MASTER

Feasibility analysis of increasing the voltage level in a low voltage distribution network

Rajan, Kiran Ray

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Master Thesis Report

Kiran Raj Rajan
(Student ID: 1284681)

Electrical Energy Systems Group, Department of Electrical Engineering
Masters in Sustainable Energy Technology
Eindhoven University of Technology

SELECT – Environomical Pathways for Sustainable Energy Systems
EIT InnoEnergy Master School

Thesis Supervisor:	Dr. Bart Kruizinga (DNV GL – Asset Management)
Graduation Supervisor:	Prof. Fred Steennis (TU/e Electrical Energy Systems Group)
Members:	Dr. P.A.A.F Wouters (TU/e Electrical Energy Systems Group) Dr. Henny Romijn (TU/e Industrial Engineering & Innovation Sciences)

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Advisor:	**Mr. Wim Boone (DNV GL)** **Mr. Denny Harmsen (Alliander)**

Scriptie begeleider:	**Dr. Bart Kruizinga (DNV GL – Asset Management)**
Afstudeer begeleider:	**Prof. Fred Steennis (TU/e Electrical Energy Systems Group)**
Leden:	**Dr. P.A.A.F Wouters (TU/e Electrical Energy Systems Group)** **Dr. Henny Romijn (TU/e Industrial Engineering & Innovation Sciences)**
Adviseur:	**Mr. Wim Boone (DNV GL)** **Mr. Denny Harmsen (Alliander)**

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Problem Description

Demand for sustainable energy is growing exponentially. New low carbon energy technologies such as renewable energy sources and electric vehicles have penetrated the low voltage electrical network in an unprecedented manner. The trend is expected to grow in the upcoming years with the reduction in costs and the advent of new energy technologies. This energy transition has caused adverse effects on the low voltage network and also serves as a bottleneck to any future development. What could be the solution to make the low voltage distribution network to be more resilient towards the energy transition?

Probleembeschrijving

De vraag naar duurzame energie groeit exponentieel. Nieuwe koolstofarme energietechnologieën zoals hernieuwbare energiebronnen en elektrische voertuigen zijn op ongekende wijze het laagspanningsnetwerk binnengedrongen. De verwachting is dat de trend de komende jaren zal groeien met de kostenverlaging en de komst van nieuwe energietechnologieën. Deze energietransitie heeft negatieve effecten op het laagspanningsnetwerk veroorzaakt en dient ook als een bottleneck voor toekomstige ontwikkelingen. Wat zou de oplossing kunnen zijn om het laagspanningsdistributienetwerk veerkrachtiger te maken ten opzichte van de energietransitie?

Summary

The Low Voltage (LV) distribution network has witnessed a substantial integration of low carbon technologies in the last 10 years. However, the network has been the least concern when it comes to new innovations or implementation. The LV networks hold the key to the future energy transition. Yet, more than half of the network in the Netherlands is older than 35 years and 20% being older than 50 years. Generation of renewable energy sources like rooftop solar (Photovoltaic – PV) units, which possess high intermittency, at the LV network level has increased the dynamic stresses on the LV cables. Moreover, demand has shifted towards clean energy technologies based on electricity like electric vehicles (EV) and heat pumps. This has resulted in the overloading of the existing network capacity at the LV distribution level.

Additional network capacity is required to cater to these demands. The network capacity can possibly be increased by increasing the operating voltage level in the existing LV network. Various network components make up the LV distribution network. Replacing all these components to meet the new voltage level is practically impossible and financially not a viable option for the network operator. Therefore, maximizing the utilization of the existing assets in the network could help bring down the costs incurred.

The main network component, LV underground power cable, must be able to withstand the higher voltage level. Current LV network operates at 400 V phase to phase for the LV distribution level. The proposal to increase this operating voltage needs a better understanding of the implications on the LV cables and its components. The dielectric strength of the component is one such implication which has been investigated briefly in this study. At high voltages, electric discharges occur in the insulation or between different interfaces. This is known as partial discharges. If the material losses its insulating property under the high voltage stress, it leads to a dielectric breakdown. An experimental setup was developed for evaluating the aforementioned implications of high voltage on low voltage underground distribution cables. The partial discharge measurements and breakdown testing were performed on both, the main LV feeder cables and service cables which connect the customer to the main feeder. The tests were also performed on service aged cable joints obtained from the Distribution Network Operator – DNO (Alliander). Test practices have been partially adopted according to the international standards to quantify the results obtained.

Although the LV cables are rated for up to 1 kV under normal operation, results indicate that the LV (main and service) cables are able to handle test voltages up to 2.5 kV without suffering a partial discharge failure. Most of the samples were also able to withstand test voltages as high as 8.5 kV without a dielectric breakdown. The partial discharge inception voltage of 3.5 kV was observed in a test sample with a branching joint connecting the service cable to the main cable. The observed voltage is five times the nominal operating voltage of the LV distribution network.

The nominal voltage of the LV network could be stepped-up at the MV/LV substation. This can be achieved by changing the tap settings on the MV/LV distribution transformer or exchanging this transformer. However, stepping down the voltage at each customer's point of connection is required but less straightforward. Therefore, a suitable solution for a step-

down converter is investigated in this proposal. Various boundaries have been considered like size (KVA – Kilovolt ampere rating), ease of procurement, impact on the customer end, cost of the installation and reliability. These parameters have played a significant impact on the realization and implementation of the step-down units. The most suitable step-down converter is identified as a silicon-carbide based MOSFET converter. Due to its compact size and power quality management, it is an appropriate solution for the customer and the network operator. These units could be placed at every customer's household to step-down the voltage to the nominal value of 400 V (phase to phase).

The proposal to increase the low voltage in the network should also comply with some national and international regulations. Legal regulations of the European Union and National norms have been considered as an overview for this work. The current framework classifies operating voltages up to 1.5 kV as low voltage distribution level. At this voltage, it is still possible to increase the network capacity by 3.5 times. Although, the proposal is still futuristic which could also help in the long-term planning of the low voltage distribution network. Hence requires some new regulations over the current framework.

Low voltage distribution network caters to the major energy demand. In the distant future, customers in the low voltage network could play an important role, moving from passive to active players in the energy market. To conclude, this thesis provides an innovative solution to the current and future energy challenges of the low voltage distribution network. Therefore, it appears it is feasible to increase the network capacity by increasing the operating voltage on the LV network level. The feasibility study from this work has produced results which shed light on the importance and potential of the LV distribution network.

Samenvatting

Het distributienetwerk voor laagspanning (LV) is de afgelopen tien jaar getuige geweest van een substantiële integratie van koolstofarme technologieën. Het netwerk was echter het minst bezorgd als het gaat om nieuwe innovaties of implementatie. De LV-netwerken zijn de sleutel tot de toekomstige energietransitie. Toch is meer dan de helft van het netwerk in Nederland ouder dan 35 jaar en 20% ouder dan 50 jaar. De opwekking van hernieuwbare energiebronnen zoals zonnepanelen op het dak (fotovoltaïsche - PV) -eenheden, die een hoge intermitterende werking hebben, op het niveau van het LV-netwerk heeft de dynamische spanningen op de LV-kabels verhoogd. Bovendien is de vraag verschoven naar schone energietechnologieën op basis van elektriciteit zoals elektrische voertuigen (EV) en warmtepompen. Dit heeft geresulteerd in overbelasting van de bestaande netwerkcapaciteit op LV-distributieniveau.

Extra netwerkcapaciteit is vereist om aan deze eisen te voldoen. De netwerkcapaciteit kan mogelijk worden verhoogd door het bedrijfsspanningsniveau in het bestaande LV-netwerk te verhogen. Verschillende netwerkcomponenten vormen het LV-distributienetwerk. Het vervangen van al deze componenten om aan het nieuwe spanningsniveau te voldoen is praktisch onmogelijk en financieel gezien geen haalbare optie voor de netwerkoperator. Daarom zou het maximaliseren van het gebruik van de bestaande activa in het netwerk kunnen helpen de gemaakte kosten te verlagen.

De hoofdnetwerkcomponent, LV-ondergrondse stroomkabel, moet bestand zijn tegen het hogere spanningsniveau. Het huidige LV-netwerk werkt op 400 V fase tot fase voor het LV-distributieniveau. Het voorstel om deze bedrijfsspanning te verhogen, heeft een beter begrip van de implicaties voor de LV-kabels en de bijbehorende componenten nodig. De diëlektrische sterkte van de component is een dergelijke implicatie die in deze studie kort is onderzocht. Bij hoge spanningen treden elektrische ontladingen op in de isolatie of tussen verschillende interfaces. Dit staat bekend als gedeeltelijke ontladingen. Als het materiaal zijn isolerende eigenschappen onder de spanning van de hoge spanning verliest, leidt dit tot een diëlektrische doorslag. Een experimentele opstelling werd ontwikkeld voor het evalueren van de bovengenoemde implicaties van hoge spanning op ondergrondse distributiekabels voor laagspanning. De gedeeltelijke ontladingsmetingen en doorslagtests werden uitgevoerd op beide hoofdstroomvoederkabels en servicekabels die de klant verbinden met de hoofdaanvoer. De tests zijn ook uitgevoerd op kabelverbindingen van verouderde dienst die zijn verkregen van de distributienetbeheerder - DNO (Alliander). Testmethoden zijn gedeeltelijk overgenomen volgens de internationale normen om de verkregen resultaten te kwantificeren.

Hoewel de LV-kabels bij normale werking tot 1 kV worden beoordeeld, geven de resultaten aan dat de LV-kabels (hoofd- en servicekabels) testspanningen tot 2,5 kV aankunnen zonder te kampen met gedeeltelijke ontlading. De meeste van de monsters waren ook bestand tegen testspanningen tot 8,5 kV zonder diëlektrische doorslag. De partiële ontladingstartspanning van 3,5 kV werd waargenomen in een testmonster met een aftakverbinding die de servicekabel met de hoofdkabel verbond. De waargenomen spanning is vijf keer de nominale bedrijfsspanning van het LV-distributienetwerk.

De nominale spanning van het LV-netwerk zou bij het MV / LV-onderstation kunnen worden opgevoerd. Dit kan eenvoudig worden bereikt door de tapinstellingen op de MV / LV-distributietransformator te wijzigen of deze transformator te verwisselen. Het verlagen van de spanning op het aansluitingspunt van elke klant is echter vereist, maar minder eenvoudig. Daarom wordt in dit voorstel een geschikte oplossing voor een step-down-omzetter onderzocht. Verschillende grenzen zijn beschouwd als grootte (KVA - Kilovolt ampere rating), gemak van aanschaf, impact op het klanteneinde, kosten van de installatie en betrouwbaarheid. Deze parameters hebben een grote invloed gehad op de realisatie en implementatie van de step-down-units. De meest geschikte step-down-omzetter wordt geïdentificeerd als een op siliciumcarbide gebaseerde MOSFET-omzetter. Vanwege het compacte formaat en het beheer van de voedingskwaliteit is het een geschikte oplossing voor de klant en de netwerkexploitant. Deze units kunnen bij het huishouden van elke klant worden geplaatst om de spanning naar de nominale waarde van 400 V (phase to phase) te verlagen.

Het voorstel om de laagspanning in het netwerk te verhogen, moet ook voldoen aan een aantal nationale en internationale voorschriften. Wettelijke voorschriften van de Europese Unie en nationale normen zijn beschouwd als een overzicht voor dit werk. Het huidige raamwerk classificeert werkspanningen tot 1,5 kV als laagspanningsverdelingsniveau. Bij deze spanning is het nog steeds mogelijk om de netwerkcapaciteit 3,5 keer te vergroten. Hoewel het voorstel nog steeds futuristisch is, wat ook kan helpen bij de langetermijnplanning van het laagspanningsdistributienetwerk. Vandaar dat er een aantal nieuwe regels nodig zijn over het huidige kader.

Laagspanningsdistributienetwerk voldoet aan de grote energievraag. In de verre toekomst zouden klanten in het laagspanningsnetwerk een belangrijke rol kunnen spelen, van passieve naar actieve spelers op de energiemarkt. Samenvattend biedt dit proefschrift een innovatieve oplossing voor de huidige en toekomstige energie-uitdagingen van het laagspanningsdistributienetwerk. Daarom lijkt het haalbaar om de netwerkcapaciteit te vergroten door de bedrijfsspanning op het LV-netwerkniveau te verhogen. De haalbaarheidsstudie van dit werk heeft resultaten opgeleverd die licht werpen op het belang en het potentieel van het LV-distributienetwerk.

Contents

Abbreviations

Alternating Current	AC
Celsius	° C
Cross-Linked Polyethylene	XLPE
Direct Current	DC
Distribution Network Operator	DNO
Electric Vehicles	EV
High Voltage Distribution System	HVDS
High Voltage	HV
Insulated Gate Bipolar Transistor	IGBT
International Electrotechnical Commission	IEC
Kilo metre	km
Kilo volt	kV
Low Voltage	LV
Medium Voltage	MV
Metal Oxide Semiconductor Field Effect Transistor	MOSFET
Microcontroller Unit	MCU
Oil Impregnated Paper	OIP
Paper Insulated Lead Covered	PILC
Partial Discharge	PD
Phase Resolved Partial Discharge	PRPD
Photovoltaic	PV
Pico Coulombs	pC
Point of Connection	PoC
Polyvinyl Chloride	PVC
Silicon Carbide	SiC
Square millimetre	sq. mm
Transmission System Operator	TSO
Voltage across the Cavity	V_c
Voltage breakdown of the gap	V^+

Chapter 1. Introduction

In an ever-changing, energy driven world, the significance of low carbon technologies in the energy supply is increasing exponentially. The huge influx of low carbon technologies, such as rooftop solar, electric vehicles (EV) and heat pumps, has led to a significant overloading on the LV distribution networks. Such distributed energy sources are mostly connected to the low voltage (LV) network. Unlike the Medium Voltage (MV) network, LV networks are designed to operate radially for top-down power flow. The integration of distributed generations combined with loads like from electric vehicles and heat pumps has resulted in dynamic power flows in the LV network. In spite of the benefits of distributed generation, overloading of the LV underground cable network [1] poses a big challenge to the distributed network operator (DNO).

With the constant growth of the renewable energy generation in the Netherlands [2], the Low voltage distribution network is pushed to its limits. The DNO defines relevant integration guidelines such as capacity, protection, harmonics, earthing and, load profiles for safe and reliable LV network operations. Integration of EV charging stations in public spaces and the addition of heat pumps have led to an unpredictable state for the DNO's. The long-term planning of distribution networks is required in order to cope up with this energy transition. Currently, management of the generation capacity and replacing older assets in the LV level is the solution for the DNO's to maintain a reliable network. Emerging strategies like load scheduling and peak shaving require huge investments and acceptance from the customers. Moreover, such measures are generally restricted to smaller network area and fail to apply for a larger part of the distribution network. Therefore, a cost-effective reliable long-term solution is required to prevent overloading of the LV network.

The impact of more distributed generation can congest the LV network capacity and also serves as a bottleneck (i.e.) preventing additional customers from installing distributed sources. Although the DNO's have the potential to predict the load profile of their individual networks, the response to the demand is much slower and may lead to voltage levels below or above the required value. This variation should be within the standard grid code of ± 10% of the nominal power supply. Figure 1 gives a general idea of the voltage profile for a week measured in the LV distribution feeder in the Netherlands at different point of connections. The voltage at the first point of connection is higher than the nominal operating voltage during the off-peak hours of the day due to the energy generation from the distributed rooftop solar installations in the feeder and lack of energy demand. At the tail end of the same feeder (at 20th point of connection), the voltage suffers a significant drop. This can be related to the peak demand in the evening when all the loads are connected. Such voltage variations pose a significant challenge to the LV network operator who needs to adhere to the grid voltage guidelines.

