical components.

A.1.1 Single phase-to-ground fault

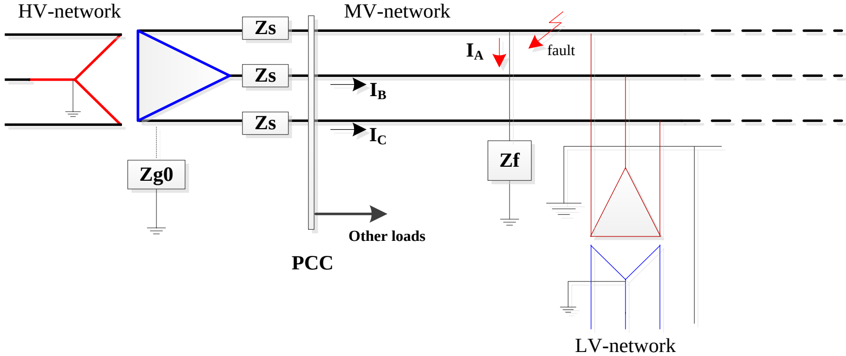


Figure A.1: Single phase-to-ground fault on an MV cable.

In the MV-network shown in Figure A.1, a single phase-to-ground fault (pgf) is considered to occur on phase A. The short-circuit currents during the fault time, assuming no currents by other loads, can be expressed by (A.1) and the symmetrical currents obtained from the asymmetrical components are given by (A.2).

$$I_A = \frac{V_A}{Z_F};\; I_B = I_C = 0 \tag{A.1}$$

$$\begin{pmatrix} I_0 \\ I_1 \\ I_2 \end{pmatrix} = \frac{1}{3}\begin{pmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{pmatrix}\begin{pmatrix} I_A \\ I_B \\ I_C \end{pmatrix} = \frac{V_a}{3Z_F}\begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix} \tag{A.2}$$

Equation (A.2) shows that the three symmetrical components of the current for the faulted are connected in series as in Figure A.2.

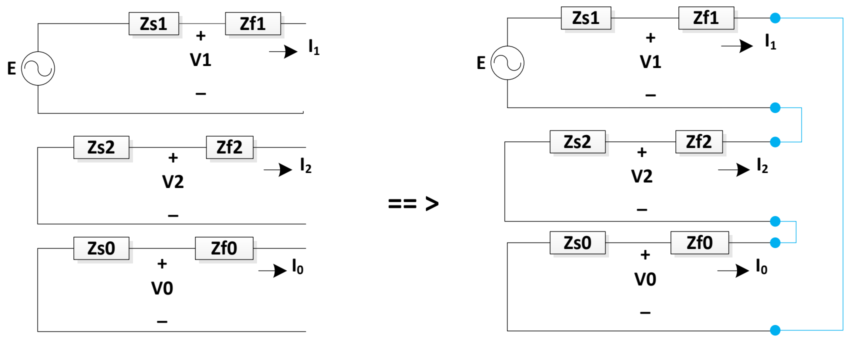


Figure A.2: Symmetrical network components and their connection during single phase-to-ground fault.

After some mathematical computation, symmetrical components of the phase-voltage at the PCC can be expressed using (A.3). Upon the back conversion of symmetrical components to asymmetrical components, the expressions for the three phase-ground voltages during the fault are shown in (A.4) [1],

$$\begin{bmatrix} V_1 & V_2 & V_0 \end{bmatrix} = \begin{bmatrix} \frac{Z_F + Z_{S0} + Z_{S2}}{Z_F + Z_S} & -\frac{Z_{S2}}{Z_F + Z_S} & -\frac{Z_{S0}}{Z_F + Z_S} \end{bmatrix} \tag{A.3}$$

$$\begin{bmatrix} V_a & V_b & V_c \end{bmatrix} = \begin{bmatrix} 1 - \frac{Z_S}{Z_F + Z_S} & a^2 - \frac{a^2 Z_{S1} + aZ_{S2} + Z_{S0}}{Z_F + Z_S} & a - \frac{aZ_{S1} + a^2 Z_{S2} + Z_{S0}}{Z_F + Z_S} \end{bmatrix} \tag{A.4}$$

where $Z_S = Z_{S1} + Z_{S2} + Z_{S0}$ and $Z_F = Z_{F1} + Z_{F2} + Z_{F0}$ are source and fault impedances in terms of three components.

A.1.2 Phase-to-phase fault

When phase-to-phase faults (ppf) occur on phases B and C of the radial network (shown in Figure A.1), the short-circuit currents of the three phases during the fault can be expressed by (A.5). Transferring the asymmetrical currents to symmetrical components, the symmetrical components are shown in (A.6) and this indicates that the positive and negative sequence network components are connected in parallel and the zero sequence network is open as shown Figure A.3.

$$I_a = 0;\ I_b = -I_c = \frac{V_b - V_c}{Z_F} \tag{A.5}$$

$$I_0 = 0, \qquad I_1 = -I_2 = \frac{V_1 - V_2}{Z_F} \tag{A.6}$$

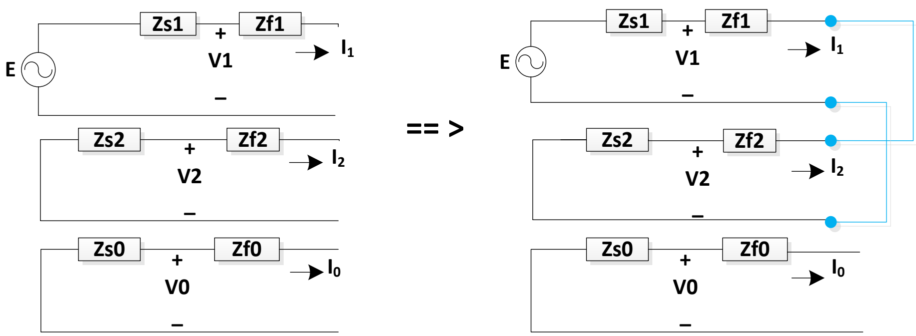


Figure A.3: Symmetrical network components and their connection during a phase-to-phase fault

Transferring the symmetrical components of phase-voltages obtained from Figure A.3, the asymmetrical voltages at the PCC can be given by (A.7) [1]. The voltages are independent of the zero sequence component of impedances. When the positive and negative sequence source impedances are the same, the voltage magnitude on the fault-free phase is not affected by the fault.

$$\begin{bmatrix} U_a \\ U_b \\ U_c \end{bmatrix} = \begin{bmatrix} 1 - \dfrac{Z_{S1} - Z_{S2}}{(Z_{S1} + Z_{S2}) + (Z_{F1} + Z_{F2})} \\ a^2 - \dfrac{a^2 Z_{S1} - aZ_{S2}}{(Z_{S1} + Z_{S2}) + (Z_{F1} + Z_{F2})} \\ a - \dfrac{aZ_{S1} - a^2 Z_{S2}}{(Z_{S1} + Z_{S2}) + (Z_{F1} + Z_{F2})} \end{bmatrix} \tag{A.7}$$

A.1.3 Two phase-to-ground fault

With two phase-to-ground fault (2pgf) on phases B and C of Figure A.1, the short circuit currents of the three phases during the fault can be expressed by (A.8). Equation (A.8) implies that the three symmetrical network components are connected in parallel as shown in Figure A.4.

$$\begin{gathered} I_A = 0; \qquad I_B = \frac{V_b}{Z_F}; \quad I_C = \frac{V_c}{Z_F} \\ \Rightarrow I_0 + I_1 + I_2 = 0 \end{gathered} \tag{A.8}$$

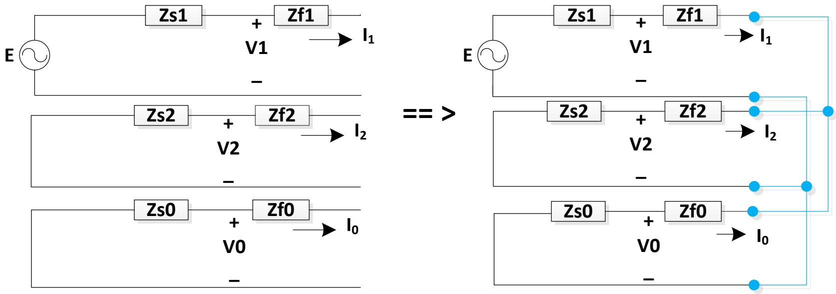


Figure A.4: Symmetrical network components and their connection during two phase-to-ground fault

Performing some mathematical computations on the network shown in Figure A.4, the asymmetrical phase-ground voltages at the PCC can be expressed by (A.9) [1],

$$\begin{bmatrix} U_a \\ U_b \\ U_c \end{bmatrix} = \begin{bmatrix} 1 + \dfrac{(Z_{S2} - Z_{S1})Z_0 + (Z_{S0} - Z_{S1})Z_2}{Z_1 Z_2 + Z_1 Z_0 + Z_0 Z_2} \\ a^2 + \dfrac{(aZ_{S2} - a^2 Z_{S1})Z_0 + (Z_{S0} - a^2 Z_{S1})Z_2}{Z_1 Z_2 + Z_1 Z_0 + Z_0 Z_2} \\ a + \dfrac{(a^2 Z_{S2} - aZ_{S1})Z_0 + (Z_{S0} - aZ_{S1})Z_2}{Z_1 Z_2 + Z_1 Z_0 + Z_0 Z_2} \end{bmatrix} \tag{A.9}$$

where the positive, negative and zero sequence components, represented by the subscripts 1, 2, 0, are $Z_1 = Z_{F1} + Z_{S1}$, $Z_2 = Z_{F2} + Z_{S2}$, and $Z_0 = Z_{F0} + Z_{S0}$.

