MASTER OF SCIENCE

Thesis

Online Diagnostics in Smart Grids

– An approach to the Future Power Grid –

Menno M.P. DE HAAS BSc

High Voltage Technology & Management Delft University of Technology

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Thesis Committee: Prof. dr. J.J. Smit Dr. ir. P.H.F. Morshuis Dr. ir. M. Popov

Chair Delft University of Technology Delft University of Technology

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Keywords: online monitoring, diagnostics, insulation aging, smart grid, space charge, XLPE, fiber optic temperature measurements, HVDC

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Summary

In this study the term *smart grid* is specified toward online diagnostics. It is investigated which online diagnostics techniques fit well within smart grids and whether existing technologies can be used in a smarter way.

Smart grids and online diagnostics

Since 2005, the term smart grids is widely used in literature. To assess what smart grid means from a component perspective, five values have been identified that describe smart grids: secure, reliable, safe, economic and efficient. If these values are translated into operational characteristics, it is concluded that *asset management* and *reliability* are very important for the future power grid. Interviews with three companies show that online monitoring is an appropriate tool to realize a smart grid. However, the costs of online diagnostics should be reduced and the interpretation of measurements should be done by expert systems to make online diagnostics more attractive.

Thereafter, smart grid is analyzed from an outside-in approach by investigating the need for data and listing available technologies to provide those data. The most frequently occurring failure modes of components in the transmission grid are listed to assess what technologies are required to fulfill the need for online diagnostics.

Partial discharge activity can be measured to assess the aging state and operational conditions of transformers, gas insulated switchgear (GIS) and cables. In addition, for high voltage direct current (HVDC) cables, space charge accumulation measurements can be used for the same purpose. Different online measurement techniques are listed and compared. Ultra High Frequency, acoustic and optical partial discharge detection are listed. Furthermore, combinations of these methods and the experimental 2-D electromagnetic partial discharge detection are investigated. For space charge measurements, the pulsed electroacoustic method is explained.

Smart use of existing technologies

Besides the development of new online diagnostic techniques, it is attractive to make smart use of existing technologies that are already installed in the grid. Fiber optics that are integrated in an increasing number of cables are used for hotspot monitoring, but can be used in a smarter way. Using distributed temperature measurements the space charge accumulation as a result of interfacial polarization in the insulation of an HVDC cable, can be determined. From the space charge distribution the electric field enhancement is calculated. If this analysis is applied to weak parts in a cable, the load can be dynamically controlled and condition-based asset management can be applied.

A model is developed that determines the space charge distribution due to a temperature gradient in the cable insulation. Consequently, the electric field enhancement is derived from the space charge distribution. The model is validated afterwards, using measurement data from a pulsed electroacoustic space charge measurement setup. A comparison between the measurements and the model reveals that the model is only valid below the electric field threshold for space charge injection. Above this threshold, a more complex model is required. If the cable is operated below the threshold, the model covers the basic requirements for a temperature-based space charge measurement system.

Contents

Sι	ımma	ary	i
Pı	refac	e	vi
N	omer	nclature	vii
1	Intr	roduction	1
	1.1	Background of Smart Grid	1
		1.1.1 European Union	1
		1.1.2 United States	2
		1.1.3 IEC	2
		1.1.4 Drivers for Smart Grid	3
	1.2	Objective of this study	3
	1.3	Outline of this study	4
Ι	\mathbf{Sn}	nart grids and online diagnostics	5
2	$\mathbf{Th}\epsilon$	e component perspective	6
	2.1	Modernizing the grid	6
		2.1.1 Smart Grid values and characteristics	6
		2.1.2 Asset management	8
	2.2	Company views on Smart Grids	9
		2.2.1 The view of TenneT TSO	10
		2.2.2 The view of Seitz Instruments	11
		2.2.3 The view of Techimp	12
	2.3	Comment on online diagnostics	12
	2.4	Transmission and distribution grid	13
	2.5	Conclusions	14