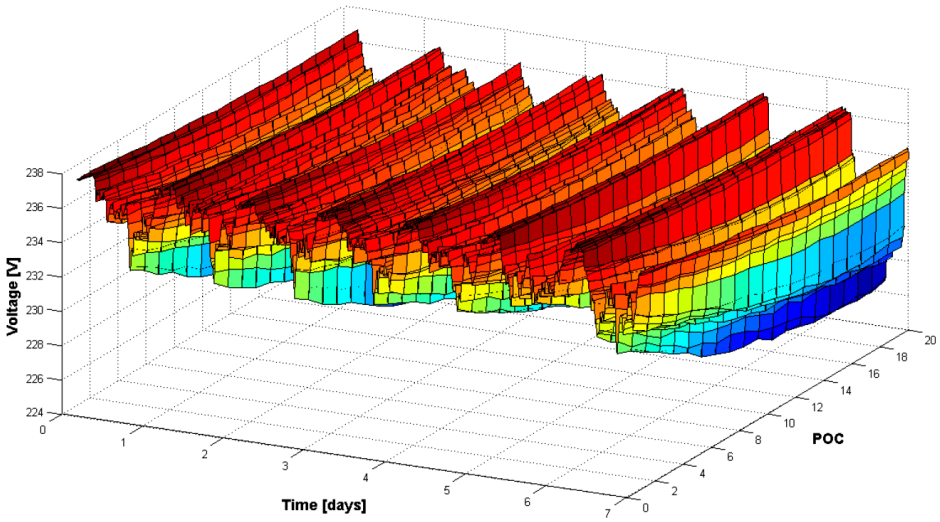


Figure 1 Voltage profile of LV customers at the point of connection in the Netherlands [3]

Hence, a future-proof solution is required to maintain a reliable operation of the distribution network. This thesis work proposes a new alternative solution to the problem of overloading in the LV distribution network by using the existing low voltage infrastructure.

The main drawback of the LV network is overloading of the LV cable which can be linked to the operating voltage limitations currently in existence. Traditional 400 V lines are rated up to 1 kV for safe operations. The transformation of LV underground cables to operate at a higher voltage level could increase the network capacity significantly. In comparison to the installation of new LV lines, maximizing the utilization of the existing assets can be economically sustainable for the utility. At present, several commercial installations exist in Europe and pilot study programs have been carried out to adapt High Voltage Distribution Systems (HVDS). The proposal to increase the voltage in the distribution networks dates back to the early 1980's by Hazelrigg G.A. [4] and theories behind this has been studied in [5]. The application of a distribution voltage at a 1 kV level has been investigated for a grid in Finland [6], [7] and [8]. For the 1 kV grid it was concluded that a 1 kV grid is economically feasible [9] and that it is a competitive solution compared to other network reinforcement strategies listed in [10].

1.1 Thesis Objectives

This solution is aimed to overcome the problem of overloading in the Low Voltage distribution network of the Netherlands. Increasing the voltage level in the existing LV network to accommodate additional network capacity is a potential solution. The following two aspects are considered the most challenging and have been the main focus of this thesis:

> The main emphasis of this study is to demonstrate the technical feasibility of increasing the operating voltage in the existing LV distribution network assets. This includes identifying a voltage up to which the LV network voltage can be increased to enable safe operation. This is outlined in Chapter 2, Chapter 3 and Chapter 4.

A second objective to achieve the overall goal is to identify a technical and economical solution to step-down the voltage at the customer's point of connection. Although increasing the voltage results in adding network capacity, the voltage needs to be step-down at the customer's point of connection (PoC) in order to supply the devices rated at the nominal operating low voltage. The different solutions have been discussed in Chapter 5.

In Chapter 6, the outcome of the feasibility study is concluded, and recommendations have been made for the future work.

1.2 Current Scenario of the LV network in the Netherlands

In the Netherlands, LV network spans for 235,985 km (underground cables) with an exception of 120 km which is an overhead line [11]. Generally, a 3 - phase distribution system with a voltage level of 400 V (phase-phase) and 230 V (phase-neutral) is used to connect the small businesses and households. In any given MV/LV station, based on the location, there can be 100-250 household connections. Each household is connected to the main LV feeder and is usually rated up to a maximum load current of 100 Amps on 3-phase with each phase not exceeding more than 40 Amps [12]. Therefore, a regular household connection in the Netherlands is rated for 10 kVA on the LV distribution network. The power ratings could vary for some specific installations. In the Netherlands, each household is connected to the main feeder cable through service cables rated at twice the maximum load. The LV (both main and service) cables are generally PVC installations but older cables (OIP) are still under operation in several parts of the Netherlands. The LV network components comprise of underground cables, cable accessories like joints, terminations, feeder (bus-bars), MV/LV substation unit, protection equipment's, etc. For this work, only low voltage cable and its accessories are considered.

1.2.1 LV Underground Power Cables

The LV feeder cables are generally four conductors with an earth screen. The main LV cable is connected to the individual customers via service cables. The diameter of the conductor and insulation differs with the current rating of the cable. Based on the type of insulation material, the LV cables can be classified into different types. The most widely used insulation materials in the Netherlands are Oil Impregnated Paper cable, Polyvinyl Chloride and Cross-linked Polyethylene.

Oil Impregnated Paper (OIP) -In the early ages, most of the LV grid has been using OIP insulated cables. In the Netherlands alone 36% [13] of the LV grid is OIP insulated and are still in operation. Figure 2 provides a clear overview of the different layers in such cables. The paper cellulose is an excellent insulator and along with the oil coating, the cable has high electrical and mechanical properties. Insulation performance of the OIP cables deteriorate gradually and can cause faults due to the electric and thermal stress [14]. One of the disadvantages of OIP is the lead sheath which is provided to prevent any water ingression. Corrosion of the lead could release lead to the environment and underground water. Due to the environmental aspects of lead and introduction of rubber, the OIP is not used for new installations today.

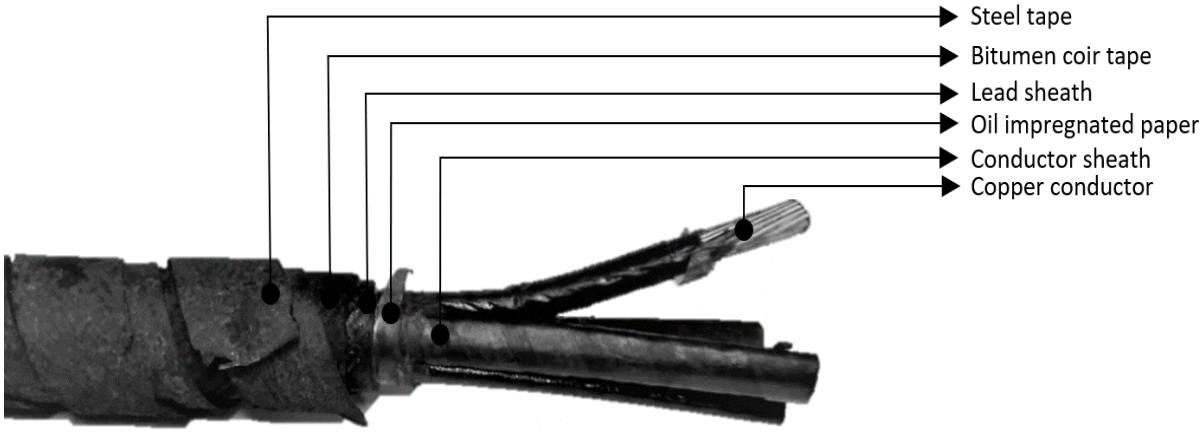


Figure 2 Different Layers of an Oil Impregnated Cable used in the Netherlands

Polyvinyl Chloride (PVC) – is the most widely used thermoplastic insulator in cables. The inexpensive material is durable and robust for low voltage cable insulations. In the Netherlands, most of the LV main cables are PVC insulated with a copper ground screen. The main conductor in the LV cable is aluminium due to its cost-effectiveness. Every LV PVC cable is made up of several layers to prevent the conductors from external impacts and meanwhile to provide flexibility. Each layer serves a different role in the underground cable but primarily to insulate the conductors from each other and between the conductor and the external environment. The main layers of the low voltage PVC cable are listed in Figure 3.

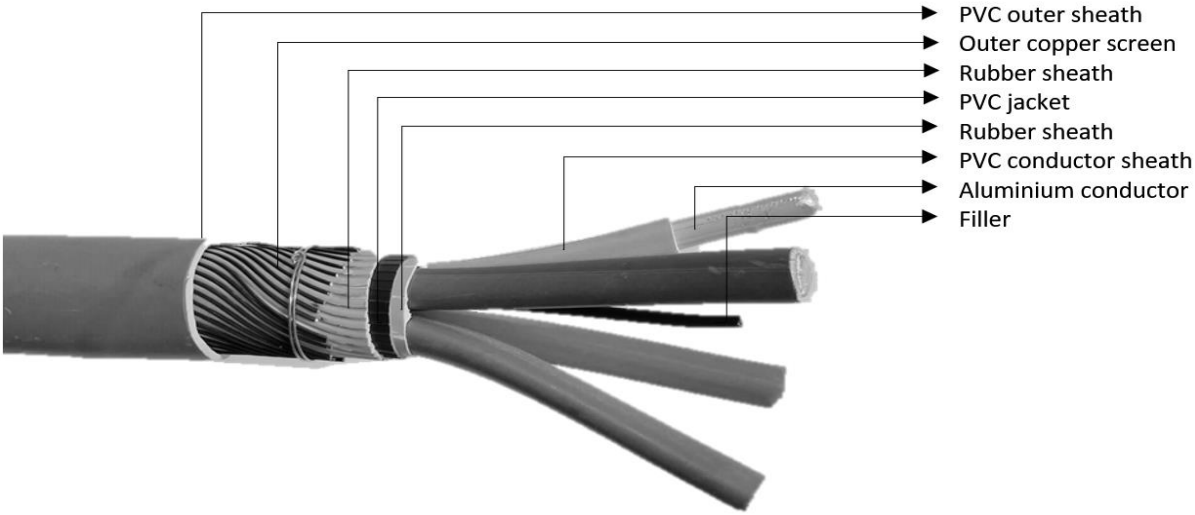


Figure 3 Different layers of a Low Voltage PVC insulated cable used in the Netherlands

Cross-Linked Polyethylene (XLPE) – The XLPE insulated cables overcome the disadvantage of the PVC cables with better mechanical and thermal properties. XLPE is composed of different polyethylene chains cross-linked together which prevent it from separating or melting in high temperatures. XLPE cables such as Figure 4 are not used in the main LV network cable but are used as service cables. In general, the conductor is made up of copper.

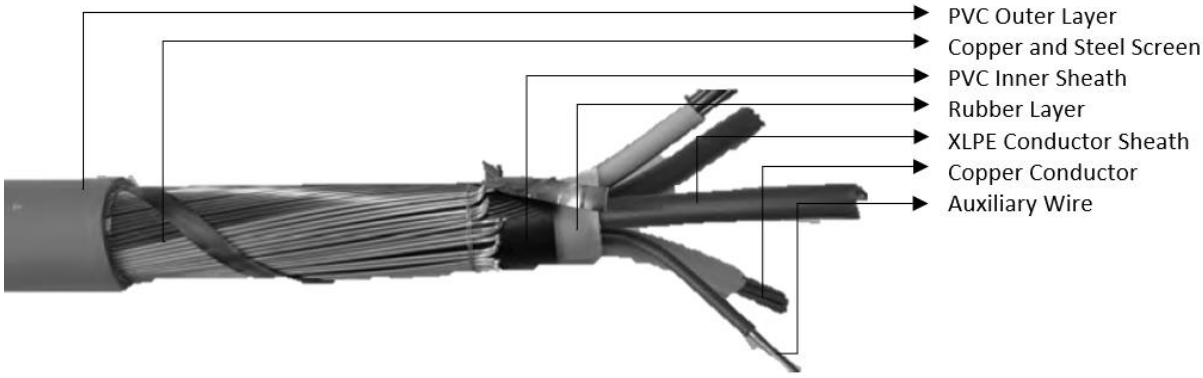


Figure 4 Different Layers of an XLPE Insulated cable used as service connections in the Netherlands [13]

1.2.2 Cable Joints

Service cables are connected to the main cable via joints. The joints are generally bolted connectors (Figure 5) and/or insulation piercing connectors (Figure 6a). In case of old bolted connector joint, a layer of bitumen is added to prevent any damage to the cable. Nowadays the main filling material used in the LV network is Poly-Urethane (PU).

Figure 5 Mass filled joint obtained from an in-service network

Branching Joints (Figure 6) are used here. For making new connections to households, a service cable is connected to the main LV cable using an armour piercing joint. So, the joint can be made when the main LV cable is live. Once the joint is made, a layer of wrapping gauze net and wrap around tape is used to create a shell around the joint. The shell is filled under pressure with a filling PU resin made from mixing two compounds. Straight through joints are seldom used in the LV grid due to the short length of the main LV network.

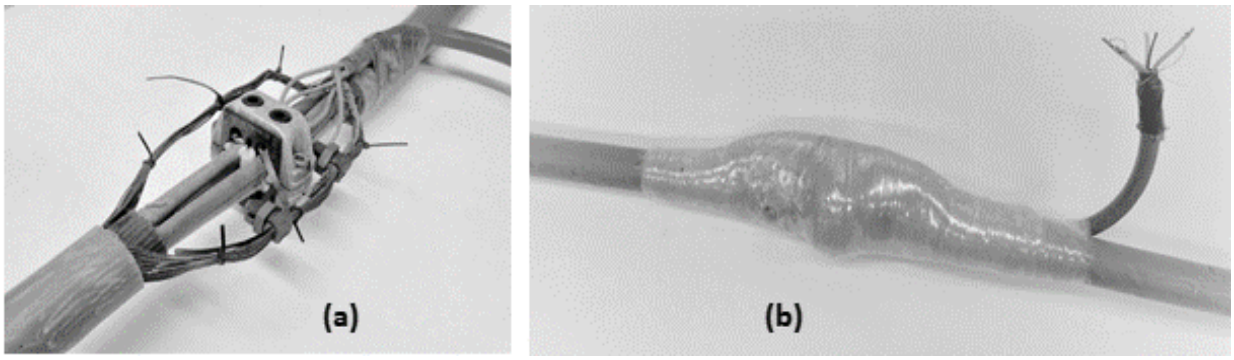


Figure 6 Branching joint before (a) and after (b) moulding

1.3 Degradation in Underground Cables

The degradation of cables in the long term is defined as intrinsic degradation. Different insulating materials have different ageing phenomena. In the case of OIP cables, increased temperature causes increased degradation. The paper in the OIP cables deteriorate with time and can cause a breakdown under higher voltage stress. PVC cables suffer from thermal expansion and degradation occurs in elevated temperatures which are outside the nominal operating temperature of the cable. In XLPE cables, the electrical treeing is the most common factor for degradation and due to the low electric field strength in LV network, a breakdown is relatively low.

In general, the aforementioned causes are applicable to all power cables. In case of LV underground cables, degradation is induced primarily by mechanical impact (which doesn't result in an immediate failure) [13] [15]. The proximity of LV cables to the residential areas has resulted in significant damage due to digging.

1.4 Degradation in Joints

In general, installation mistake is the main cause of degradation in joints which leads to water ingress and corrosion. The loose connections, as a result of poor workmanship, often causes overheating locally. In some cases, a design mistake could also possibly cause degradation in LV cable joints.