Assuming the same values for the positive and negative sequence components of impedances, Figure A.5 indicates the variation of voltages at the PCC for various faults occurring along a 10 km feeder in the MV-network. A single phase-to-ground fault (Figure A.5(a)) occurring along the feeder of an isolated MV-network sees an infinite path of return path. The very large zero sequence source impedance reduces the occurrence of large short-circuit current and results in very deep dips on the faulted phase and overvoltage in the fault-free phases. This can be confirmed from (A.4) that the voltages during the fault become $\lim_{Z_{s0} \to \infty} (u_a, u_b, u_c) \to \left[0,\ a^2 - 1,\ a - 1\right]$. From this point of view, such faults occurring throughout the MV-network would be seen as deeper dips. For phase-to-phase faults, Figure A.5(b) shows that the voltage on the fault-free phase is not affected because the voltage drop depends on the difference in positive and negative sequence source impedances which are usually equal. On the other hand, faulted phases show voltage drop proportional to $\left(\dfrac{1}{2}\dfrac{Z_{s1}}{Z_{s1} + Z_{F1}}\right)$. A fault at the PCC would lead to a voltage drop of ~50% of nominal voltage. When the fault distance increases from the PCC, the denominator increases which reduces the voltage drop.

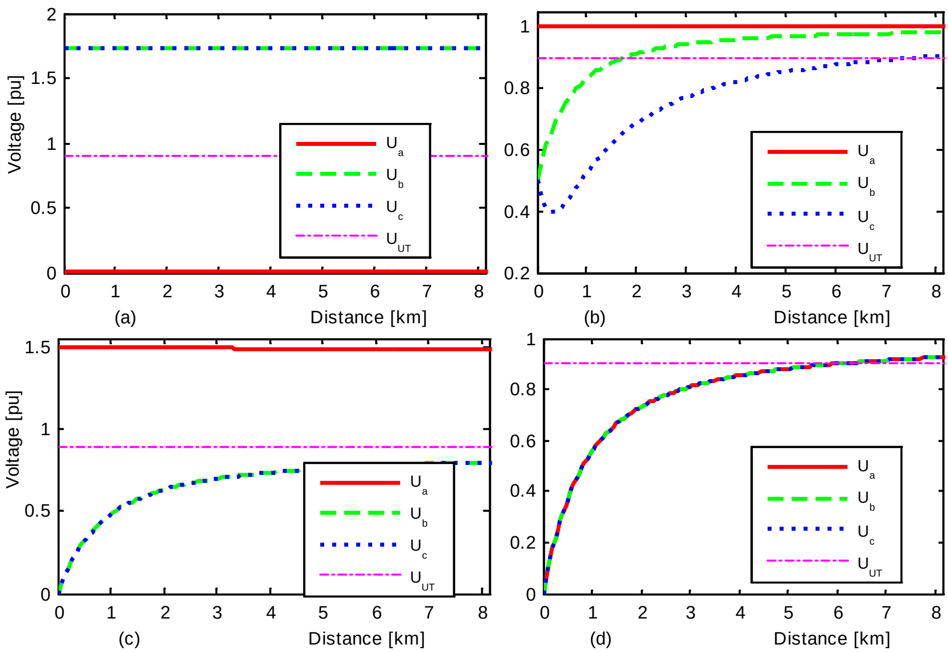


Figure A.5: Voltage dip variation with fault location in isolated MV-network for- (a) single phase-to-ground fault, (b) phase-to-phase fault, (c) two phase-to-ground fault, (d) three-phase fault.

With two phase-to-ground faults (Figure A.5(c)), there are voltage drops in the faulted phases and overvoltage in the fault-free phase. Depending on the fault location, deeper to shallow dips are seen at the PCC due to such faults throughout the network. During balanced three-phase faults, the voltages only depend on the positive sequence impedances. Hence, Figure A.5(d) shows balanced dips at the PCC varying from deeper to shallow depending on the fault location.

A.2 Effect of system grounding on voltage magnitude

For an MV-network with isolated, impedance grounded and solidly grounded system, simulation results of phase-to-ground and phase-to-phase voltages as a function of the fault distance from the PCC are shown in Figure A.6, Figure A.7 and Figure A.8 for the four types of faults. As the fault distance varies from the PCC, the remaining voltage (dip) is compared with a reference voltage having an upper threshold (U_{UT}) value of 90% for each type of fault.

Single phase-to-ground faults in an isolated or impedance system grounding can cause deeper phase-dips which are not perceived in the phase-phase voltages at the PCC of the MV-network. In solidly grounded system, this type of fault can cause dips in the phase-to-ground and phase-phase voltages. The other types of faults can cause dips related to both phase-to-ground and phase-phase voltages with magnitude varying depending on the type of fault and system grounding. Except for the single phase-to-ground fault, the phase-phase dips due to the other faults seen from the PCC are the same in the three types of system grounding. It has to be recalled that the phase-dips and phase-phase dips due to balanced faults are the same and are independent of system grounding type. Voltage dips due to phase-phase faults are not dependent on the type of system grounding.

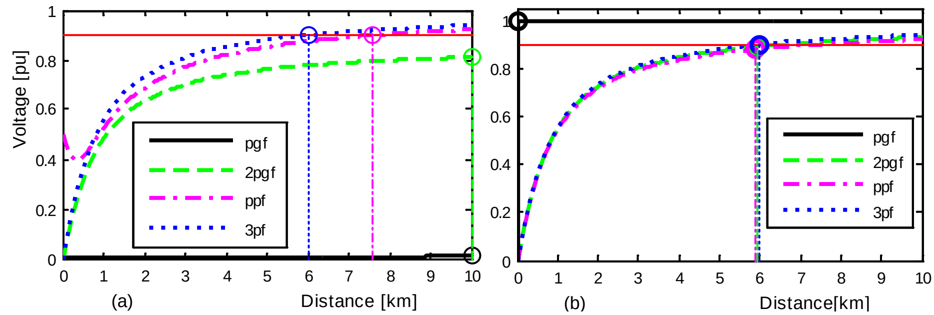


Figure A.6: Different faults in an isolated MV-network and variation of voltage magnitude with fault location for – (a) phase-to-ground voltages, (b) phase-phase voltages.

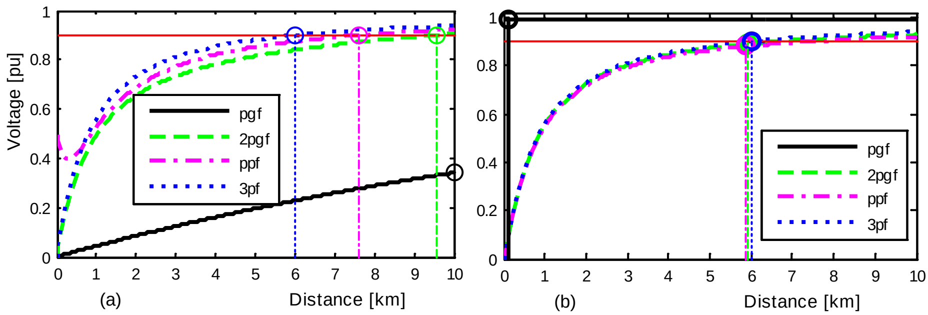


Figure A.7: Different faults in an impedance grounded MV-network and variation of voltage magnitude with fault location for– (a) phase-to-ground voltages, (b) phase-phase voltages

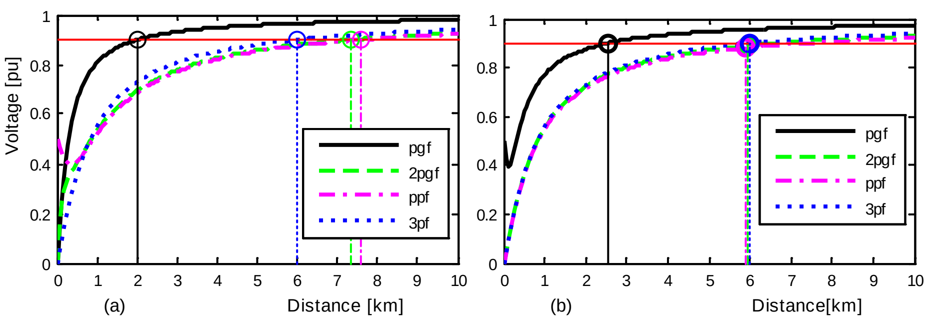


Figure A.8: Different faults in a solidly grounded MV-network and variation of voltage magnitude with fault location for – (a) phase-to-ground voltages, (b) phase-phase voltages

B

Monitoring voltage dips

B.1 Transfer of dips from monitoring data

For voltage dips caused by various types of faults and monitored in the MV-networks, the changes in voltage characteristics during the propagation to the LV-networks through Dyn transformers can be demonstrated by the examples shown in Figure B.1 through Figure B.3. It can be seen that one-phase dips are hardly transferred to the LV-networks while balanced three-phase dips mostly transfer without change in magnitude.