1.5 Failure of Low Voltage Networks

Compared to the medium and high voltage networks, the effect of an outage in an LV grid is highly confined to a few numbers of customers. Based on the recent public data [15] available, a conclusion can be drawn for the Dutch low voltage distribution network. Table 1 provides an overview of the total number of failures in the LV network of the Netherlands with respect to their three major causes. Digging is one of the main reasons for a failure in the LV network [15] of the Netherlands. The main and service cables alone contribute to more than 50% of the outages in the LV distribution network. Performance of the PVC cables is better in comparison with the OIP cables, for both main and service type in terms of ageing wear. Joints have contributed to more than 11% [15] of the outage.

Table 1 Number of LV failures per component [15]

Component		**Digging**	**Ageing Wear**	**Internal Defects**
Main Cable	**OIP**	761	458	267
	PVC	1312	183	304
Service Cable	**OIP**	1083	663	179
	PVC	1827	211	294
Joint	**Plastic**	143	347	479
	Mass Filled	84	552	341

Considering ageing and digging causes, it can be said that the LV network is robust when it remains undisturbed. The high failure rates are attributed to the several factors and in a few cases due to (doubtful) intrinsic degradation. The outdated assets still in operation contribute to a less percentage of the network share yet surpass the number of failures from new assets. Many assessment methods for the HV and MV networks may not be applicable to the LV network. The LV network also lacks redundancy in terms of a number and point of connections, which makes it tedious to assess the faults. Distributed generation and new low carbon technologies have increased in the Netherlands at the LV level could aggravate the current problems. The LV interruptions in the year 2017 have increased by 8.1% (refer to Annex), compared to the average for the year 2012 to 2016. Furthermore, a steady increase in this percentage can be seen from the year 2015 which coincides with the growth of renewable energy at the LV level.

The LV network components are a primary part of the proposal to increase the operating voltage in the LV network for additional network capacity. Based on the above-mentioned statistics, a special attention is required on the LV cables and joints currently in service.

Chapter 2. Theory

Partial discharge and dielectric breakdown measurements are well-known methods for MV and HV cable diagnostics. Partial discharge measurements provide a valuable information on the presence of any defect in the cables. PD measurements could be still used to determine the withstand voltage and dielectric condition under higher operating voltage.

2.1 Partial Discharge

Partial Discharges (PD) are electric discharges that occur in the insulation or at interfaces between the conductor and insulation, or at the surface of the cables if the electric field stress is high enough to cause ionization of the medium in which the components are located. Charge transfer is a result of a partial discharge and is measured in pico-coulombs (pC). The LV cables are generally not intended at partial discharge free operation since the voltage required for PD inception is highly unlikely to occur under normal operation. The LV cables used in power plants are sometimes subjected to such type testing. Such tests reveal the presence of any defects, which are imperative to perform maintenance on low voltage control cables used in critical applications [16].

Partial discharges originate in different discharge types such as

(i) internal discharges occurring in voids or cavities within a solid or liquid dielectric insulation medium.

(ii) surface discharges at the boundaries of the insulation medium and

(iii) continuous impact of discharges leading to discharge channels or treeing or corona discharge [17].

The characteristic of the PD can also be determined by the type of the insulating material and operating conditions such as applied voltage, load and time. According to IEC 60270 standard for PD measurements, PD's are initiated at a voltage called partial discharge inception voltage (PDIV). The applied voltage at which repetitive PD's cease to occur when the voltage is gradually decreased from the PDIV is called Partial Discharge Extinction Voltage (PDEV). Therefore, Partial Discharge Extinction Voltage (PDEV) is always lower than Partial discharge inception voltage (PDIV). Partial discharge inception voltage can be affected by the rate of rise (of the applied voltage), whereas Partial Discharge extinction voltage can be affected by the amplitude and time of voltage application and also by the rate of decrease of voltage.

2.1.1 Partial Discharge Initiation for a Cavity at AC Voltage

It is also necessary to understand the principle behind a partial discharge phenomenon. Imagine a cavity (with capacitance C_c) as given in Figure 7 within an insulating medium. For a given equivalent electrical circuit, the cavity is in series with a capacitance of the insulation medium C_b under the influence of applied high voltage stress (V_a) and C_a is the capacitance of the rest of the medium. Increasing the applied voltage (V_a) causes an increase in voltage across the cavity (V_c) and upon reaching the maximum voltage breakdown strength of the gap (V^+), a discharge occurs and V_c collapses. A current impulse (i) is recorded whenever a discharge occurs. The same theory is applicable to the negative half cycle of the applied voltage. For an increasing value of the applied high voltage AC across the cavity, the first discharges will appear at the rising slope of the half cycle which can also be witnessed in Figure 7 [18]. As a result, PD clusters are observed at the rising slopes of the sinusoidal waveform. Hence, a single defect or cavity results in multiple discharges during the positive and negative cycle (of the applied AC sinusoidal waveform) for increasing and decreasing voltage respectively. In general, PD's can occur without leading to a direct breakdown. Some PD sources can continue to exist for many years without causing a breakdown. When a PD causes gradual erosion of the walls within the cavity, it is very well possible that as a result, an electric tree grows within the insulating medium. Consecutive cycles of discharges may eventually lead to the bridging between the conductors causing an electric breakdown.

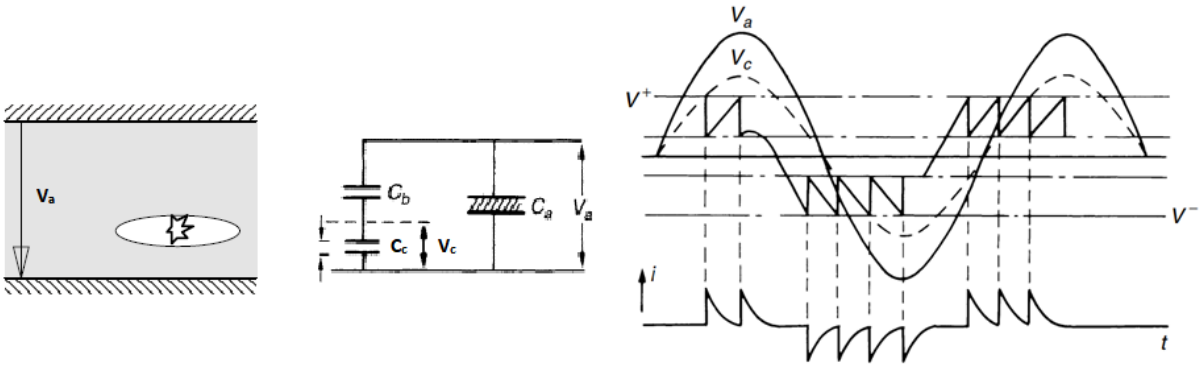


Figure 7 Equivalent circuit and sequence of a cavity breakdown under AC voltage [18]

The PD inception voltage is affected by the shape of the cavity/defect and composition of the filling gas. Closer to the conductor, the partial discharge inception voltage is lower (for a similar cavity further away from the conductor) because of the higher electrical stress near the conductor. In case of internal defects (cavity), voltage pulses have a pulse width of a few nanoseconds. Whereas, surface discharges have a pulse width in tens of nanoseconds. Cables in general act as transmission channels for such high-frequency signals and cause signal attenuation in long cables as a result of losses in the dielectric medium. This significantly reduces the pulse amplitude as a function of distance propagated (especially for the higher frequency content of partial discharge pulses), in turn limiting the detection bandwidth to 300 kHz for PILC and PVC cables [19].

2.1.2 Phase Resolved Partial Discharge (PRPD) Mapping

PD's can occur throughout the length of the cable, also in joints and other accessories (terminations, etc.). There is a necessity to identify the type/source of the discharge occurring

in the length of the cable and classify them according to “dangerous” or “harmless” PD or noise. Time-domain method and Phase Resolved Partial Discharge pattern recognition are the two methods to identify the source of the discharge. Rest of the discharges are too small to be observed in the off-field environments in short cable samples. Therefore, PRPD pattern is suitable in this thesis to identify the type of PD within the sample. A Phase Resolved Partial Discharge (PRPD) pattern is an illustration of a PD activity relative to the applied sinusoidal AC waveform in the frequency domain. It can be used to differentiate a source of the partial discharge from unwanted noise. The phase-resolved patterns also provide a description of the source of a discharge in conjunction with the test environment. Figure 8 provides a picture of the typical phase resolved patterns. Yet, no single PD classification database currently exists and in particular for low voltage distribution cables. The different sources of discharge observed in Figure 8 is an interpretation from previous experiments. The location of the void within the insulation is another important factor to analyze the PRPD pattern. For example, if a void located in the middle of the test medium would give rise to a discharge symmetrical at positive and negative half cycles.

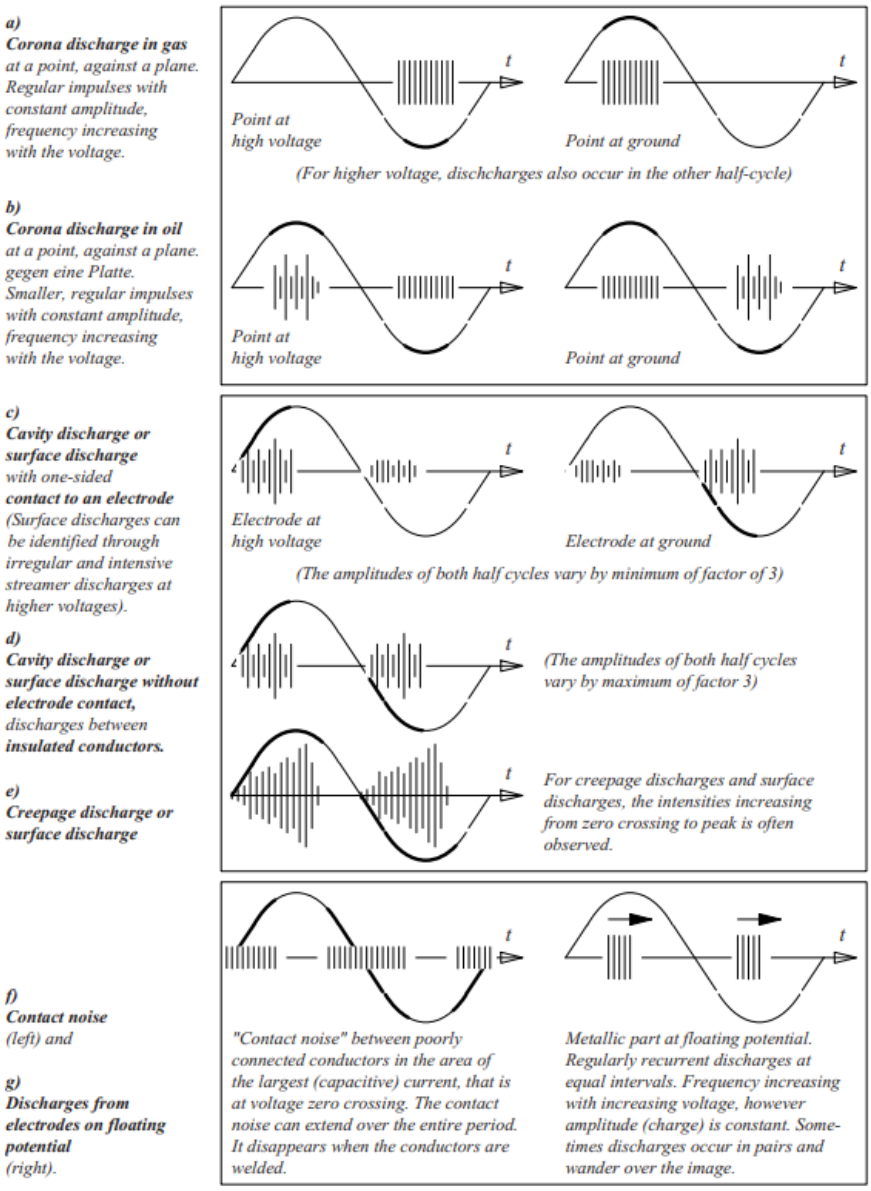


Figure 8 PRPD pattern recognition in different environments for different discharges [20]

To eliminate the effect of external (and unwanted) corona discharge (**a** and **b** in Figure 8), care should be taken to make terminations smooth and installing corona rings (if applicable). The contact between high voltage hook-up wire and the test sample can be made free of contact noise (**f** in Figure 8) by bolting the contacts with each other and wrapping a layer of semi-conductive tape. Background noise and HV source noise are briefly discussed in Chapter 3.5. Apart from the aforementioned patterns, a distinct pattern known as "rabbit ear" pattern exists, as shown in Figure 9. These patterns are a result of surface discharges and are observed in HV cables, transformers and Gas Insulated Switchgear systems. Such rabbit ear patterns are observed on top of other surface discharges (surface discharges **c** and **d** in Figure 8) in a PRPD diagram but sometimes might be overlapped in test samples of shorter lengths.

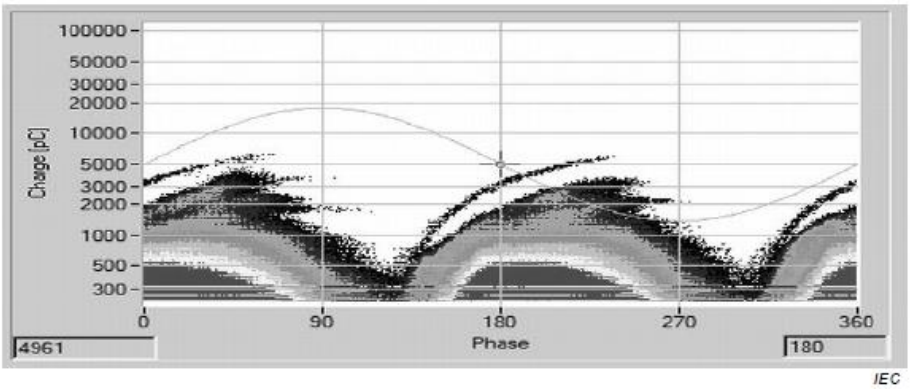


Figure 9 IEC 60270 High Voltage Testing Techniques - Partial Discharge Measurements PRPD Rabbit Ear Pattern

2.2 Dielectric Strength in Solid Insulating Materials

A dielectric strength test is one of the main acceptance tests to be performed by the manufacturer. In solid insulating materials, a dielectric failure occurs when the conductance of the material under test increases beyond a certain limit. The material loses its property of non-conductance (insulation) temporarily or permanently. This is termed as a dielectric breakdown and the potential at which the test material suffers a failure is known as breakdown voltage. It is usually measured in kV/mm and depends on various factors for an individual material. The primary focus of this thesis is to identify if the voltage stress on the LV cable can be increased without suffering a dielectric breakdown.

The thickness of the insulation, impurities, testing medium, temperature of the test object, duration of the test and type of electrodes are some of the few factors which influence the dielectric strength of the test material.

Chapter 3. Experimental

A test setup needs to be realized to pick up a PD pulse and interpret it using the PRPD pattern mentioned in the previous chapter. The IEC 60270 is a standard test procedure for the measurement of partial discharges in electrical components at power frequencies. The standard provides a detailed layout of the test setup and defines the quantities to be measured. So, the layout specified under the test circuits of the IEC 60270 standard has been adopted in this study.