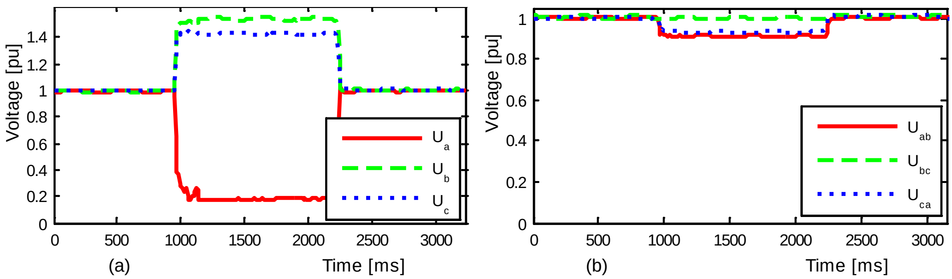


Figure B.1: Transfer of one-phase dip in isolated MV-network- (a) phase-to-ground voltages in the MV-network, (b) phase-phase voltages in the MV-network (=phase-voltages in the LV-network).

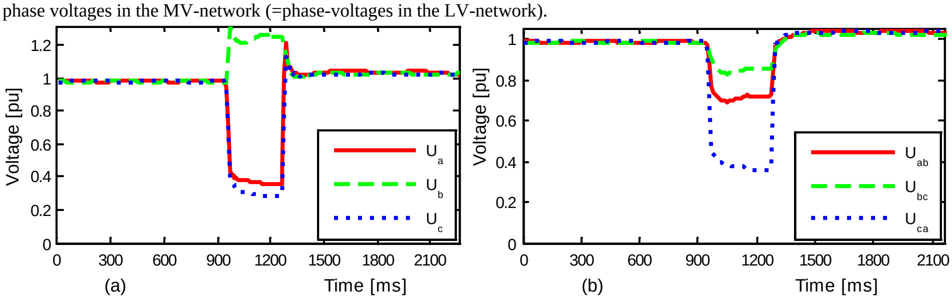


Figure B.2: Transfer of two-phase dips in isolated MV-network- (a) phase-to-ground voltages in the MV-network, (b) phase-phase voltages in the MV-network (=phase-to-ground voltages in the LV-network).

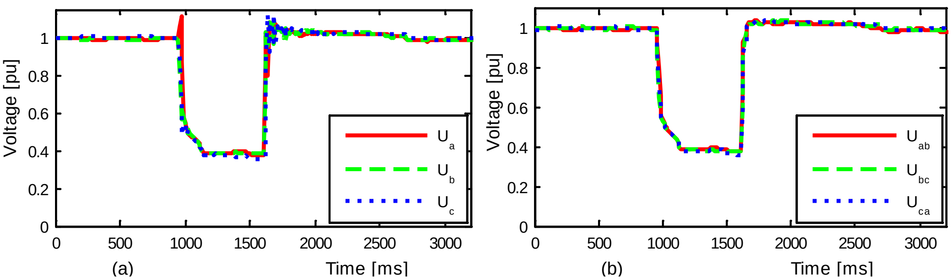


Figure B.3: Transfer of three-phase dips in isolated MV-network- (a) phase-to-ground voltages in the MV-network, (b) phase-phase voltages in the MV-network (=phase-to-ground voltages in the LV-network).

B.2 Scatter plots for all qualified dips

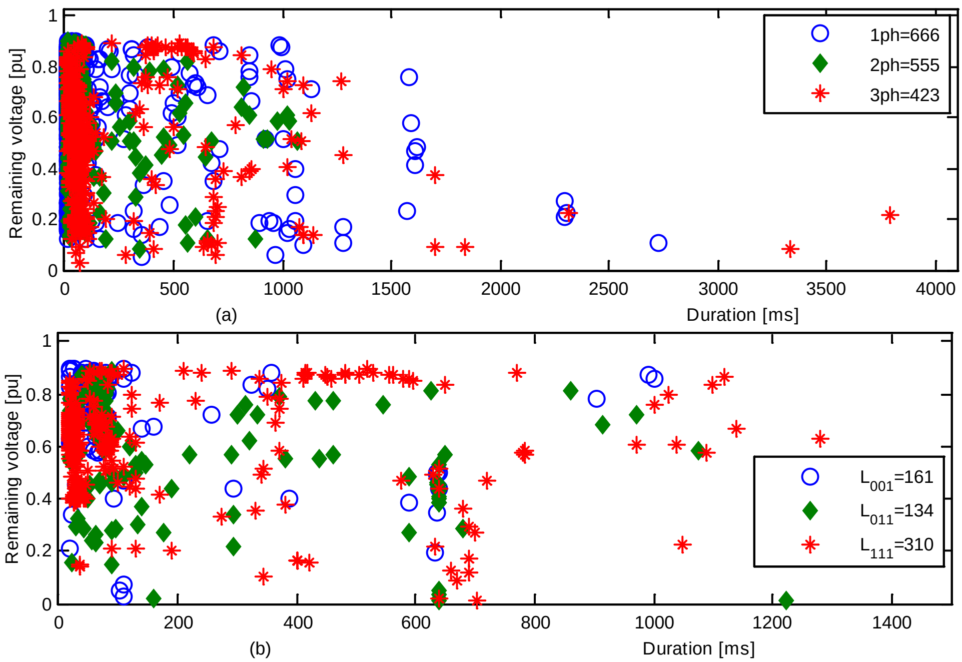


Figure B.4: Scatter plot of total dips with all qualified dip counted individually (no aggregation) related to- (a) phase-ground voltages in the MV-networks, (b) phase-phase voltages in the MV-networks.

B.3 Voltage dip profiles

Table B.1 shows a comparison about the effect of different aggregation techniques on the number and severity of the monitored phase-dips in the Dutch MV-networks. It can be seem that the use of aggregation methods with multiple-dips reduced the average occurrence of dips from about 27 to 15 dips per year. The severity of dips, however, can be different depending on the choice of aggregation method.

Table B.1: Annual voltage dip profiles for phase-ground voltages using no-aggregation (M0), lowest magnitude-total duration aggregation (M1), lowest magnitude-sum of duration aggregation (M2), lowest magnitude- longest duration aggregation (M3), voltage sag aggregation method (M4) and voltage dip severity index method of aggregation (M5)

Remaining voltage [%]		Duration [s] $\Delta t \le 0.2$			$0.2 < \Delta t \le 0.5$			$0.5 < \Delta t \le 1$			$1 < \Delta t \le 5$			$5 < \Delta t \le 60$			
		1ph	2ph	3ph	1ph	2ph	3ph	1ph	2ph	3ph	1ph	2ph	3ph	1ph	2ph	3ph	Tot.
90>u ≥80	M0	2.74	2.82	0.55	0.08	0.02	0.21	0.07	0.02	0.17	0.00	0.00	0.00	0.00	0.00	0.00	6.67
	M1	1.19	1.43	0.29	0.00	0.00	0.08	0.07	0.00	0.16	0.00	0.00	0.00	0.00	0.00	0.00	3.22
	M2	1.25	1.45	0.29	0.04	0.00	0.21	0.07	0.02	0.16	0.00	0.00	0.00	0.00	0.00	0.00	3.48
	M3	1.25	1.45	0.29	0.04	0.00	0.21	0.07	0.02	0.16	0.00	0.00	0.00	0.00	0.00	0.00	3.48
	M4	1.25	1.45	0.29	0.04	0.00	0.21	0.07	0.02	0.16	0.00	0.00	0.00	0.00	0.00	0.00	3.48
	M5	1.25	1.45	0.29	0.04	0.00	0.21	0.07	0.02	0.16	0.00	0.00	0.00	0.00	0.00	0.00	3.48
80>u ≥70	M0	2.11	2.95	0.66	0.05	0.04	0.05	0.06	0.02	0.02	0.05	0.00	0.06	0.00	0.00	0.00	6.08
	M1	0.53	1.76	0.24	0.06	0.07	0.04	0.05	0.02	0.03	0.04	0.00	0.06	0.00	0.00	0.00	2.90
	M2	0.62	1.75	0.32	0.05	0.04	0.05	0.06	0.02	0.02	0.05	0.00	0.06	0.00	0.00	0.00	3.03
	M3	0.62	1.75	0.32	0.05	0.04	0.05	0.06	0.02	0.02	0.05	0.00	0.06	0.00	0.00	0.00	3.03
	M4	0.62	1.75	0.32	0.05	0.04	0.05	0.06	0.02	0.02	0.05	0.00	0.06	0.00	0.00	0.00	3.03
	M5	0.62	1.75	0.32	0.05	0.04	0.05	0.06	0.02	0.02	0.05	0.00	0.06	0.00	0.00	0.00	3.03
70>u ≥40	M0	3.03	2.69	3.46	0.08	0.12	0.08	0.11	0.15	0.02	0.04	0.06	0.07	0.00	0.00	0.00	9.90
	M1	0.97	1.78	1.76	0.03	0.11	0.20	0.08	0.18	0.02	0.04	0.06	0.06	0.00	0.00	0.00	5.30
	M2	1.36	1.46	1.87	0.03	0.09	0.08	0.10	0.15	0.02	0.04	0.06	0.06	0.00	0.00	0.00	5.33
	M3	1.36	1.46	1.87	0.03	0.09	0.08	0.10	0.15	0.02	0.04	0.06	0.06	0.00	0.00	0.00	5.33
	M4	1.36	1.46	1.87	0.03	0.09	0.08	0.10	0.15	0.02	0.04	0.06	0.06	0.00	0.00	0.00	5.33
	M5	1.36	1.46	1.87	0.03	0.09	0.08	0.10	0.15	0.02	0.04	0.06	0.06	0.00	0.00	0.00	5.33
40>u ≥5	M0	1.65	0.83	1.56	0.14	0.03	0.06	0.11	0.05	0.16	0.12	0.00	0.06	0.00	0.00	0.00	4.76
	M1	0.34	0.36	2.07	0.04	0.03	0.16	0.02	0.07	0.23	0.11	0.00	0.06	0.00	0.00	0.00	3.50
	M2	0.70	0.43	1.24	0.14	0.03	0.05	0.11	0.05	0.16	0.12	0.00	0.06	0.00	0.00	0.00	3.08
	M3	0.70	0.43	1.24	0.14	0.03	0.05	0.11	0.05	0.16	0.12	0.00	0.06	0.00	0.00	0.00	3.08
	M4	0.70	0.43	1.24	0.14	0.03	0.05	0.11	0.05	0.16	0.12	0.00	0.06	0.00	0.00	0.00	3.08
	M5	0.70	0.43	1.24	0.14	0.03	0.05	0.11	0.05	0.16	0.12	0.00	0.06	0.00	0.00	0.00	3.08
5>u	M0	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02
	M1	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02
	M2	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02
	M3	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02
	M4	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02
	M5	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02
Sub. Total	M0	9.53	9.29	6.25	0.34	0.21	0.40	0.35	0.24	0.37	0.20	0.06	0.19	0.00	0.00	0.00	**27.42**
	M1	3.03	5.33	4.37	0.14	0.20	0.48	0.23	0.28	0.44	0.19	0.07	0.18	0.00	0.00	0.00	**14.94**
	M2	3.93	5.09	3.73	0.26	0.16	0.38	0.34	0.24	0.36	0.20	0.06	0.18	0.00	0.00	0.00	**14.94**
	M3	3.93	5.09	3.73	0.26	0.16	0.38	0.34	0.24	0.36	0.20	0.06	0.18	0.00	0.00	0.00	**14.94**
	M4	3.93	5.09	3.73	0.26	0.16	0.38	0.34	0.24	0.36	0.20	0.06	0.18	0.00	0.00	0.00	**14.94**
	M5	3.93	5.09	3.73	0.26	0.16	0.38	0.34	0.24	0.36	0.20	0.06	0.18	0.00	0.00	0.00	**14.94**