3.1 Working Principle and Test Setup

A simplified working principle of an (off-line testing) PD detection circuit is illustrated in Figure 10. The sample under test is considered to have a defect which could give rise to a PD signal. If a discharge occurs from the test sample due to the applied high voltage, the voltage across the sample suffers a voltage drop proportional to the PD pulse charge. To compensate for this drop, the coupling capacitor in parallel to the test sample delivers the equivalent charge voltage experienced due to the drop. This, in turn, creates a low impedance path for the high-frequency PD pulse signals. Therefore, a coupling capacitor provides a means of detecting the PD pulse and reproduces as a voltage signal to be sent to the detection unit. Coupling capacitors also block the power frequency signal (50Hz) and permit high-frequency PD signals. For the high-frequency PD signal, a current signal is sent to the measuring impedance which converts it to a PD voltage signal. The detection unit has a PD input measurement which is capable to pick up this PD voltage signal. In addition to the measuring impedance, a blocking impedance is added before the coupling capacitor to avoid any noise from the High Voltage source from reaching the detector and to avoid that a breakdown of the test object will cause a too high short circuit current. In addition to this, filters can be added to prevent any background noise in the system.

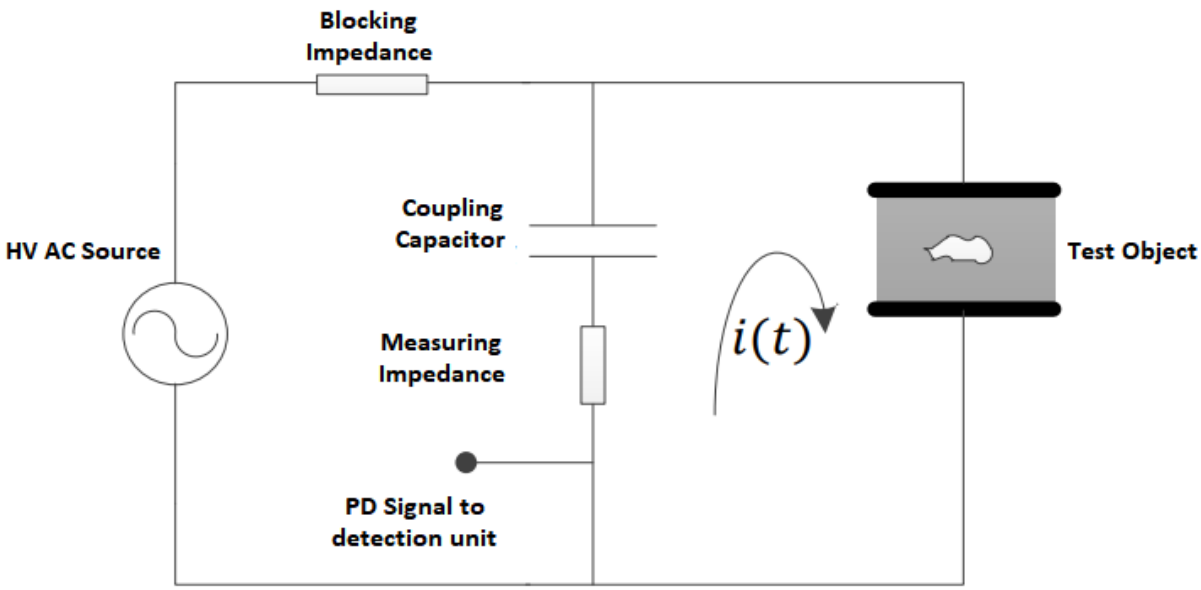


Figure 10 Partial Discharge Measurement Circuit - Working Principle

A detailed schematic of the actual setup is given in Figure 11. The detection unit is an Omicron MPD 600 PD measurement unit with a frequency range of 0 kHz - 20 MHz. The MPD 600 unit is a partial discharge acquisition and analysis tool used to detect, record and analyze PD events. The MPD 600 unit is limited with a voltage signal (up to 10 V_{rms}) input for measuring the test voltage applied to the test sample. A voltage divider made up of two resistors – R1 (10 MΩ) and R2 (16 kΩ) with a division ratio of (R1/R2) 625 is used to measure the high voltage applied to the test sample. The high voltage transformer (T2) in the test setup is rated 30 kV which is PD free up to 23 kV. It is limited by a current rating of 61 mA. By using an auto-variac (T1) located outside the test cage at a safe distance, and a transformer ratio ($\frac{T_2}{T_1}$) of 136.36, it is possible to control the high voltage source inside the HV test cage. A fiber optic cable runs from the MPD 600 unit to a microcontroller unit (MCU) which is also located outside the HV test cage. An additional protection using 1 A fuse (S1) is provided to enable safe PD and breakdown testing. Since the test setup is used for PD measurements, internal discharge values should be lower than 5 pC threshold [21].

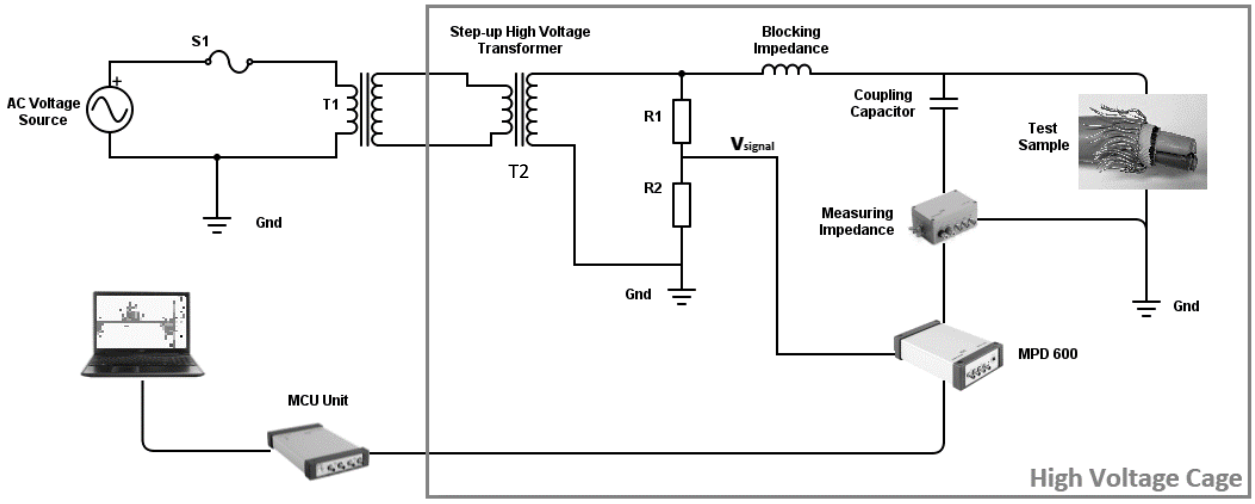


Figure 11 Schematic representation of the test setup

3.2 Choice of Mid-band frequency and bandwidth

Due to the limitation of the length of the cable sample, the frequency domain is used to analyze the PD pulses. The mid-band frequency and bandwidth by default on Omicron MPD 600 unit are f_{center} = 250 KHz and △f= 300 KHz (IEC 60270 compliant) respectively. But, this mid-band frequency and bandwidth are relatively low for general PD measurements in short power cables. Since, the samples used in this study are 1 to 3 meters in length which makes it harder to differentiate the PD pulse from the reflection. Pulse resolution time is the shortest time interval between two consecutive input pulses of very short duration, with the same shape, polarity and charge for which peak value of the resulting response will not change more than 10% for a single pulse [22]. It is also inversely proportional to the bandwidth △f and an indication of the ability of the system to measure successive events. Therefore, wider bandwidth results in shorter pulse resolution time (Figure 12 provides a comparison of Narrow and Wide bandwidth pulse resolution). For wide bandwidths, pulse resolution is generally given around <10 µs. Since IEC standard bandwidths are smaller, leading to longer pulse resolution time, wider bandwidths were used (with f_{center} = 3 MHz and △f= 300 KHz).

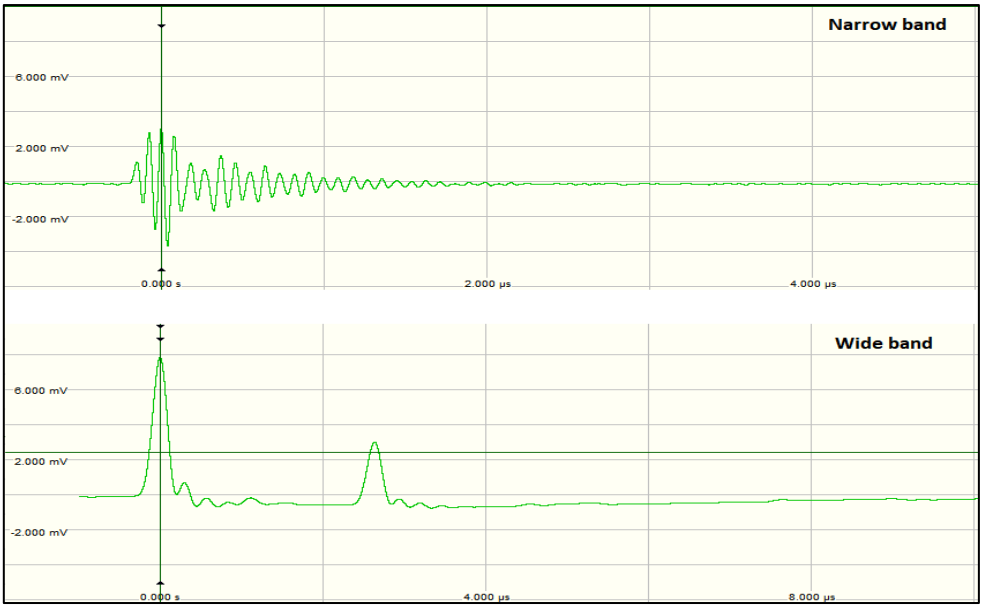


Figure 12 Time response of a PD pulse in Narrowband and Wideband

3.3 Calibration of the Test Setup

Before performing any measurements using the MPD unit, the test setup needs to be calibrated. The calibration is performed before applying the high voltage. A PD calibrator CAL1 from PD Diagnostix is used for this test setup. The positive lead is connected to the test setup's high voltage line and negative lead is common grounded. Initially, a positive charge pulse of 0.2 nC is applied to the test setup. The MPD unit automatically detects this test pulse applied to the setup and the system is calibrated according to the IEC 60270 standards by default. If the measured value is different from the applied charge of 0.2 nC, the unit can be manually calibrated. The mid-band frequency and bandwidth (center frequency and delta f respectively) can be changed later.

3.4 Standard Test Procedure

A combination of IEC 60270 and ASTM International standard D 149 is used as the general test procedure for this work. The Omicron MPD 600 unit is factory calibrated to align with the IEC 60270 standard. But, a standard test procedure is required which has not been considered in the IEC standard. Therefore, the ASTM D 149 standard test method for dielectric breakdown voltage and strength of solid insulating materials at power frequencies is adopted as a standard test procedure. Some general requirements of the standard are also adopted, such as maximum current rating of 40 mA and test power of 0.5 KVA. The tests are carried out at 50 Hz frequency and the voltage applied is from zero or from a specific initial voltage specified under one of the following test methods. Three different types of voltage application methods are described in the ASTM D 149 standard: Short Time Test, Step-by-Step Test and Slow rate of rise test. Short time test is used for quality control testing. Step-by-Step and Slow rate of rise tests are generally used to compare the test results between different test materials and produce results comparable to each other. The slow rate of rise method is the preferred procedure here due to its simplicity over the step-by-step method [23].

3.4.1 Slow Rate of Rise Test

Normally, the initial voltage for a slow rate of rise test is given by the initial voltage used in the step-by-step test. The initial voltage is fixed here to 230 V by the auto-variac (T1 from Figure 11). While performing the PD testing, if the breakdown occurs less than 1.5 times or more than 2.5 times the initial voltage, the initial voltage was reduced or increased respectively. The applied voltage to the test specimen is gradually increased until a value at which the first discharge is observed (V_{PDIV}). The voltage is then reduced gradually until the extinction voltage (V_{PDEV}) of the partial discharge can be measured. After the VPDEV is logged, the applied voltage is increased to 20% above the V_{PDEV}, provided no partial discharge pulses are observed, the cable is considered to have passed the partial discharge test. Figure 13 provides an overview of a slow rate of rise test performed in this study. Generally, a step-by-step test is performed later to approximate the average rate for a slow rate of rise test.

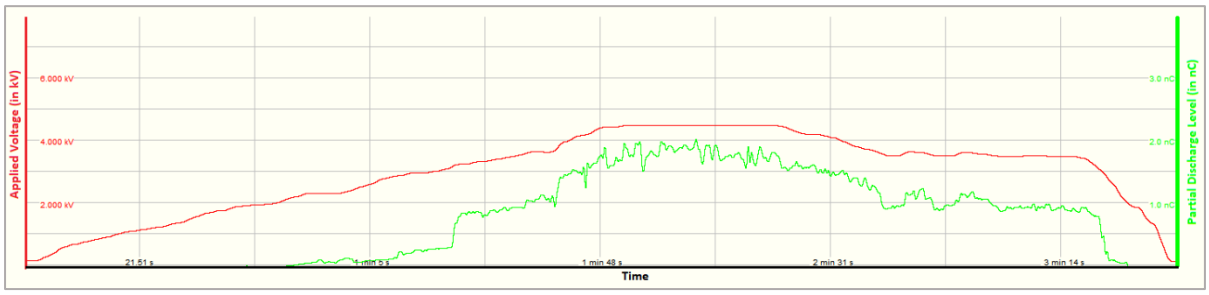


Figure 13 Slow rate of rise

The partial discharge inception voltage is observed when the magnitude of the PD pulse equals or exceeds the threshold value. This threshold value differs for each individual compound. For example, 100 pC could be dangerous for certain materials but for others may not affect its performance. Very little knowledge currently exists for determining this threshold in low voltage cables, especially used in LV power distribution. But it is necessary that the measured values need to be higher than the background noise and internal noise of the test setup. Some research [17][24][25] indicate this value could be 10 pC for Ethylene Propylene Rubber (EPR) power cables and hundreds of pC for laminated OIP cables. Therefore, two thresholds for this study have been considered; 10 pC and 1000 pC (or 1 nC).

3.5 Disturbances

Disturbances often occur in the system and could exist even if the circuit is not energized. Several factors like the switching loads in the lab (where the test cell is located), internal noise of the measuring unit and other radio interference from nearby circuits occur. Although the test was carried out in a laboratory environment, care was taken to avoid any switching operation of loads (machines). The internal system noise is <15 fC which is well below the PD threshold limit of 10 pC.

Generally, measuring PD in cables can have various sources of disturbances. The PD threshold in the "Omicron Software for MPD and MI" can be varied according to the user's requirement. For initial recordings, PD threshold was set to 10 pC for various testing methods. Moreover, the addition of bipolar sensitivity in the recordings prevented any such disturbances.

3.5.1 Background Noise and Air Corona Discharge

Initial tests performed on the samples yielded results which had significant background noise and air corona discharges, higher than the threshold limit. To make sure the HV source is PD free, the sample is removed from the test setup and a test with the hook-up wires and contact terminations were performed. The results obtained in Figure 14 had corona activity (indicated by the black box in Figure 14) and the inception voltage was around 15 kV originating from the end terminations of the high voltage hook-up wires. The background noise can be witnessed in Figure 14 and Figure 15 is marked with a red box. The noise value of 5 pC observed were well below the threshold limit of 10pC (along the y-axis).

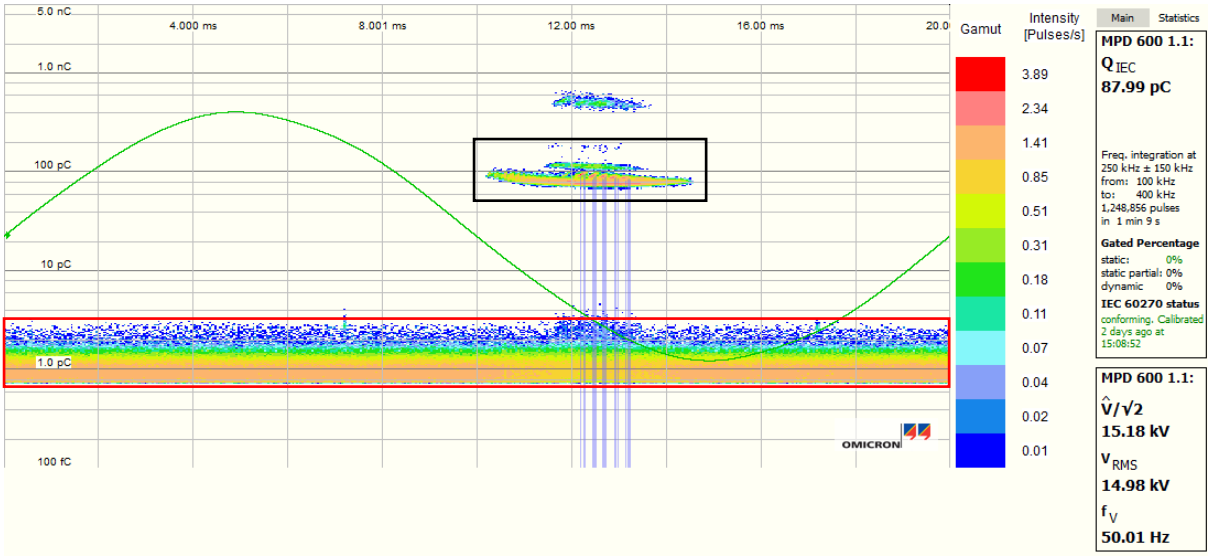


Figure 14 PRPD pattern of air corona for a suspended conductor

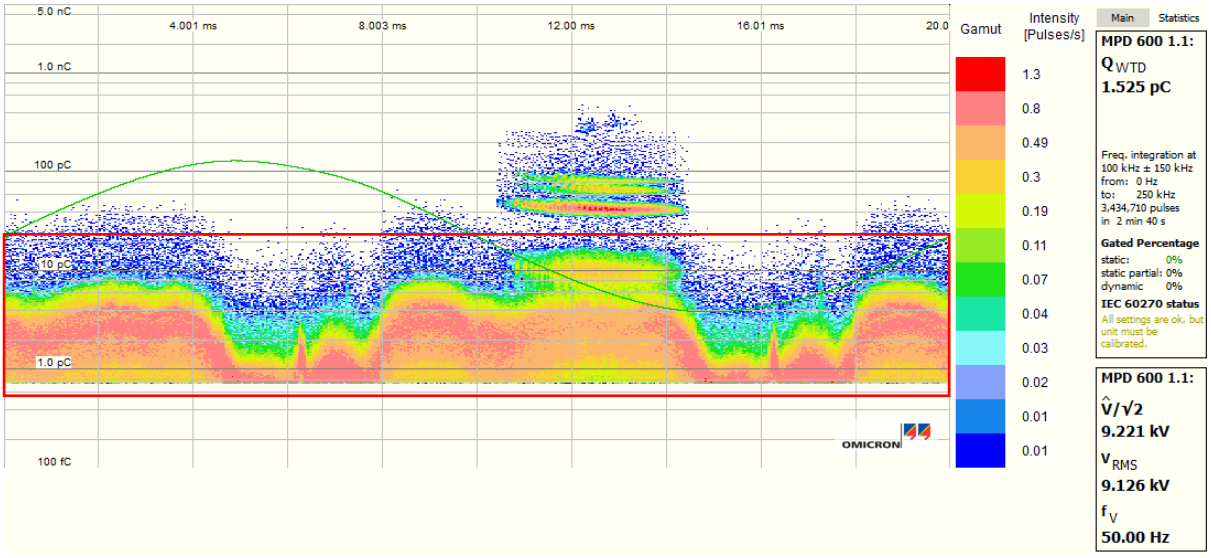


Figure 15 PRPD pattern of background noise at low bandwidth

As per the IEC 60270 standard for PD measurements [22], the disturbance values didn't exceed 50% of the maximum permissible PD magnitude applicable for the estimated highest test voltage. Yet, measures were taken (rounding off sharp edges and avoiding large loops) to avoid any corona discharge. It was ensured that the contact between the high voltage hook-up wire and the test sample was good to prevent any air corona at high test voltages. This was accomplished by increasing the contact area of the two surfaces, by the surface mounting of the hook-up wire directly on the test sample (conductor) using through-hole screws.

Overall, the system was able to maintain a low background noise level below 5 pC and well below the threshold limit of 10 pC. Due to the comparison between different insulating materials and different components, a standard threshold limit needs to be applicable to this study. The threshold limits were set at two different levels; lower limit of 10 pC and higher limit of 1nC charge. Tests were performed with both threshold limits for all test samples. A 3-Mhz Mid-frequency for the measurements with a bandwidth of 300 KHz or ±150 KHz was used to detect the PD signals. Phase Resolved Partial Discharge (PRPD) pattern recognition was used to recognize the PD discharges from the samples. Although, it should be noted that the pattern recognition might not be accurate at all times due to the limited knowledge available on the LV cables.

3.5.2 Air Corona Discharge at the Terminations

Terminations in the samples were terminated similarly to the terminations observed in the actual network. The LV terminations are generally simple and not made to withstand high voltages. For test voltages above 6.5 kV to the sample, air corona started to produce background noise in the recordings. Sharp edges and bolting points (coupling with hook-up wire) started to produce air-corona pulses combined with audible sound. Visual electric arc took place between the energized conductor and adjacent grounded conductors at even higher voltages. Contact discharges (as described in Figure 8) was observed in the initial tests, which was later prevented by enabling better contact between the conductors and terminating with semi-conductive tapes. Therefore, increasing the voltage above PDIV eventually lead to a breakdown and terminations could also contribute to it.

Chapter 4. Experimental Results and Discussion

In this chapter, the results obtained from the partial discharge and breakdown testing will be discussed. The tests were performed on LV underground cables obtained from various sources. As mentioned in Chapter 1.2.1, different types of LV distribution cables are used in the Netherlands.

4.1 Test Samples

For the purpose of this study, both main and service cables of the LV distribution network have been considered with different insulation materials. The PVC insulated LV cables of two different cross-sections; 16 sq. mm and 95 sq. mm is used to portray the service and main cable respectively. The service cable has an XLPE insulation material with a mixture of copper and steel screen wire. The PVC and XLPE insulated cables are not service aged and were manufactured in the year 2013. A service aged OIP insulated paper cable of 1.5 meters in length have also been included in this study. The OIP cables have been obtained from the LV network in the Netherlands and the amount of information available on these cables is limited. All the LV cable samples have a 0.6/1 kV standard voltage rating. A detailed description of the LV distribution cable samples used in this study is tabulated under Table 2.

Table 2 LV distribution cable samples used in this study

Type of Insulation	Cross-section	Length of the sample	Description
XLPE Insulated	16 sq. mm	1 meter	4 core conductors with a Copper and steel screen wire
PVC Insulated	95 sq. mm	1 and 3 meters	4 core conductors with an S-shaped copper screen
OIP Insulated	35 sq. mm	1.5 meters	4 core conductors with a layer of the lead sheath cover

Tests were also performed on LV joints; a branching joint and a mass filled joint, typically found in the Dutch LV network. The branching joint was obtained naked without any outer shell or protective covering as observed in Figure 6a. Therefore, a taped resin injection joint as seen in Figure 16 was made to carry out the tests on the sample. The mass filled LV joint from Figure 5 was obtained from the local network operator (Alliander B.V). Test samples were prepared before the test could be performed. The conductor ends were terminated to connect the high voltage hook-up wire. The non-energized conductors were terminated with the ground circuit. A layer of semi-conductive tape as seen in Figure 17 was used to cover the terminations, as it helps to reduce the air corona discharges.

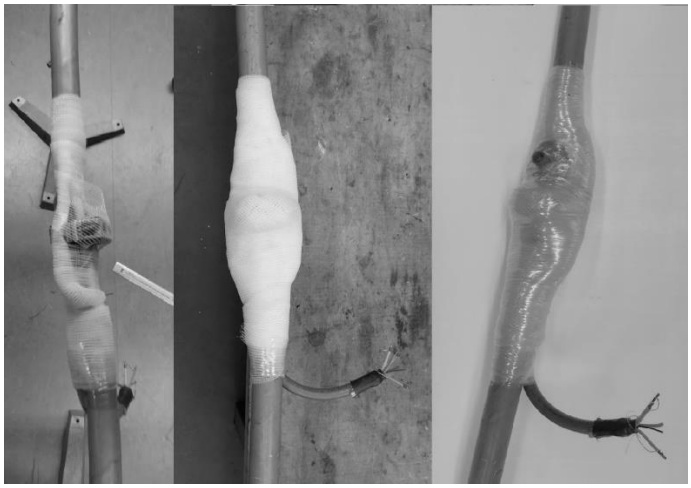


Figure 16 Procedure to manufacture an LV Taped Resin Injection Branching Joint

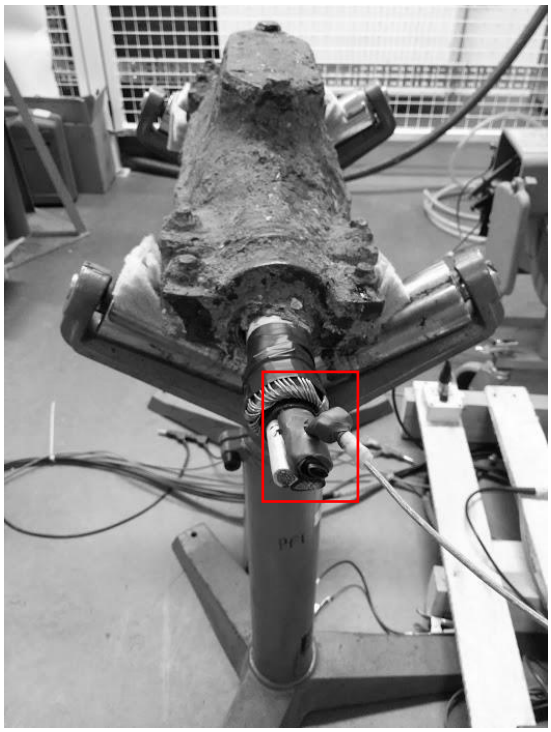


Figure 17 A semi-conductive taped termination connecting the test sample and HV hook-up wire

4.2 Inference

The results obtained from the partial discharge tests at two different thresholds; 10 pC and 1 nC have been tabulated in Table 3 and Table 4 respectively. It is evident that setting higher threshold limits cause higher PD inception and extinction voltage. The difference between the PD inception and extinction voltage varied across the samples, ranging from few tens of volts to 1 kV. Consecutive testing on the same sample resulted in lower PDIV which is an indication of partial discharges formed from the previous tests. Throughout the test, necessary caution was taken to prevent the influence of external noise or factors. Any switching noise due to the equipment's in the test environment was removed.

Table 3 Partial discharge observed at 10 pC threshold

Sample Type	PDIV (KV)	PDEV (KV)	f_{center} + bandwidth	Sample Code
16 sq.mm	4.069	3.021	3 MHz ± 150 KHz	A
95 sq. mm – 1-meter length	2.411	1.98	3 MHz ± 150 KHz	B
95 sq. mm – 3-meter length	1.831	0.966	3 MHz ± 150 KHz	C
95 sq. mm – with a branching joint	1.58	1.54	3 MHz ± 150 KHz	D
35 sq. mm - OIP Sample 1	1.604	1.232	3 MHz ± 150 KHz	E
Mass filled joint	3.073	2.8	3 MHz ± 150 KHz	F

Table 4 Partial discharge observed at 1 nC threshold

Sample Type	PDIV (kV)	PDEV (kV)	f_{center} + bandwidth	Sample Code
16 sq.mm	5.323	4.996	3 MHz ± 150 KHz	A
95 sq. mm – 1-meter length	7.047	5.869	3 MHz ± 150 KHz	B
95 sq. mm – 3-meter length	5.051	4.331	3 MHz ± 150 KHz	C
95 sq. mm – with a branching joint	3.64	3.53	3 MHz ± 150 KHz	D
35 sq. mm - OIP Sample 1	4.114	3.921	3 MHz ± 150 KHz	E
Mass filled joint 1	6.05	5.791	3 MHz ± 150 KHz	F

After the partial discharge measurements, the samples were subjected to dielectric breakdown testing. All the samples were able to hold up to several kilovolts without suffering a breakdown with an exception for sample C which suffered a breakdown at a voltage of 8.886 kV. The rest of the samples led to the overloading of the high voltage source leading to a shutdown. Therefore, the results from the dielectric breakdown tests in LV cables is limited. The Table 5 provides an overview of the different maximum withstand voltages observed.

Table 5 Maximum withstand voltage observed in the different samples

Sample Code	Sample Type	Breakdown Voltage (in kV)
A	**16 sq.mm**	>10.15
B	**95 sq. mm – 1-meter length**	>9.434
C	**95 sq. mm – 3-meter length**	8.886
D	**95 sq. mm – with a joint**	>7.882
E	**OIP Sample 1**	>8.048
F	**Mass filled joint**	>8.45

The PD charge value during these peak breakdown voltages was in several thousands of pC, which need to be taken into consideration. The normal operation of LV cables with such high PD charge (pC) could eventually lead to a breakdown.

A detailed trend comparison for the PD inception, extinction and breakdown voltage between the various samples tested has been made in Figure 18 and Figure 19. Usually, devices must be dimensioned for operating voltage well below the partial discharge extinction voltage [18]. In this way, any partial discharges incepted by temporary overvoltage's will be extinguished under normal operating conditions. The PDEV or partial discharge extinction voltage is therefore considered to be the main parameter for this study. From Figure 18, it can be observed that the lowest PDEV for 10 pC threshold was observed for a 95 sq. mm PVC cable sample (3 meters in length). The sample is considered to be an oddity due to its individual test results. The next closest PDEV was 1.232 kV observed in a service aged OIP paper cable. Rest of the samples had PDEV above 1.5 kV, especially the joints outperforming the cable samples. The XLPE insulated 16 sq.mm service cable had the highest PDEV voltage of 3 kV and highest withstand voltage of 10.15 kV. This is obvious due to the excellent dielectric properties of the cross-linked polyethylene.