Similarly, Table B.2 shows that the average occurrence of phase-phase dips in the Dutch MV-networks are about 10 dips per year when no aggregation is used with multiple-dips. When multiple-dips occurring within short-time interval are aggregated, the average number dips over all monitoring locations is reduced to about 9.5 dip per year.

Table B.3 shows that the number of voltage dips occurrence varies significantly between countries. As can be seen from the data, the average number of dips (related to phase-to-ground/phase-phase voltages) in the Netherlands greatly lower than the other European countries.

Table B.2: Annual voltage dip profiles for phase-phase voltages using no-aggregation (M0), lowest magnitude-total duration aggregation (M1), lowest magnitude-sum of duration aggregation (M2), lowest magnitude- longest duration aggregation (M3), voltage sag aggregation method (M4) and voltage dip severity index method of aggregation (M5)

Remaining voltage [%]		Duration [s]															
		Δt ≤ 0.2			*0.2 < Δt ≤ 0.5*			*0.5 < Δt ≤ 1*			*1 < Δt ≤ 5*			*5 < Δt ≤ 60*			
		L_{001}	L_{011}	L_{111}	L_{001}	L_{011}	L_{111}	L_{001}	L_{011}	L_{111}	L_{001}	L_{011}	L_{111}	L_{001}	L_{011}	L_{111}	Tot.
90>u ≥80	M0	1.69	0.37	0.27	0.04	0.00	0.21	0.02	0.02	0.17	0.02	0.00	0.02	0.00	0.00	0.00	2.85
	M1	1.67	0.34	0.25	0.00	0.00	0.10	0.02	0.02	0.16	0.02	0.00	0.02	0.00	0.00	0.00	2.61
	M2	1.67	0.34	0.25	0.00	0.00	0.20	0.02	0.02	0.17	0.02	0.00	0.02	0.00	0.00	0.00	2.72
	M3	1.67	0.34	0.25	0.00	0.00	0.20	0.02	0.02	0.17	0.02	0.00	0.02	0.00	0.00	0.00	2.72
	M4	1.67	0.34	0.25	0.00	0.00	0.20	0.02	0.02	0.17	0.02	0.00	0.02	0.00	0.00	0.00	2.72
	M5	1.67	0.34	0.25	0.00	0.00	0.20	0.02	0.02	0.17	0.02	0.00	0.02	0.00	0.00	0.00	2.72
80>u ≥70	M0	0.55	0.39	0.46	0.02	0.08	0.03	0.02	0.02	0.00	0.00	0.00	0.04	0.00	0.00	0.00	1.60
	M1	0.51	0.35	0.31	0.00	0.05	0.08	0.02	0.02	0.00	0.00	0.00	0.04	0.00	0.00	0.00	1.37
	M2	0.51	0.35	0.31	0.02	0.08	0.03	0.02	0.02	0.00	0.00	0.00	0.04	0.00	0.00	0.00	1.37
	M3	0.51	0.35	0.31	0.02	0.08	0.03	0.02	0.02	0.00	0.00	0.00	0.04	0.00	0.00	0.00	1.37
	M4	0.51	0.35	0.31	0.02	0.08	0.03	0.02	0.02	0.00	0.00	0.00	0.04	0.00	0.00	0.00	1.37
	M5	0.51	0.35	0.31	0.02	0.08	0.03	0.02	0.02	0.00	0.00	0.00	0.04	0.00	0.00	0.00	1.37
70>u ≥40	M0	0.30	0.53	2.84	0.04	0.04	0.05	0.08	0.19	0.14	0.00	0.02	0.05	0.00	0.00	0.00	4.28
	M1	0.17	0.47	2.26	0.06	0.04	0.10	0.06	0.21	0.16	0.00	0.02	0.04	0.00	0.00	0.00	3.59
	M2	0.19	0.45	2.26	0.04	0.04	0.05	0.08	0.19	0.14	0.00	0.02	0.04	0.00	0.00	0.00	3.50
	M3	0.19	0.45	2.26	0.04	0.04	0.05	0.08	0.19	0.14	0.00	0.02	0.04	0.00	0.00	0.00	3.50
	M4	0.19	0.45	2.26	0.04	0.04	0.05	0.08	0.19	0.14	0.00	0.02	0.04	0.00	0.00	0.00	3.50
	M5	0.19	0.45	2.26	0.04	0.04	0.05	0.08	0.19	0.14	0.00	0.02	0.04	0.00	0.00	0.00	3.50
40>u ≥5	M0	0.06	0.25	0.23	0.00	0.04	0.08	0.06	0.12	0.07	0.00	0.00	0.00	0.00	0.00	0.00	0.89
	M1	0.02	0.13	0.21	0.00	0.04	0.08	0.04	0.14	0.07	0.00	0.00	0.01	0.00	0.00	0.00	0.73
	M2	0.02	0.13	0.21	0.00	0.04	0.07	0.06	0.12	0.07	0.00	0.00	0.00	0.00	0.00	0.00	0.71
	M3	0.02	0.13	0.21	0.00	0.04	0.07	0.06	0.12	0.07	0.00	0.00	0.00	0.00	0.00	0.00	0.71
	M4	0.02	0.13	0.21	0.00	0.04	0.07	0.06	0.12	0.07	0.00	0.00	0.00	0.00	0.00	0.00	0.71
	M5	0.02	0.13	0.21	0.00	0.04	0.07	0.06	0.12	0.07	0.00	0.00	0.00	0.00	0.00	0.00	0.71
5>u	M0	0.04	0.02	0.00	0.00	0.00	0.00	0.00	0.06	0.04	0.00	0.02	0.00	0.00	0.00	0.00	0.17
	M1	0.04	0.02	0.00	0.00	0.00	0.00	0.00	0.06	0.04	0.00	0.02	0.00	0.00	0.00	0.00	0.17
	M2	0.04	0.02	0.00	0.00	0.00	0.00	0.00	0.06	0.04	0.00	0.02	0.00	0.00	0.00	0.00	0.17
	M3	0.04	0.02	0.00	0.00	0.00	0.00	0.00	0.06	0.04	0.00	0.02	0.00	0.00	0.00	0.00	0.17
	M4	0.04	0.02	0.00	0.00	0.00	0.00	0.00	0.06	0.04	0.00	0.02	0.00	0.00	0.00	0.00	0.17
	M5	0.04	0.02	0.00	0.00	0.00	0.00	0.00	0.06	0.04	0.00	0.02	0.00	0.00	0.00	0.00	0.17
Sub. Total	M0	2.64	1.55	3.81	0.10	0.16	0.36	0.17	0.42	0.42	0.02	0.04	0.11	0.00	0.00	0.00	**9.79**
	M1	2.40	1.32	3.03	0.06	0.13	0.36	0.13	0.45	0.42	0.02	0.04	0.11	0.00	0.00	0.00	**8.48**
	M2	2.42	1.30	3.03	0.06	0.16	0.34	0.17	0.42	0.42	0.02	0.04	0.11	0.00	0.00	0.00	**8.48**
	M3	2.42	1.30	3.03	0.06	0.16	0.34	0.17	0.42	0.42	0.02	0.04	0.11	0.00	0.00	0.00	**8.48**
	M4	2.42	1.30	3.03	0.06	0.16	0.34	0.17	0.42	0.42	0.02	0.04	0.11	0.00	0.00	0.00	**8.48**
	M5	2.42	1.30	3.03	0.06	0.16	0.34	0.17	0.42	0.42	0.02	0.04	0.11	0.00	0.00	0.00	**8.48**

Table B.3: Numer of voltage dips in the MV-networks of different European countries

Country	Monitoring period	Average dips per year	Major[11] dips per year	Reference
Netherlands	2010-2015	14.94/8.48	3.94/1.56	*Chapter 3*
Italy	2008-2010	113.10	20.43	[49]
Norway	2014	36.12	10.01	[144]
Portugal	2014	110.36	19.01	[144]
Hungary	2009	167.60	13.30	[49]
Slovenia	2014	236.01	47.18	[144]

[11] Dips below the "indicative responsibility-sharing curve" proposed in the European Energy Regulators' (CEER 2011) report. The curve is based on (40%, 200 ms), (70%, 500 ms) and (80%, 5 s) combinations of test levels and durations, and it is intended to distinguish the dips that mostly concern the customers from the minor dips.