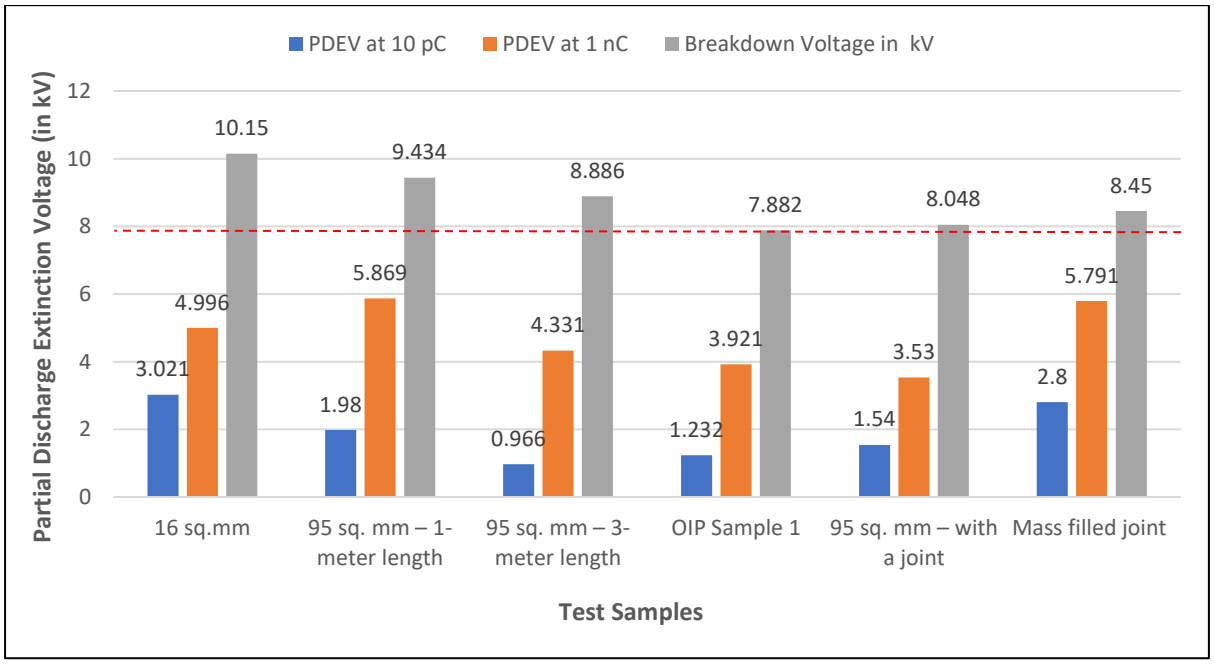


Figure 18 Partial Discharge Extinction Voltage observed in different samples

The results with respect to the PD inception voltage given in Figure 19 were not much different from the PDEV comparison. The main difference was observed in the OIP cable and the PVC based joint. Both samples have a PDIV of 1.6 kV, lower than the 95 sq. mm PVC cable sample (3 meters in length). Even the lowest value recorded is approximately three times higher than the nominal operating voltage for a service aged cable and joints. Though the results look promising, additional measurements on different LV cables and accessories, including service aged samples, are required to get a comprehensive set of data.

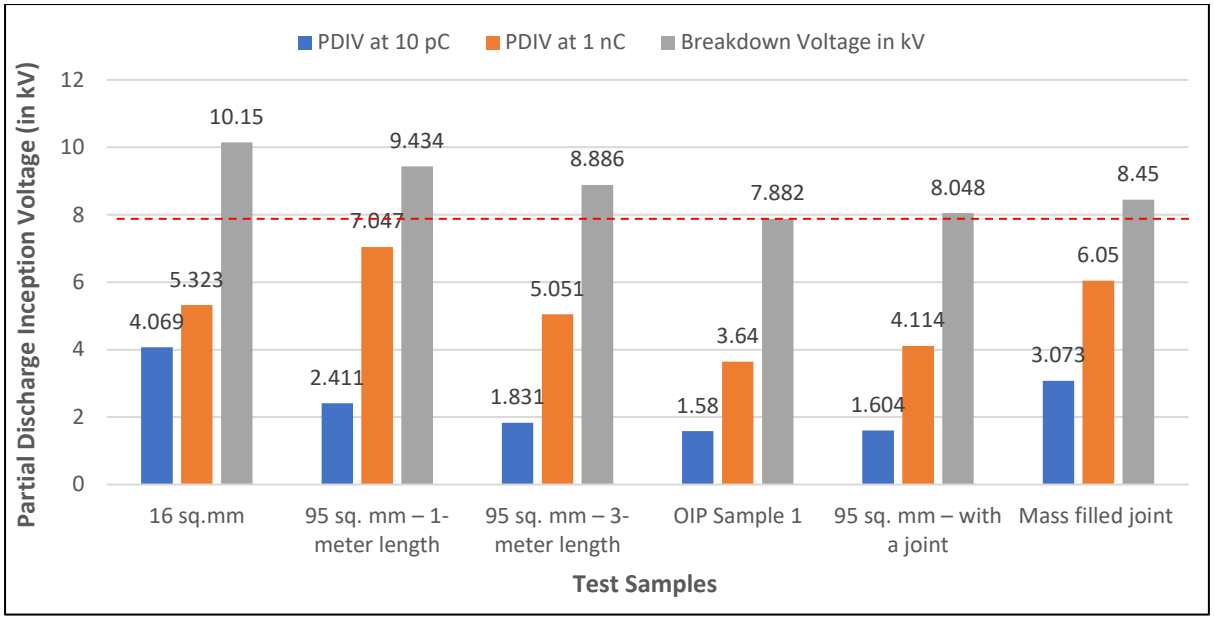


Figure 19 Partial Discharge Inception Voltage observed in different samples

4.2.1 PRPD Pattern – Surface Discharge

The distinct strokes of the PD pulses observed during the measurements are called as rabbit ear patterns. This could be cross verified with Figure 9 (Refer Chapter 2.1.2) from the IEC 60270 (Standard for High Voltage test techniques – Partial Discharge measurements) and previous literature work [26] on power cable testing. The rabbit ear patterns are a result of the surface discharges of the test sample. Generally, the discharges are clustered to the rising slope or zero crossing of the sinusoidal AC source. The discharges start from the rising slope of the sinusoidal waveform and end before the peak. Unlike the long cables in the actual LV network, the test samples used are very short in length which made them vulnerable to high reflections and tedious to differentiate from the main pulse. Sometimes in PRPD patterns, multiple events can overlap leading to the loss of identifying the defect. In case of the Omicron MPD/MI interface, the overlapping is denoted by a wide colour gamut from Green to Red (low to high) density respectively. As the measuring impedance unit is connected in series with the coupling capacitor, the positive pulse is inverted [27]. To detect the polarity of the events and their absolute charge, the bipolar mode is enabled [28]. Therefore, we get a complete cosine function including the negative discharge pulses (Figure 20, Figure 21, Figure 22 – have bipolar mode enabled).

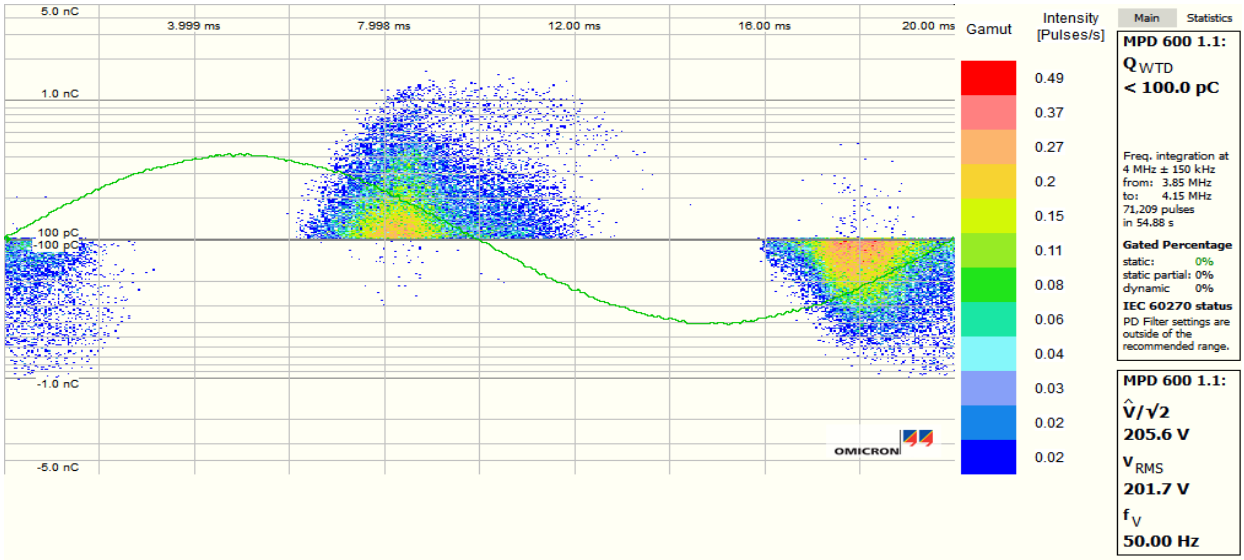


Figure 20 PRPD pattern observed in sample A

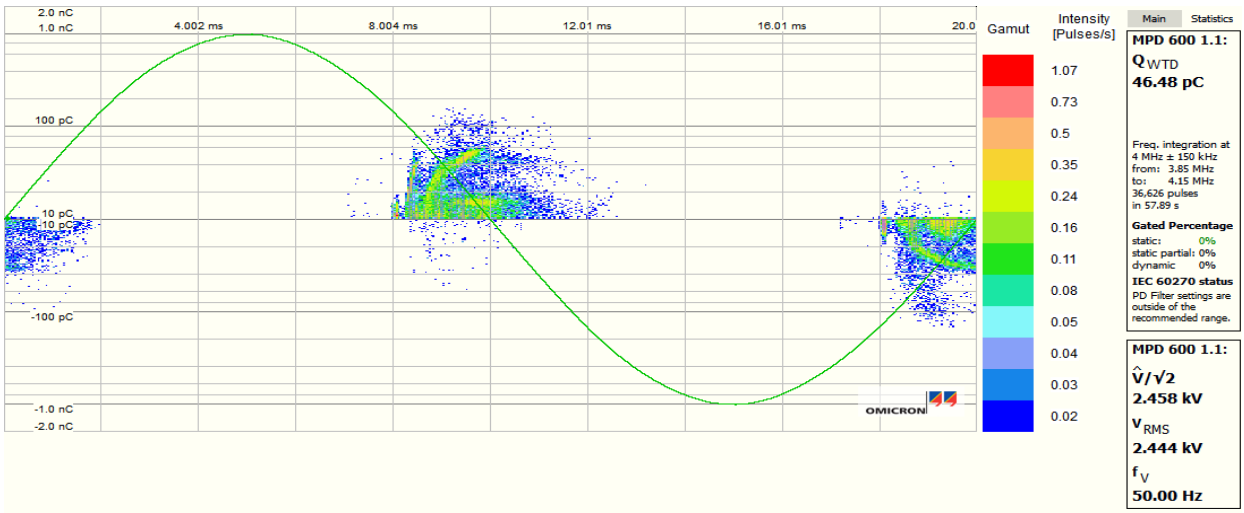


Figure 21 PRPD pattern observed in sample D

4.2.2 Internal Voids

In Figure 22, the PRPD pattern clearly indicates the presence of an internal void within the test sample. The clusters (marked in the red box) indicate the concentration of the PD pulse as a result of an internal defect present in the sample. Additionally, the figure also indicates the presence of a PD absolute charge at the negative phase sequence. It is to be noted that the PRPD patterns found in the figures cannot be associated with a particular void type of a given cable and might produce different patterns during the course of its lifetime [29].

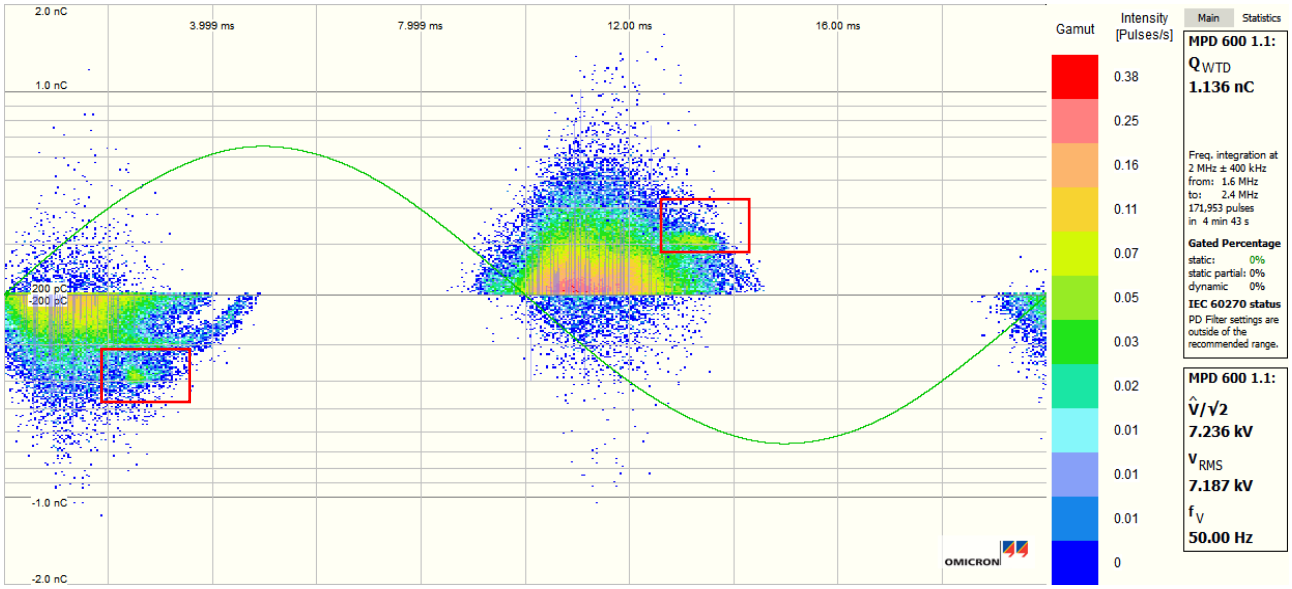


Figure 22 PRPD pattern observed in sample E

4.2.3 Discharge Investigation

The 95 sq. mm PVC cable sample (3 meters in length) suffered a breakdown at 8.886 kV with a PD absolute charge of 5.098 nC. The cable was hot when removed from the test setup. A detailed power failure investigation revealed the point of electrical discharge on the innermost rubber layer (refer to Figure 23) and the insulation covering of the energized conductor (refer to Figure 24). The PRPD pattern obtained from the MPD unit also supports the hypothesis of a void discharge which eventually led to a breakdown. Electrical trees or any other form of discharge were not observed during the investigation in the immediate layers of the cable. Yet, the layers turned brittle which is evident from the heat radiating from the sample post testing period.

Figure 23 Source of PD inception observed in the rubber layer of the cable C

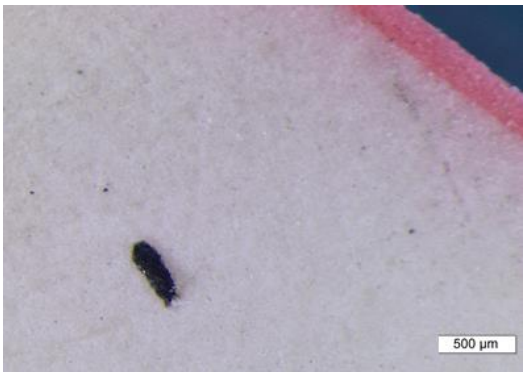


Figure 24 Source of the PD activity within the insulation covering the energized conductor of cable C

4.2.4 Thermal Aspects

The samples lost flexibility (increased brittleness) after performing the measurements. The typical PVC cables have high conductivity and by the basic conductance model, power loss is directly proportional to the square of the voltage. Therefore, a significant value of degradation is expected under such high voltages. For example, samples were warm up to 15 minutes after the measurements were taken. So, there is possibility of higher degradation due to the application of high voltage through the LV cables. The increased brittleness of the cable can be related to the evaporation of the plasticizers from the cable jackets [30]. Thermal aspect of high voltages should also be considered as an important parameter in this proposal.

Chapter 5. LV Distribution Transformers

In the previous chapters, a brief study on the impact of the high voltage on LV underground cables has been discussed. This chapter analyzes the various technologies which could step-up and step-down the voltage in the distribution network. Irrespective of the voltage, the customer at the end point of connection consumes power at 230 V AC supply (based on single or three phase connection). Therefore, the voltage distribution network needs to supply at this rated voltage. This can be achieved through the installation of various step-up and down units, which are collectively owned by the DNO.