C

Dip immunity of devices

C.1 Voltage-tolerance curves of AC contactors

C.1.1 VTC of contactors for dips initiated at 0° and 90°

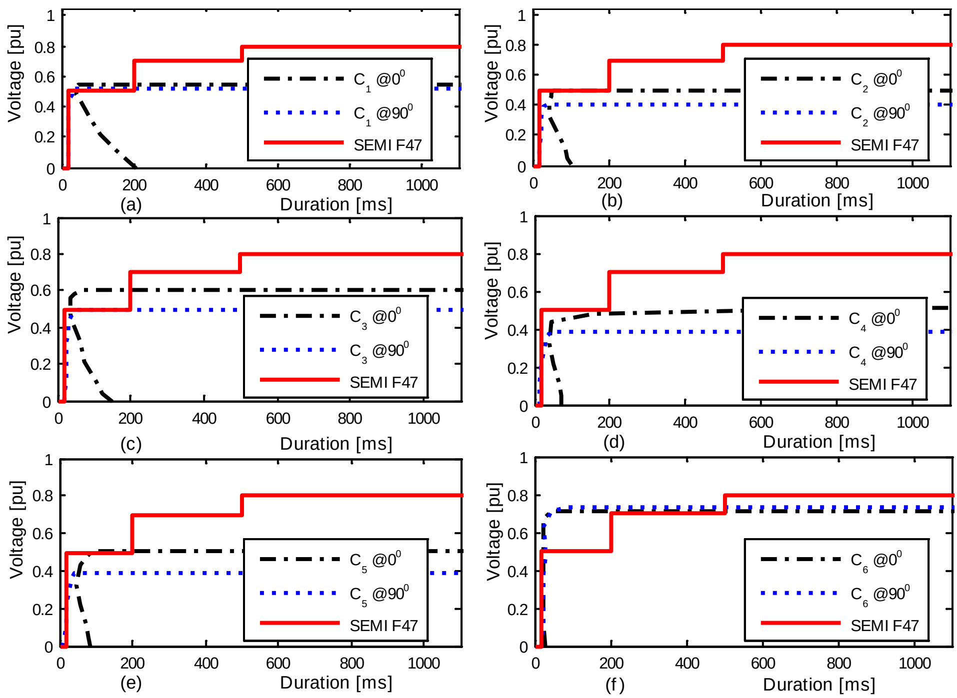


Figure C.1: VTC of various contactors for voltage dips initiated at 0° and 90°.

C.1.2 Impact of load variation on the VTC of a contactor

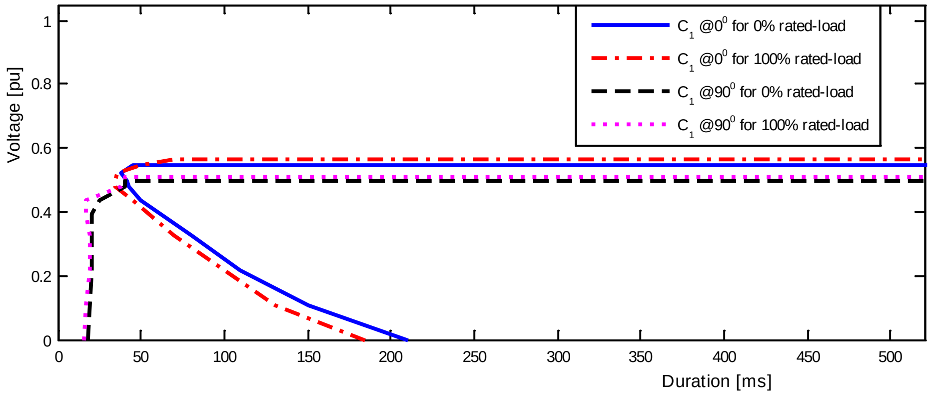


Figure C.2: Impact of load variation on the voltage-tolerance curves of a contactor C_1.

C.1.3 Mitigation and improvement in the VTC of an AC contactor

When the contactor coil is supplied with a phase-phase voltage (Figure C.3(a)), a minimum voltage of ~0.58 pu can be obtained at its terminals during voltage dips affecting only one of the phases. This is large enough (>0.54 pu) to energize the AC-coil and to keep the contacts connected. When the two phases supplying the AC-coil are affected by dips, the voltage-tolerance curve of the coil is the same as the case before mitigation.

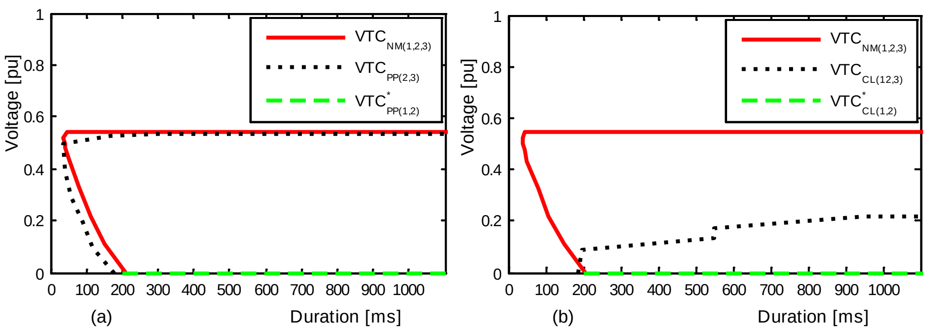


Figure C.3: Improvement in the VTC of an AC contactor C_1 as compared to the case when no-mitigation (NM) with –

(a) Phase-phase mitigation ($TC_{PP(2,3)}$➔both phases supplying the coil are affected by dips; $TC^*_{PP(1,2)}$➔ not both phases supplying the coil are affected by dips),

(b) Coil-Lock mitigation ($TC_{CL(1,2,3)}$➔when any dip affects the contactor coil; $TC^*_{CL(1,2)}$➔ when one-phase and two-phase dips are not on the coil).

With a Coil-Lock mitigation (Figure C.3(b)), the AC-coil is energized from the supply via the Coil-Lock. With this mitigation method, the ride-through capability of the contactor coil can be improved (in his case down to 24% of the nominal) during any type of dip on the phase supplying the contactor coil. When the dips are on the phases other than the phase supplying the AC-coil, the contacts do not disengage but the load experiences the same disturbance as in the supply. The phase-phase mitigation is more effective against single-phase dips than Coil-Lock mitigation while the Coil-Lock mitigation is more superior the former method with polyphaser dips.

C.2 Voltage dip immunity of ASD

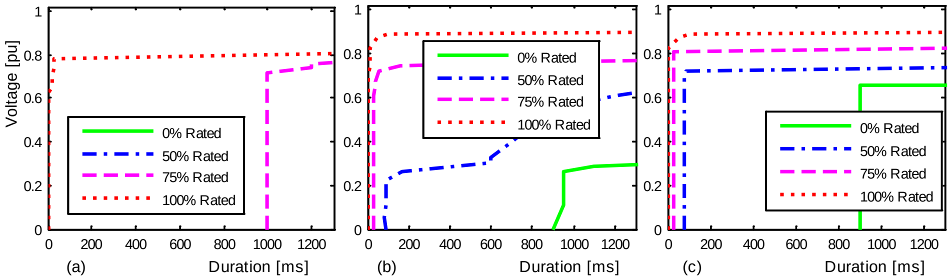


Figure C.4: VTCs of an ASD against voltage dips under various loading situations and keeping the dip type constant- (a) one-phase dips, (b) two-phase dips, (c) three-phase dips.

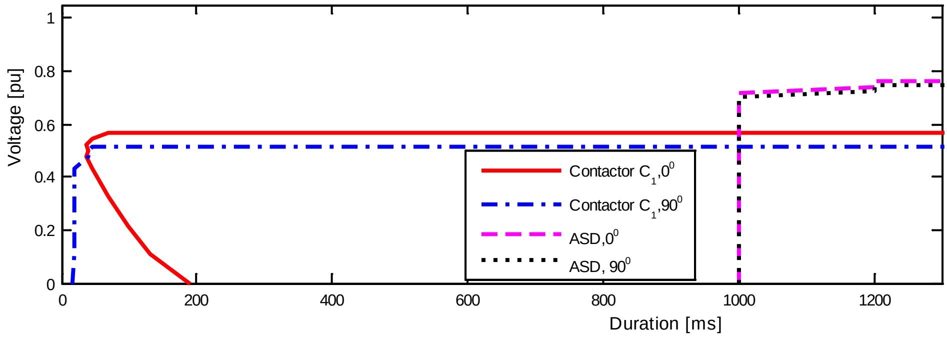


Figure C.5: Impact point-on-wave initiations on the VTCs of an ASD and contactor C_1 at 75% rated-load with one-phase dips.