5.1 Step-up unit

The MV/LV station which is generally located in a public location and used to step-down the Medium Voltage to Low Voltage for distribution. Instead of 230 V or 400 V on the LV side, the voltage is raised up (Step-up) using the On-Load Tap Changer or using an external transformer for the rated voltage. The cost of one such unit (1 kV – 630 kVA Three-coil distribution transformer 20/1.0/0.4 kV) is around €10500 Euros.

5.2 Step-down unit

At the customer's point of connection, voltage is step-down to 230 V (or 400 V) and called as the step-down unit. In order to install this converter at every point of connection, various parameters have to be considered. These include cost, reliability, availability, impact on the customer and specifications. A comparison has been made based on these parameters and tabulated in Table 6. The general power capacity of each connection is rated at 10 kVA.

Table 6 Comparison of various AC/AC step-down units

Unit	Easy to Procure	Reliable	Availability at 10 kVA Rating	Impact of Size on the Customer	Cost per kVA
SiC-based MOSFET unit	No	Yes	Yes	Minimum	€285
AC/AC Matrix converter	Yes	Yes	Yes	Minimum	€432
Tunnel Transformers	Yes	Yes	Yes	High	€569
Conventional Transformers	Yes	Yes	Yes	High	€ 213

A traditional approach is a back to back converter with a DC link bus. The main advantage of such a system is a bi-directional flow of power with low harmonic distortions at power frequencies. The topology includes a combination of a full bridge rectifier in series with an inverter circuit. In-between the two circuits, a DC link such as a power capacitor is used. Although, the circuit lacks a common neutral bus which limits its application for this proposal.

Both, step-up and step-down units need to handle the bi-directional flow of electricity. Based on different technologies available and considering the aforementioned constraints, the following solutions have been briefly discussed.

5.2.1 Silicon Carbide (SiC) based MOSFET AC Chopper

Silicon Carbide (SiC) based MOSFET technology has been recently used in solar inverters which could achieve 30% less switching losses at 1700 V rating. This exceeds the performance of the current IGBT technologies. A similar unit [31] of 6.1 KW output power achieved a peak efficiency of 95% with a high volumetric power density of 5.0 kW/L. One of the main advantages of power electronic based units is power quality improvement due to better gate control and handling symmetrical short circuit fault. A lot of research work has been published in the past for adapting power electronic based distribution transformers.

5.2.2 AC/AC Matrix converter

The AC/AC direct matrix converters provide control of voltage magnitude and variable frequency. Some of the advantages of these units include supplying unity power factor to most demanding loads, bidirectional power flow, frequency control (higher than the source frequency) and simple – compact design. Unlike a back to back AC-DC-AC converter, matrix converters lack DC link bus or any additional capacitive filters for energy storage. But, matrix converters require additional semiconducting devices when compared to the traditional back to back converter. In addition, due to its niche application, matrix converters are generally expensive per kVA rating.

5.2.3 Tunnel Transformers

In confined spaces such as underground tunnels, power distribution over long distances generally employ a special type of transformers called tunnel transformers as seen in Figure 25. Such transformers are generally dry type and fire retardant in nature which come in compact form factors suitable for residential applications. The only disadvantage of such units is the initial investment for the entire network. Due to the limited number of suppliers combined with a low demand, tunnel transformers are the most expensive units per kVA. Although, the losses due to the conventional 400 V units are much higher than the 1 kV distribution units. A typical feeder length of 1 km using a tunnel transformer rated at 30 kVA requires 25 mm² cables (cross-section) whereas a 400 V line requires 150 mm² cables. Therefore, the overall voltage drop at the customer's point of connection is also reduced due to the higher voltage.

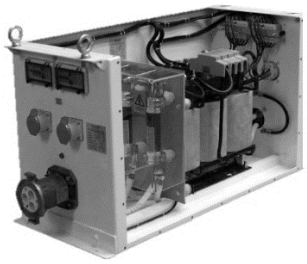


Figure 25 Tunnel transformer 3.3/0.4 kV - 35 KVA

5.2.4 Conventional Distribution Transformers

The main difference between a commercial distribution transformer and a step-down unit for our proposal is the power rating (kVA). Commercially, 50, 100, 150 or higher ratings are preferred for the public installations. Some lower power rating transformers are bespoke units based on the customer's requirements and for private installations. In general, conventional transformers are bulky and have higher power ratings, which has an increased impact on the customer's household. One major advantage of installing step-down transformers is the cost per kVA. Therefore, one unit could connect multiple households bringing the cost further down. The units are also ideal for rural distribution feeders where the number of connections is minimum and at much longer lengths. Suur-Savon Sähkö distribution Company (SSS Ltd.) in Finland used such transformers to renew their medium voltage network using 1 kV distribution network.

5.3 Summary

To step-down the voltage at every point of connection, several factors have been considered. Most of the solutions include currently available or proven technologies. Some solutions can be purchased from Original Equipment Manufacturers (OEM) and others are bespoke (customer specific) solutions. A detailed cost comparison of the technology reveals that traditional transformers are the best option for the DNO's. But, in comparison with the impact on the end customer, through the installation of large transformers in households would be impractical. The next closest solution is to manufacture silicon carbide-based MOSFET units through third party vendors. Since the solution can be implemented along with the smart meter units and cost effective per KVA rating, SiC MOSFET units would be the effective solution in the long run. The technology is also fairly new, and costs are expected to decline with additional manufacturers entering into this field. The ability to include a DC bus in the step-down unit can also be attractive to future low carbon energy technologies. Most of the low power appliances require a DC source and electric vehicle chargers could be replaced with the same DC bus. The concept of the vehicle to grid using EV could be implemented using the semi-conducting voltage control units. The additional benefits of using SiC MOSFET is the implementation of power quality regulation in every household. The power generation from renewable energy technologies is known for its intermittency. Therefore, the application of semiconductor devices at the connections enable a fair control of the power injected into the network. A detailed cost breakdown of the various 1/0.4 kV distribution transformers can be found in [32]. The requirement of protection systems can also be integrated into one single unit at a reduced cost.

Chapter 6. Conclusions and Recommendations

6.1 Conclusion

The growing demand for sustainable energy will pose a significant challenge towards a reliable LV distribution network in the future. Additional network capacity is required to meet this demand and investing in new networks is not financially sustainable. An alternate solution to the energy dilemma is by increasing the operating voltage of the existing LV distribution network in the Netherlands. LV underground cables and its accessories play a significant role when the voltage in the LV network is increased. In this study, experiments on LV cables and joints for different materials found in the Dutch LV network have provided a better insight into the implications of higher operating voltages in the existing LV network. The test results indicate that for Partial discharge inception voltage (PDIV) at 10 pC threshold for the cable with and without a joint were found to be at least 3 times the nominal operating voltage. The results based on the threshold of the PD charge (1 nC) were significantly higher than the lower threshold of the PD charge (10 pC). However, such high PD charges are deemed hazardous for both type of materials; PVC and OIP, which could eventually lead to an immediate breakdown. Phase Resolved Partial Discharge (PRPD) patterns have facilitated to distinguish the source of the discharge originated from the test sample. The patterns observed include the presence of internal voids, especially in joints and service aged OIP cables. Surface discharges was observed in case of both old and new cables through PD clusters and a distinct rabbit ear pattern respectively. Overall, at higher test voltages the patterns intensify indicating the influence of high voltage in LV components. This is an indication of degradation being enhanced by the applied voltage.

The samples were also able to withstand voltages beyond 8 kV and this differs for each individual test material. One possible explanation is that components are designed for a basic insulation level several times higher than the nominal operating voltage. Cross-linked polyethylene-based service cables had a better performance overall in comparison with other test materials. It should also be noted that the conductor material used in the XLPE based service cables are copper. So, the service cables shouldn't be a bottleneck to the realization of the high voltage distribution system. The same applies to the joints in the Dutch LV distribution network. The Joints had significantly high withstand voltages, on par with the PVC and service aged OIP samples. Even a service aged mass filled joint obtained from the present-day Dutch LV network observed high PD inception voltage. Statistics obtained on the Dutch LV network also point to the small contribution of a joint related failure. A comparison of the two different types of joint, Poly Urethane and mass filled, cannot be predicted due to the limited set of samples available. Additional measurements need to be performed in the future on these materials.

Therefore, it is now conclusive, the feasibility to increase the operating voltage in the low voltage distribution network does exist. The LV network capacity can be increased by adopting a higher voltage for LV distribution. It was observed that the LV cables are capable to handle operating voltages higher than 7.8 kV. But, the long-term impact of such high voltage still remains unclear.

To step-down the voltage back to the distribution level, the most suitable solution recommended here is silicon carbide-based MOSFET converter units. Apart from compact design and higher power capacities, the role of power electronics in the power quality management enable better integration of the low carbon technologies. One of the challenges of the project is to contemplate the infrastructure required to implement the solution in an existing distribution network. This includes various primary and secondary components such as higher rating transformers on the MV/LV substation and step-down transformers or solid-state converters (SST) at the customer's point of connection. Figure 26 provides a general overview of the solution proposed in this thesis work. The MV/LV transformer at the entrance of the LV feeder is set to a tap setting higher than the conventional 400 V AC supply. The AC/AC Silicon Carbide based converters are installed at every household to step-down the voltage to the nominal operating level. Some of the components such as protection systems need to be retrofitted in the LV feeder to provide an additional electric insulation against the high voltage in the LV feeder. However, the low voltage distribution network components are cost-effective; cheaper to design and for production.

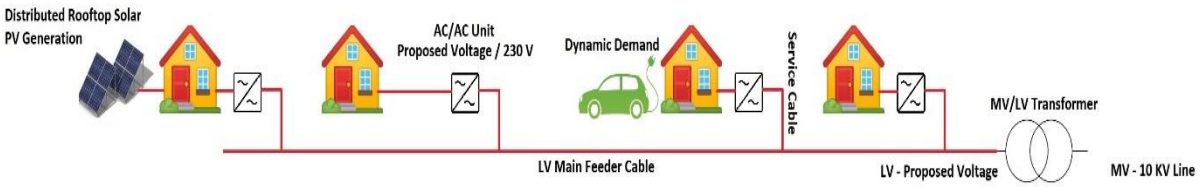


Figure 26 A general overview of the proposed solution

In comparison with urban distribution networks, rural networks run longer and supply lighter loads with high intermittency. Network operators often experience flicker and safety issues in rural networks which often requires reinforcements. A recent report from the Dutch Network Management agency revealed the importance of the rural networks, which experience more than 26% in power quality variations compared to the 13% in urban areas. Addition of solar PV and EV chargers might aggravate the existing problem. The risk can be mitigated through the adoption of the high voltage distribution network at the LV level. The step-down units can also be bulky as it could supply more than one customer and installed effortlessly in rural areas. Further advantages include a reduction in distribution network losses and long-term planning of the rural network to support additional demand.

6.2 Recommendations for Future Work

The main objective of this thesis is focussed on increasing the LV network capacity by increasing the operating voltage of the existing LV network. Although the impact of such a proposal on the existing Dutch LV network is analyzed (and the results are promising), the measurements are too limited to conclude on adopting this proposal. The tests were performed on a selective number of samples which is quite limited information regarding the LV network. More research on the LV cables needs to be conducted especially using service aged cables which are also longer in lengths. The measurements should also consider the factor of degradation initiated by the HVDS. Therefore, the tests should be performed on an extended time frame which provides a better insight into the actual impact on the assets.

Localization of the discharge on the joint or terminations would be interesting towards the utility perspective. This would enable which component in the network would require a replacement to support the HVDS. Evaluation of the impact of HVDS on the rural networks could provide a pilot study for obtaining practical implementation in urban areas. This could also include a practical experience obtained from the Finnish three voltage model. The AC/AC step-down unit on its own requires an extensive research. Realizing an actual AC/AC converter at the low voltage level could make this application more attractive. The possibility to include the smart metering in the voltage control unit could bring down the cost of the overall unit and reduce the impact on the end user.

Bibliography

[1] M. Cavlovic, “Challenges of optimizing the integration of distributed generation into the distribution network,” in *8th International Conference on the European Energy Market (EEM)*, pp. 419–426, 2011.

[2] C. B. voor de Statisiek, “Hernieuwbare elektriciteit: productie en vermogen,” 2018. [Online].Available:https://opendata.cbs.nl/statline/CBS/nl/dataset/82610NED/table.

[3] S. Cobben, “Course on ‘Power Quality Phenomena,’” Eindhoven, 2017.

[4] G. A. Hazelrigg, R. B. Adler, and W. G. Kirn, “Higher Voltage Distribution and Utilization Systems--Benefits and Problems,” *IEEE Trans. Power Appar. Syst.*, vol. PAS-101, no. 6, pp. 1679–1688, Jun. 1982.

[5] L. Ramesh, M. Madhusudhanaraju, S. P. Chowdhury, and S. Chowdhury, “Voltage Profile Improvement through High Voltage,” *Second Int. Conf. Sustain. Energy Intell. Syst.*, no. Seiscon, pp. 468–473, 2011.

[6] J. Lohjala, T. Kaipia, J. Lassila, and J. Partanen, “Experiences of using the 1 kV three phase supply in rural electricity distribution,” *Pap. Present. Annu. Conf. - Rural Electr. Power Conf.*, pp. 1–6, 2006.

[7] J. Lohjala, T. Kaipia, J. Lassila, J. Partanen, and P. Jarventausta, “Potentiality and effects of the 1 kV low voltage distribution system,” *Int. Conf. Futur. Power Syst.*, pp. 1–6, 2005.

[8] J. Lohjala, “Development of rural area electricity distribution system - potentiality of using 1000 v supply voltage,” Lappeenranta Univ. of Tech., Lappeenranta, Finland, 2005.

[9] J. P. J. Lohjala, T. Kaipia, J. Lassila, “Overview to economical efficiency of 1000 V low voltage distribution systems,” *Proc. 6th Nord. Conf. Espoo*, 2004.

[10] J. Lassila, S. Honkapuro, K. Salovaara, and J. Partanen, “Profitable or not-A method to study network investment in the new regulation environment,” no. April, 2015.

[11] Netbeheer Nederland, “Betrouwbaarheid van elektriciteitsnetten in Nederland,” 2016.

[12] AusNet Services, “Distribution Connection Policy,” 2017.

[13] Bart Kruizinga, “Low Voltage Underground Power Cable Systems: Degradation Mechanisms and the Path to Diagnostics,” Eindhoven University of Technology, 2017.

[14] J. Zhou *et al.*, “Electrical Conduction of Aged Oil Impregnated Paper,” no. Icdl, pp. 17–20, 2017.

[15] Netbeheer Nederland, “‘Betrouwbaarheid van elektriciteitsnetten in Nederland-ENGLISH,’” 2017.

[16] J. P. Steiner and F. D. Martzloff, “Partial discharges in low-voltage cables,” *IEEE Int. Symp. Electr. Insul.*, 1990.

[17] IEEE Standards, “IEEE Guide for Partial Discharge Testing of Shielded Power Cable Systems in a Field Environment,” 2007.

[18] E. Kuffel, W. S. Zaengl, and J. Kuffel, *High Voltage Engineering, Fundamentals*, vol. 1, no. c. 2001.

[19] S. Boggs and J. Densley, “Fundamentals of partial discharge in the context of field cable testing,” *IEEE Electr. Insul. Mag.*, vol. 16, no. 5, pp. 13–18, 2000.

[20] A. Küchler, “Electric Strength,” in *High Voltage Engineering*, Berlin, Heidelberg: Springer Berlin Heidelberg, p. 259, 2018.

[21] William A. Thue, *Electrical Power Cable Engineering : Second: Edition*, Second Edi. New York: Taylor & Francis, 1999.
[22] D. Kind, K. Feser, and D. Kind, *IEC 60270 High-voltage test techniques*, 3.1., 2015.
[23] ASTM Standards Association, "ASTM D 149," Pennsylvania, United States of America, 2004.
[24] E. Gulski *et al.*, "On-site testing and PD diagnosis of high voltage power cables," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 15, no. 6, pp. 1691–1700, 2008.
[25] "Medium Voltage Cable Defects Revealed by Off-Line Partial Discharge Testing at Power Frequency."
[26] E. A. Morris and W. H. Siew, "A comparison of AC and DC partial discharge activity in polymeric cable insulation," in *IEEE 21st International Conference on Pulsed Power (PPC)*, pp. 1–4, 2017.
[27] M. G. Niasar and H. Edin, "Corona in oil as a function of geometry, temperature and humidity," in *Annual Report Conference on Electrical Insulation and Dielectic Phenomena*, pp. 1–4, 2010.
[28] Omicron, "MPD 600 User Manual." p. 254, 2011.
[29] F. Gutfleisch and L. Niemeyer, "Measurement and simulation of PD in epoxy voids," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 2, no. 5, pp. 729–743, 1995.
[30] G. M. Csányi, Z. Á. Tamus, and Á. Varga, "Impact of Distributed Generation on the Thermal Ageing of Low Voltage Distribution Cables," Springer, Cham, pp. 251–258, 2017.
[31] B. Whitaker, "A High-Density, High-Efficiency, Isolated On-Board Vehicle Battery Charger Utilizing Silicon Carbide Power Devices," *IEEE Trans. Power Electron.*, vol. 29, no. 5, pp. 2606–2617, May 2014.
[32] J. Lohjala, T. Kaipia, J. Lassila, and J. Partanen, "The three voltage level distribution using the 1000 V low voltage system," in *18th International Conference and Exhibition on Electricity Distribution (CIRED 2005)*, vol. 2005, pp. v5-17-v5-17, 2005.

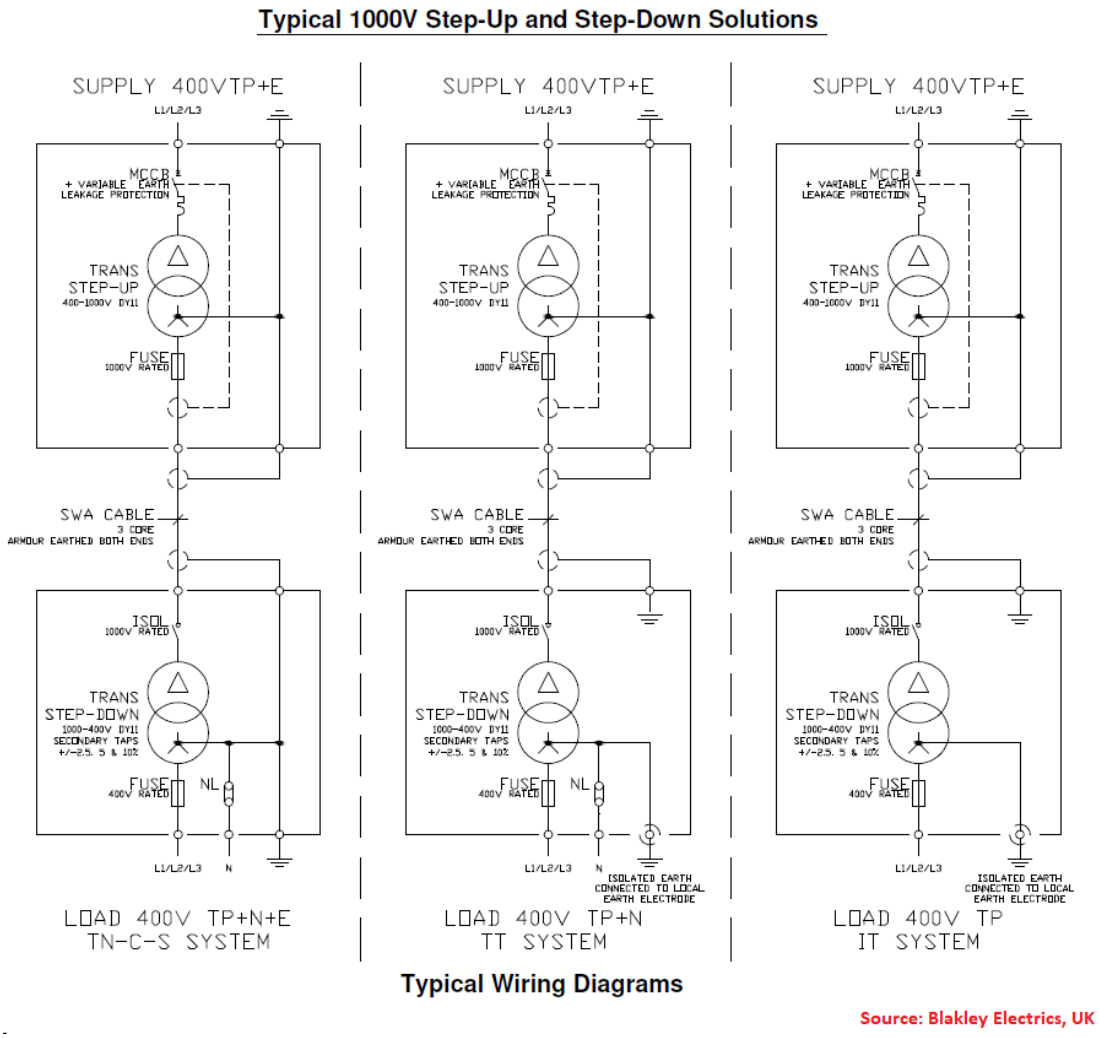
Annexe

QUALITY INDICATOR	2017	AVERAGE 2012-2016	DIFFERENCE 2017 COMPARED TO 2012-2016
INTERRUPTIONS	**20,193**	**18,943**	6.6%
EHS NET	0	1.0	**-**
HS NET	27	32	**-15.1%**
MS NET	1,783	1,908	**-6.6%**
LS NET	18,383	17,002	**8.1%**
AFFECTED CUSTOMERS PER BREAK	**115**	**138**	-17.1%
EHS NET	0	202,650	**-**
HS NET	29,822	16,224	**83.8%**
MS NET	658	824	**-20.1%**
LS NET	18	19	**-6.0%**
GEM. BREAK TIME [MIN]	88.3	**77.2**	14.4%
EHS NET	0.0	98.5	**-**
HS NET	87.0	26.8	**224.6%**
MS NET	72.8	74.4	**-2.3%**
LS NET	146.2	157.2	**-7.0%**
ANNUAL FAILURE PERIOD [MIN/YEAR]	**24.4**	**24.8**	-1.7%
EHS NET	0.0	2.4	**-**
HS NET	8.4	1.7	**392.1%**
MS NET	10.2	14.3	**-29.1%**
LS NET	5.8	6.3	**-8.2%**
BREAK FREQUENCY [NUMBER/YEAR]	**0.276**	**0.322**	-14.1%
EHS NET	0.000	0.025	**-**
HS NET	0.097	0.064	**51.6%**
MS NET	0.140	0.193	**-27.4%**
LS NET	**0.040**	**0.040**	**-1.3%**

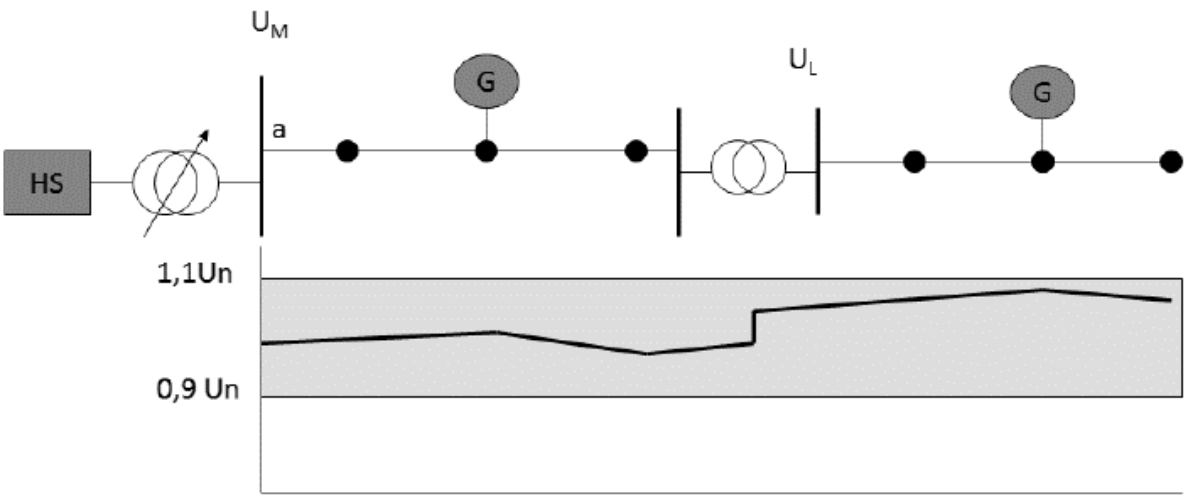
Source 1 Quality indicators for unforeseen interruptions in the Netherlands [15]

Investointimääriä		2016	2017
Ilmajohtoja	110 kV	12 km	9 km
	20 kV	112 km	67 km
	1 kV	16 km	16 km
	0,4 kV	43 km	50 km
Maa- ja vesikaapelia	20 kV	134 km	253 km
	1 kV	96 km	146 km
	0,4 kV	336 km	480 km
Muuntamoita	Muuntajakoneita	451 kpl	524 kpl
	Pylväsmuuntamoita	104 kpl	92 kpl
	Puistomuuntamoita	217 kpl	376 kpl
	Haaroituskaappeja	883 kpl	169 kpl
	Jakokaappeja	968 kpl	2 146 kpl
1 kV järjestelmiä	Emomuuntamoita	53 kpl	96 kpl
	joissa 1/0,4 kV muuntamoita	110 kpl	165 kpl
Investoinnit yhteensä		39 679 673 €	47 268 612 €

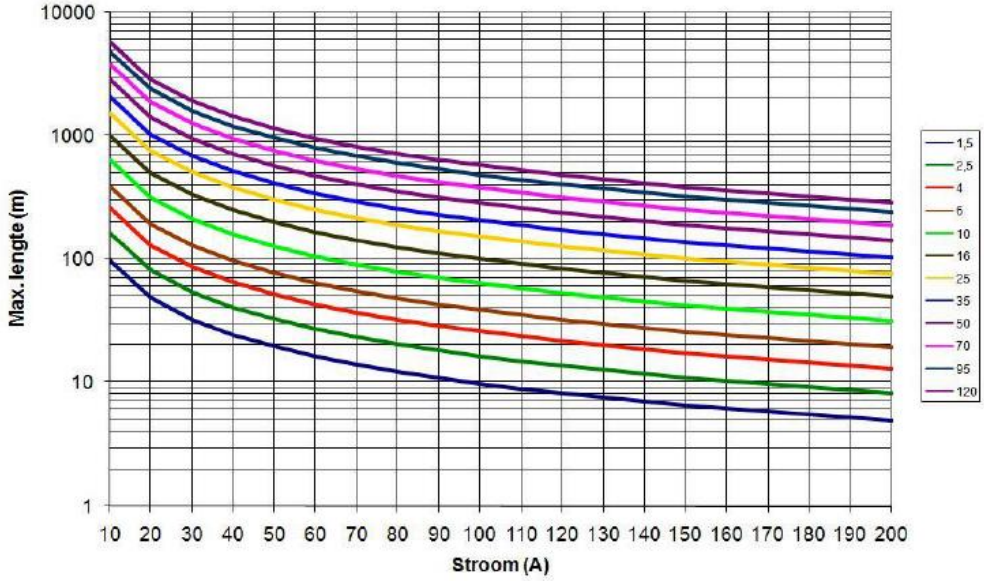
Source 2 Suur-Savon Sähkö, Finland



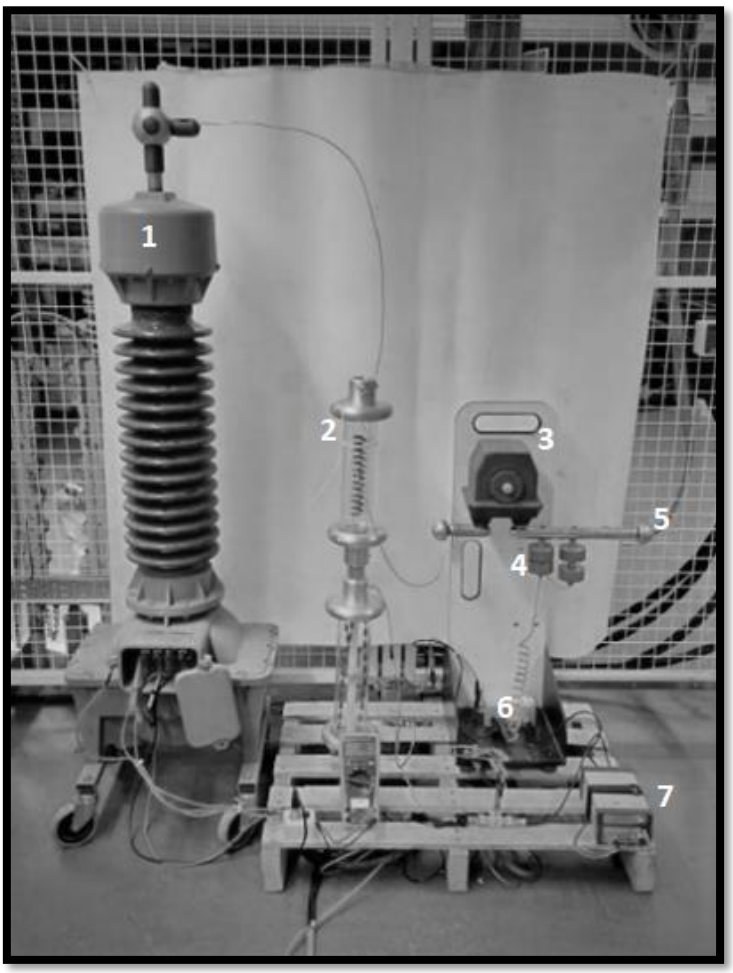
Source 3 Blakley Electrics, United Kingdom



Source 4 Impact of decentralized power generation on the voltage profile (Un – Nominal Voltage) [3]



Source 5 Voltage losses in LV cables [3]



Source 6 Experimental test setup (1) HV Transformer (2) Voltage Divider (3) Blocking Impedance (4) Coupling Capacitor (5) HV hook-up end (6) Measuring Impedance (7) Omicron MPD 600 Unit

Technische Universiteit
Eindhoven
University of Technology

Declaration concerning the TU/e Code of Scientific Conduct

I have read the TU/e Code of Scientific Conduct[i].

In carrying out research, design and educational activities, I shall observe the five central values of scientific integrity, namely: trustworthiness, intellectual honesty, openness, independence and societal responsibility, as well as the norms and principles which follow from them.

Date

17 - 08 - 2018

Name

KIRAN RAJ RAJAN

ID-number

1284681

Signature

17/08/18

Submit the signed declaration to the student administration of your department.

[i] See: http://www.tue.nl/en/university/about-the-university/integrity/scientific-integrity/
The Netherlands Code of Conduct for Academic Practice of the VSNU can be found here also.
More information about scientific integrity is published on the websites of TU/e and VSNU

January 15 2016