C.3 Voltage dip immunity of a simple process

C.3.1 Impact of loading on the process immunity against voltage dips

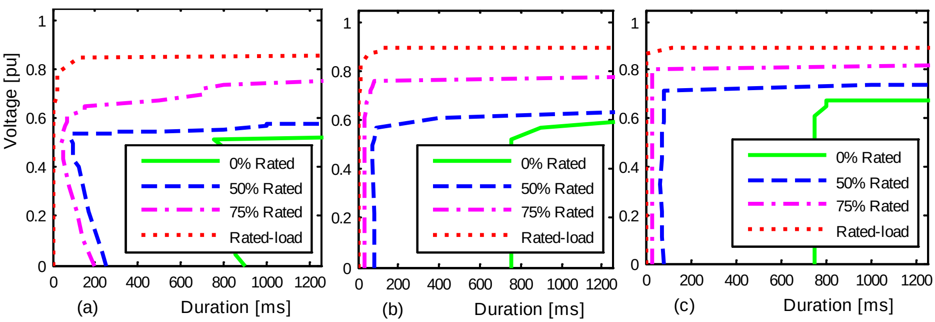


Figure C.6: Impact of load variation on process immunity for various types of voltage dips- (a) one-phase, (b) two-phase, (c) three-phase.

C.3.2 Weakest link of process equipment to voltage dips

For the (tested) simple process, comparisons of the equipment and process voltage-tolerance curves against two-phase and one-phase dips under various loading conditions are shown Figure C.7 and Figure C.8.

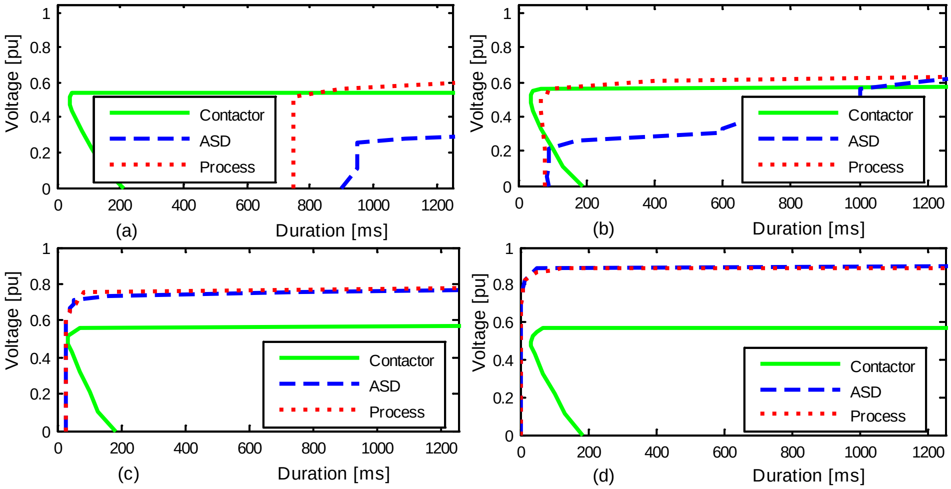


Figure C.7: Comparison for the immunity of a contactor C_1, an ASD and the process against two-phase dips at loadings- (a) 0% rated-load, (b) 50% rated-load, (c) 75% rated-load, and (d) 100% rated-load.

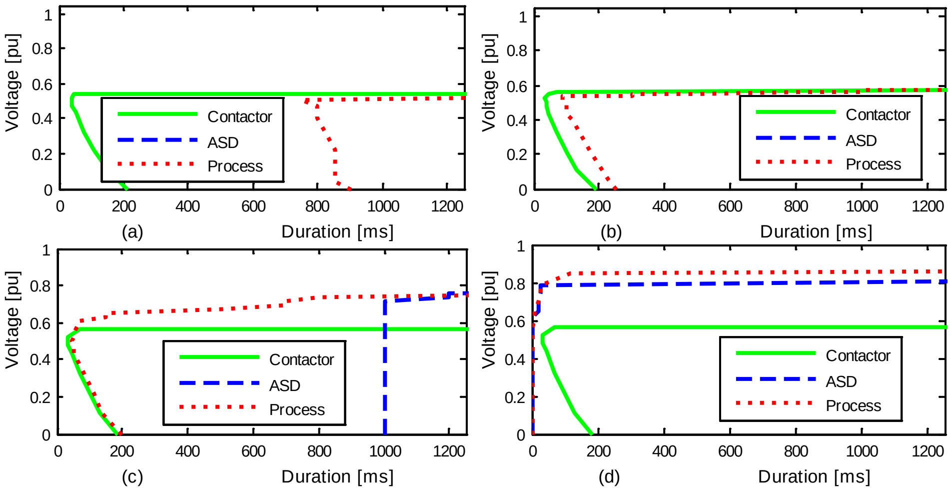


Figure C.8: Comparison for the immunity of a contactor C_1, ASD and Process against single-phase dips at loadings- (a) 0% rated-load, (b) 50% rated-load, (c) 75% rated-load, and (d) 100% rated-load.

For two-phase dips, three-phase interruptions caused by the contactor trip triggered the tripping of the ASD and hence the process at no-load conditions (Figure C.7(a)). The contactor is, therefore, the weakest link component of the process at no-load. At 50%

rated-load (Figure C.7(b)), the ASD tripped before the contactor to voltage drops below 25% of the nominal voltage and this caused the process trip. For dips above 25% of nominal voltage, the disruptions caused by contactor trip triggered the ASD to fail and hence the process at 50% rated-load to trip. Therefore, the contactor or ASD can be the weakest link depending on the magnitudes of the remaining voltage. At 75 and 100% of rated-loads (Figure C.7(c-d)), the ASD tripped before the contactor for two-phase dips and the ASD is the weakest link.

With one-phase dips, the three-phase interruptions due to the disturbance on the AC-coil of the contactor triggered the tripping of the ASD and hence the process at no-load and 50% rated-load (Figure C.8(a-b)) even though the ASD was immune to all dips. At 75% rated-load, the voltage-tolerance curve of the process shifted even closer to that of the contactor. At full-load, the voltage-tolerance curve of the process followed that of the ASD. From this, it can be said that the contactor is the weakest link for loading conditions up to 75% rated-load and the ASD is the weakest link at full-load conditions during one-phase dips.

C.3.3 Process immunity time

The process immunity time (PIT) is defined in the CIGRE/CIRED/UIE JWG [2] as the time interval between the start of the voltage interruption and the moment when the process parameter goes out of the allowed tolerance limit. This concept is applied to the (tested) simple process, and the PITs for the equipment and process tested against different types of voltage disturbances and at various loading conditions are given in Table C.1. The criticalities of the equipment are ranked based on the PIT values.

For interruptions on one phase of the supply voltages, the contactor has the shortest PIT and it receives higher priority than the ASD except during the rated-load condition. For interruptions on two or on three of the supply voltages, the ASD during actual loading conditions has the shortest PIT and is ranked first. The critical process equipment ranked first, based on the PIT values, can be considered as the weakest link component. However, the PIT of the process can be different from that of the weakest link component in the process. The type of disturbance and the loading condition also have influence on the actual PIT values of the process.

Table C.1: PITs of equipment and process for various types of voltage disturbances under different loading condtions

Component	**(a) Interruptions on one phase of the supply voltages**							
	0% rated-load		***50% rated-load***		***75% rated-load***		***100% rated-load***	
	PIT[ms]	*Priority*	*PIT[ms]*	*Priority*	*PIT[ms]*	*Priority*	*PIT[ms]*	*Priority*
Contactor	210	1	190	1	190	1	190	2
ASD	NT*	2	NT	2	1000	2	10	1
Process	900		240		200		10	
	(b) Interruptions on two phases of the supply voltages							
Contactor	210	1	190	2	190	2	190	2
ASD	900	2	80	1	30	1	10	1
Process	750		80		30		10	
	(c) Interruptions on three phases of the supply voltages							
Contactor	210	1	190	2	190	2	190	2
ASD	900	2	80	1	30	1	10	1
Process	750		80		30		10	

*Not Trip

C.3.4 Performance of the process at various loadings to field data

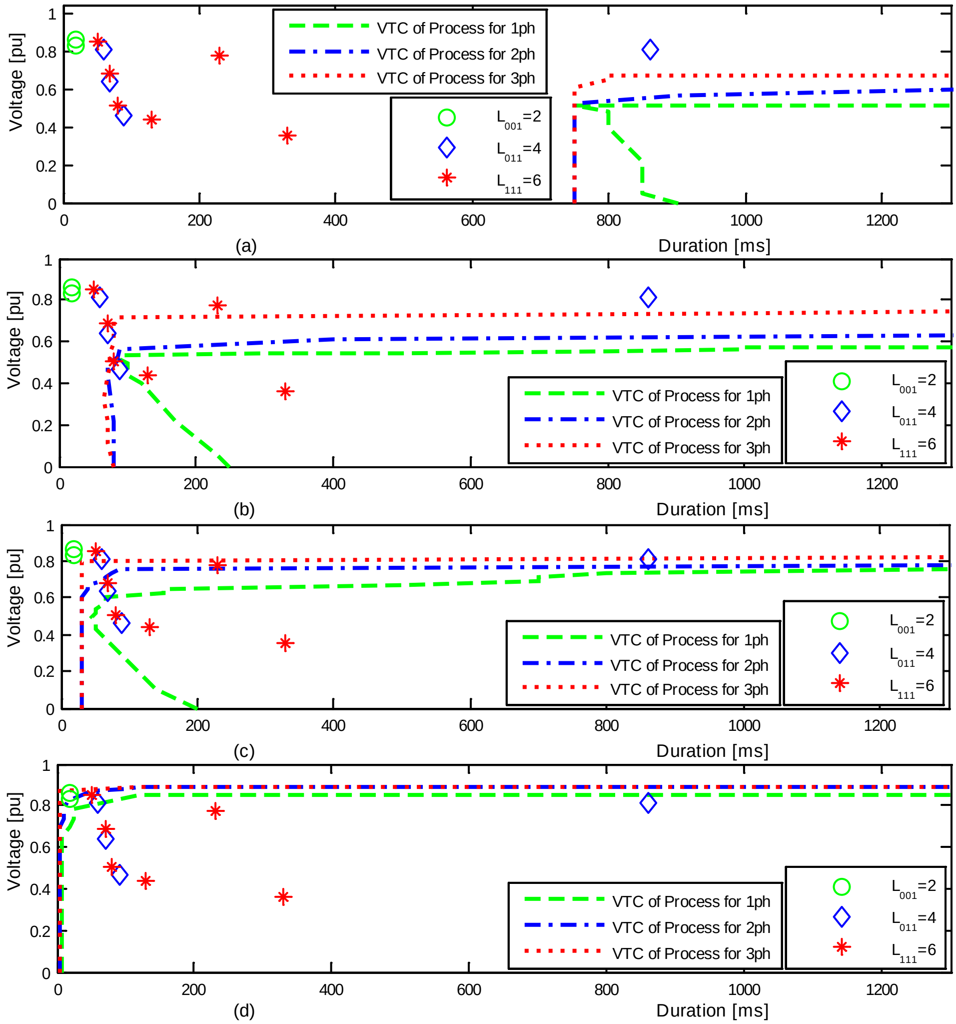


Figure C.9: Performance of the process to one-phase (L_{001}), two-phase (L_{011}) and three-phase (L_{111}) dips transferred from an MV-network- (a) 0% rated-load, (b) 50% rated-load, (c) 100% rated-load.

Table C.2: Voltage dips performance of a process with load variations

Dip types in an MV-network	Total number of dips in 4 years	Number of dips below the VTC of the process at various loading			
		0% rated	*50% rated*	*75% rated*	*100% rated*
L_{001}	2	0	0	0	0
L_{011}	4	0	1	2	4
L_{111}	6	0	3	5	6
Total	***12***	***0***	***4***	***7***	***10***
Mean	***3.00***	***0.00***	***1.00***	***1.75***	***2.50***

D

Dip impact on aggregated customers

D.1 Relative loss of loads Vs dip parameters

The scatter plots shown in Figure D.1 through Figure D.5 depict the effect voltage dip parameters on the relative loss of power for the aggregated customers connected to the different MV-networks. In each network, the relative loss of power gets higher when the severity of dips, which is characterized by the magnitude, duration and type of dips, increases. This indicates that there is a strong correlation between the severity of voltage dips and their impact on the aggregated loads connected to the networks during the occurrence of dip events.

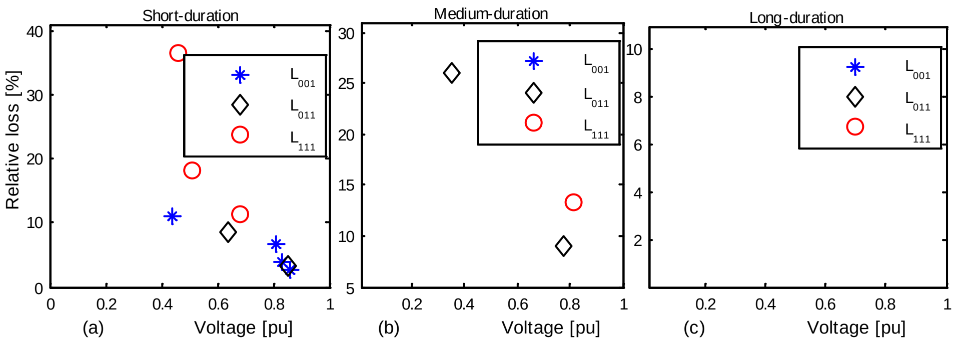


Figure D.1: Relative loss of aggregated loads for different types of dips in **NK1** with duration- (a) Δt≤200 ms, (b) 200<Δt≤1000 ms, and (c) Δt>1000 ms.

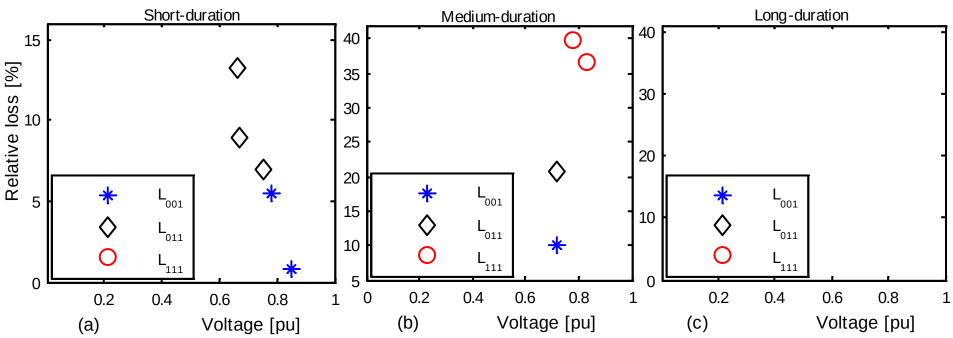


Figure D.2: Relative loss of aggregated loads for different types of dips in **OHK** with duration- (a) Δt≤200 ms, (b) 200<Δt≤1000 ms, and (c) Δt>1000 ms.

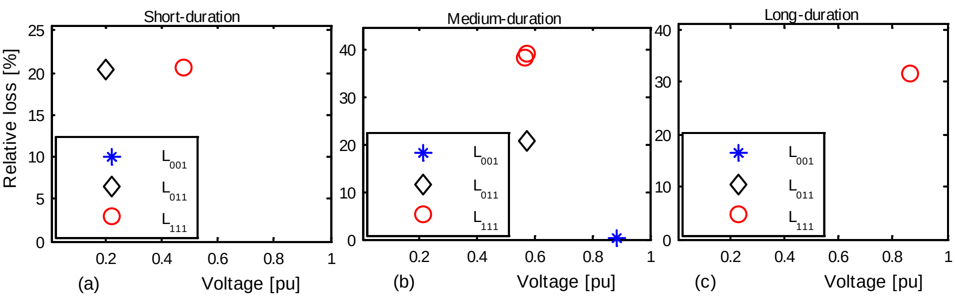


Figure D.3: Relative loss of aggregated loads for different types of dips in **WEW1** with duration- (a) Δt≤200 ms, (b) 200<Δt≤1000 ms, and (c) Δt>1000 ms.

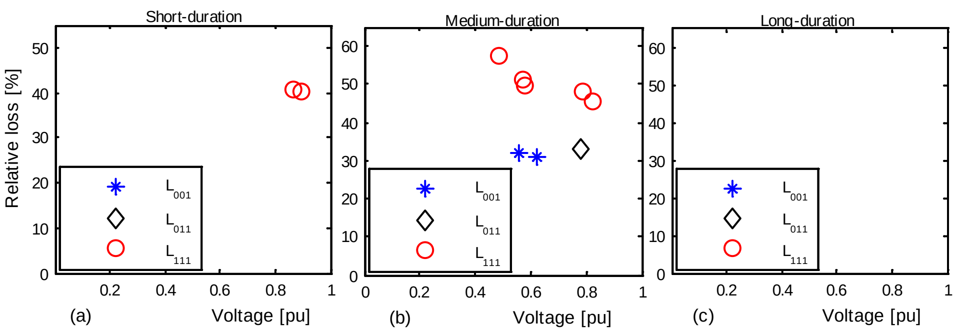


Figure D.4: Relative loss of aggregated loads for different types of dips in **ZBM1** with duration- (a) Δt≤200 ms, (b) 200<Δt≤1000 ms, and (c) Δt>1000 ms.

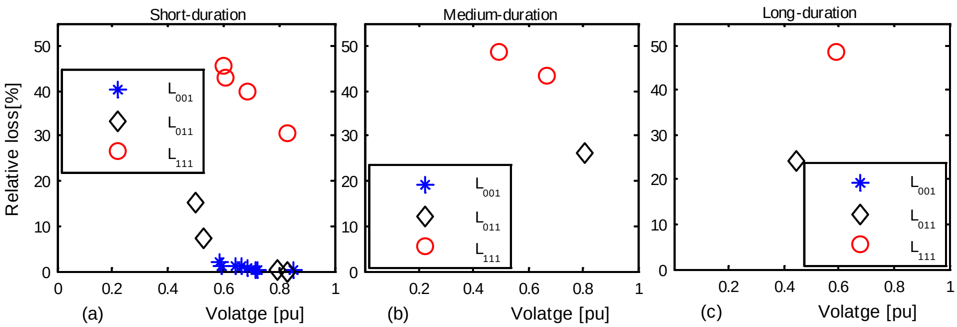


Figure D.5: Relative loss of aggregated loads for different types of dips in WWGB with duration- (a) Δt≤200 ms, (b) 200<Δt≤1000 ms, and (c) Δt>1000 ms.

D.2 X-percentile of weighting factors

As described in *Chapter 5*, average voltage dip severity weighting factors (WFs) are obtained for the various types of dips based on the weighted average of the relative loss of power for the aggregated customers connected to the MV-networks.

The severity WFs factors can be used for estimating the economic impact of customers relative to that of interruptions. Depending on the type of customer categories and sensitivity of processes, customers may use other values of WFs (like 25-, 50-, 75-, 95- and 99-percentiles) instead of the average WFs. Table D.1 through Table D.4 are values of weighting factors for the 25-, 50-, 75- and 99-perecentailes obtained from the average WFs.

Table D.1: 25-percentile of WFs (%) for various types of dips

Remaining voltage [%]	L_{001} dips (p=1)					L_{011} dips (p=2)					L_{111} dips (p=3)				
	Duration [s]					Duration [s]					Duration [s]				
	Δt≤0.2	Δt≤0.5	Δt≤1	Δt≤5	Δt>5	Δt≤0.2	Δt≤0.5	Δt≤1	Δt≤5	Δt>5	Δt≤0.2	Δt≤0.5	Δt≤1	Δt≤5	Δt>5
90>u≥80	0	0	1	1	1	1	10	15	16	16	9	19	23	26	30
80>u≥70	0	5	7	8	8	5	15	16	19	19	17	22	26	28	33
70>u≥40	3	15	17	18	18	17	23	24	25	28	26	28	30	38	44
40>u≥5	10	21	25	25	26	29	34	40	42	44	35	37	42	59	65
5>u	11	21	25	26	27	31	37	46	49	50	37	42	48	67	73

Table D.2: 50-percentile of WFs (%) for various types of dips

Remaining voltage [%]	L_{001} dips (p=1)					L_{011} dips (p=2)					L_{111} dips (p=3)				
	Duration [s]					Duration [s]					Duration [s]				
	Δt≤0.2	Δt≤0.5	Δt≤1	Δt≤5	Δt>5	Δt≤0.2	Δt≤0.5	Δt≤1	Δt≤5	Δt>5	Δt≤0.2	Δt≤0.5	Δt≤1	Δt≤5	Δt>5
90>u≥80	0	1	2	2	2	1	12	18	19	19	11	22	27	30	34
80>u≥70	1	7	9	10	10	6	18	19	22	22	20	26	29	32	37
70>u≥40	4	17	20	21	21	19	27	28	29	32	30	32	34	42	48
40>u≥5	12	24	28	29	29	33	38	44	46	49	39	41	46	64	71
5>u	13	25	29	30	30	35	42	51	54	55	41	46	53	73	79

Table D.3.: 75-percentile of WFs (%) for various types of dips

Remaining voltage [%]	L_{001} dips (p=1)					L_{011} dips (p=2)					L_{111} dips (p=3)				
	Duration [s]					Duration [s]					Duration [s]				
	Δt≤0.2	*Δt≤0.5*	*Δt≤1*	*Δt≤5*	*Δt>5*	*Δt≤0.2*	*Δt≤0.5*	*Δt≤1*	*Δt≤5*	*Δt>5*	*Δt≤0.2*	*Δt≤0.5*	*Δt≤1*	*Δt≤5*	*Δt>5*
90>u≥80	0	2	3	3	3	2	14	21	22	22	14	26	30	34	38
80>u≥70	1	9	11	12	12	8	21	22	26	26	23	29	33	36	41
70>u≥40	6	20	23	24	24	22	30	32	32	35	34	36	38	46	53
40>u≥5	15	27	32	33	33	37	42	49	51	54	43	46	51	70	76
5>u	16	28	33	34	34	39	46	56	59	60	46	51	58	78	85

Table D.4: 99-percentile of WFs (%) for various types of dips

Remaining voltage [%]	L_{001} dips (p=1)					L_{011} dips (p=2)					L_{111} dips (p=3)				
	Duration [s]					Duration [s]					Duration [s]				
	Δt≤0.2	*Δt≤0.5*	*Δt≤1*	*Δt≤5*	*Δt>5*	*Δt≤0.2*	*Δt≤0.5*	*Δt≤1*	*Δt≤5*	*Δt>5*	*Δt≤0.2*	*Δt≤0.5*	*Δt≤1*	*Δt≤5*	*Δt>5*
90>u≥80	2	4	6	7	7	5	21	29	30	31	20	34	40	43	48
80>u≥70	4	14	17	18	18	13	28	30	34	34	31	39	43	46	52
70>u≥40	10	28	32	32	33	31	40	41	42	45	44	46	49	58	65
40>u≥5	21	36	41	42	43	47	53	60	63	66	54	57	63	84	91
5>u	23	37	42	43	44	49	58	69	72	73	57	63	71	93	100

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Nomenclature

List of abbreviations

Index	Meaning
A/C	Air Conditioner
AC	Alternating Current
AFE	Active Front End
ALOC	Annual load outage cost
ASD	Adjustable Speed Drive
AVC	Active Voltage Conditioner
BB	Busbar
CB	Circuit Breaker
CHP	Combined Heat and Power
CIGRE	International Council on Large Electric Systems
CIRED	International Agency for Research on the Environment and Development
CL	Coil-Lock
CPU	Central Processing Unit
CVT	Constant Voltage Transformer
DC	Direct Current
DFR	Digital Fault Recorder
DG	Distributed Generation
DPI	Dip Proofing Inverter
DSO	Distribution System Operator
DUT	Device Under Test
DVR	Dynamic Voltage Restorer
DySC	Dynamic Sag Corrector
EI	Equivalent interruption
EMC	Electromagnetic Compatibility
EU	European Union
FW	Flywheel
HV	High Voltage

IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IGBT	Insulated-gate Bipolar Transistor
IRR	Internal Rate of Return
IPC	In-plant Point of Coupling
IT(IC)	Information Technology (Industry Council)
JWG	Joint Working Group
LV	Low Voltage
LVTA	Lost Voltage-time Area (ms)
MV	Medium Voltage
NCF	Net Cash Flow
NPV	Net present value
OMC	Operating and maintenance cost
PAJ	Phase Angle Jump
PBT	Payback time
PC	Personal Computer
PCC	Point of Common Coupling
pgf	Single phase-to-ground fault
Ph-ph	Phase-phase
PI	Profitability index
PIT	Process Immunity Time
PLC	Programmable Logic Controller
POC	Point of Connection
ppf	Phase-to-phase fault
PQ(M)	Power Quality (Monitoring)
pu	Per unit
RMS	Root Mean Square
sc	Short-circuit
SEMI	Semiconductor Equipment and Materials International
STS	Static Transfer Switch
TSO	Transmission System Operator
UIE	International Union for Electricity applications
UPS	Uninterruptable Power Supply
VDC	Voltage Dip Compensator
VTC	Voltage-tolerance Curve
WF	Weighting Factor
1ph	Single-phase
2pgf	Two phase-to-ground fault
2ph	Two-phase
3pf	Three-phase fault
3ph	Three-phase

List of symbols

Index	Meaning
A	Ampere
Al	Aluminum
C	Capacitance
d_{cr}	Critical distance
D_{cr}	Dips within the critical distance
DG_{PL}	Penetration level of DG-units
D_{miss}	Dips missed by a PQ-meter
Dyn	Delta-star transformer connection with neutral
E_{vs}	Voltage Sag Energy index (ms)
I	Current
kHz	Kilo Hertz
km	Kilometer
L_{001}	One phase-to-phase dipped voltage
L_{011}	Two phase-to-phase dipped voltages
L_{111}	Three phase-to-phase dipped voltages
P	Active power
P_{CG}	Power of the central unit
P_{DG}	Total power of DG-units
P_{dur}	During dip power
P_{post}	Post-dip power
P_{pre}	Pre-dip power
R	Resistance
R^2	Coefficient of determination (measure of goodness)
S	Apparent power
S_e	Severity index
U	Voltage magnitude
U_{cr}	Critical voltage
U_{UTH}	Upper threshold voltage
V	Volt
VA	Volt Ampere
W	Watt
X	Reactance
Z	Impedance
ΔP	Change of power due to a voltage dip
Δt	Dip duration
Ψ	Phase angle
Φ	Magnetic flux
Ω	Ohm

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Curriculum Vitae

Leake Enquay Weldemariam was born on 20th February 1984 in Seglamen, Ethiopia. After finishing his secondary school in 2002, he studied Electrical and Electronics Engineering at Mekelle Institute of Technology, Mekelle, Ethiopia. He obtained his BSc degree with Very Great Distinction in July 2007 with a graduation project on "*Design of Automated Charge Controller for Standalone PV Lighting Systems for Rural Areas*". From August 2007 to July 2008, he was appointed as an assistant lecturer at Mekelle Institute of Technology within the Electrical and Electronics Engineering department.

In August 2008, he was awarded the 'Faculty Africa Scholarship 2008-2010' to the MSc program in Electrical Engineering, track Electrical Power Engineering at TU Delft, The Netherlands. He obtained his MSc diploma with Cum Laude in September 2010 with a thesis on the topic "*Genset-Solar-Wind Hybrid Power Systems for Off-grid Rural Applications*". From September 2010 to June 2013, he worked as a lecturer within the department of Electrical and Electronics Engineering at Mekelle Institute of Technology, Ethiopia.

From June 2013 he started a PhD project within the Electrical Energy System group at Eindhoven University of Technology, The Netherlands, under the supervision of prof.dr.ir. J.F.G. Cobben and dr. V. Cuk. In his research, he focused on 'Voltage Dips' concerning the estimation, classification, impact on customers, and making a regulation proposal for the Dutch MV-network. The results of his research are presented in this dissertation.

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