9	The	outside in ennreach	16				
ა	2 1 ne	Cubetetione	17				
	J.1	211 Therefore and	17				
		2.1.9 External ingulation	11				
		3.1.2 External insulation	20				
	2.0	3.1.3 Gas-insulated Substation	21				
	3.2	Underground cables	23				
	3.3	Overhead lines	24				
	3.4	Overview of data required	26				
1	Onl	ine measurement techniques	27				
т	1 1	Focus and selection of required data	27				
	4.1	Partial Discharge measurement	21				
	4.2	4.2.1 HE/VHE/UHE measurement	20				
		4.2.1 hr/vhr/ohr measurement	29 20				
		4.2.2 Acoustic measurement	04 04				
		4.2.3 Optical measurement	34				
		4.2.4 Combination of acoustic and UHF measurement	35				
	4.0	4.2.5 2-D EM field imaging technique	36				
	4.3	Space charge measurement	36				
		4.3.1 Space charge and electric field	37				
		4.3.2 Space charge and insulation aging	37				
		4.3.3 Online space charge measurement	37				
	4.4	Overview of measurement techniques	39				
тт	C.						
		$\omega_{0}\omega_{1}$	40				
11	51	mart use of existing technology	40				
11 5	Spa	ce charge accumulation model	40 41				
11 5	Spa 5.1	mart use of existing technology ce charge accumulation model Smart temperature measurements	40 41 41				
11 5	Spa 5.1 5.2	mart use of existing technology ce charge accumulation model Smart temperature measurements	40 41 41 43				
5	Spa 5.1 5.2 5.3	mart use of existing technology ce charge accumulation model Smart temperature measurements Model structure Temperature gradient	40 41 41 43 44				
5	Spa 5.1 5.2 5.3 5.4	mart use of existing technology ce charge accumulation model Smart temperature measurements	40 41 41 43 44 46				
5	Spa 5.1 5.2 5.3 5.4 5.5	mart use of existing technology ce charge accumulation model Smart temperature measurements Model structure Temperature gradient Capacitive field Conductivity gradient	40 41 41 43 44 46 47				
5	Spa 5.1 5.2 5.3 5.4 5.5 5.6	mart use of existing technology ce charge accumulation model Smart temperature measurements Model structure Temperature gradient Capacitive field Conductivity gradient Space charge distribution	40 41 41 43 44 46 47 48				
5	Spa 5.1 5.2 5.3 5.4 5.5 5.6 5.7	mart use of existing technology ce charge accumulation model Smart temperature measurements Model structure Temperature gradient Capacitive field Conductivity gradient Space charge distribution Space charge field	40 41 41 43 44 46 47 48 40				
5	Spa 5.1 5.2 5.3 5.4 5.5 5.6 5.7 5.9	mart use of existing technology ce charge accumulation model Smart temperature measurements Model structure Temperature gradient Capacitive field Conductivity gradient Space charge distribution Space charge field Space charge field	40 41 41 43 44 46 47 48 49 51				
5	Spa 5.1 5.2 5.3 5.4 5.5 5.6 5.7 5.8 5.0	mart use of existing technology ce charge accumulation model Smart temperature measurements Model structure Temperature gradient Capacitive field Conductivity gradient Space charge distribution Space charge field Resistive field Space charge distribution	40 41 41 43 44 46 47 48 49 51 52				
5	Spa 5.1 5.2 5.3 5.4 5.5 5.6 5.7 5.8 5.9 5.1	mart use of existing technology ce charge accumulation model Smart temperature measurements Model structure Temperature gradient Capacitive field Conductivity gradient Space charge distribution Space charge field Space charge distribution revised Space charge distribution revised	40 41 41 43 44 46 47 48 49 51 52 52 52				
5	Spa 5.1 5.2 5.3 5.4 5.5 5.6 5.7 5.8 5.9 5.10	mart use of existing technology ce charge accumulation model Smart temperature measurements Model structure Temperature gradient Capacitive field Conductivity gradient Space charge distribution Space charge field Space charge distribution revised Alternative use of fiber optics	40 41 41 43 44 46 47 48 49 51 52 56 57				
5	Spa 5.1 5.2 5.3 5.4 5.5 5.6 5.7 5.8 5.9 5.10 5.11	mart use of existing technology ce charge accumulation model Smart temperature measurements Model structure Temperature gradient Capacitive field Conductivity gradient Space charge distribution Space charge field Space charge distribution revised Alternative use of fiber optics Conclusions	40 41 41 43 44 46 47 48 49 51 52 56 57				
5	Spa 5.1 5.2 5.3 5.4 5.5 5.6 5.7 5.8 5.9 5.10 5.11 Ten	mart use of existing technology ce charge accumulation model Smart temperature measurements Model structure Temperature gradient Capacitive field Conductivity gradient Space charge distribution Space charge field Space charge field Alternative use of fiber optics Conclusions	40 41 41 43 44 46 47 48 49 51 52 56 57 58				
5 6	Spa 5.1 5.2 5.3 5.4 5.5 5.6 5.7 5.8 5.9 5.10 5.11 Tem 6.1	mart use of existing technology ce charge accumulation model Smart temperature measurements Model structure Temperature gradient Capacitive field Conductivity gradient Space charge distribution Space charge field Space charge field Alternative use of fiber optics Conclusions Space tharge the space charge measurements	40 41 41 43 44 46 47 48 49 51 52 56 57 58 58				
5 6	Spa 5.1 5.2 5.3 5.4 5.5 5.6 5.7 5.8 5.9 5.10 5.11 Tem 6.1	mart use of existing technology ce charge accumulation model Smart temperature measurements Model structure Temperature gradient Capacitive field Conductivity gradient Space charge distribution Space charge field Space charge field Alternative use of fiber optics Conclusions Space charge measurements Experimental setup	40 41 41 43 44 46 47 48 49 51 52 56 57 58 58 58				
5 6	Spa 5.1 5.2 5.3 5.4 5.5 5.6 5.7 5.8 5.9 5.10 5.11 Tem 6.1	mart use of existing technology ce charge accumulation model Smart temperature measurements Model structure Temperature gradient Capacitive field Conductivity gradient Space charge distribution Space charge field Space charge distribution revised Space charge distribution revised Alternative use of fiber optics Conclusions Space charge measurements Experimental setup 6.1.1 Test object	40 41 41 43 44 46 47 48 49 51 52 56 57 58 58 58 58				
5 6	Spa 5.1 5.2 5.3 5.4 5.5 5.6 5.7 5.8 5.9 5.10 5.11 Tem 6.1	mart use of existing technology ce charge accumulation model Smart temperature measurements Model structure Temperature gradient Capacitive field Conductivity gradient Space charge distribution Space charge field Space charge field Alternative use of fiber optics Conclusions Alternative use of fiber optics Alternative use of fiber optics Alternative use of fiber optics Conclusions Conclusions Temperature and space charge measurements Experimental setup 6.1.1 Test object Temperature gradient	40 41 41 43 44 46 47 48 49 51 52 56 57 58 58 58 58 58 58 58				
5	Spa 5.1 5.2 5.3 5.4 5.5 5.6 5.7 5.8 5.9 5.10 5.11 Tem 6.1 6.2 6.2	mart use of existing technology ce charge accumulation model Smart temperature measurements Model structure Temperature gradient Capacitive field Conductivity gradient Space charge distribution Space charge field Space charge field Alternative use of fiber optics Conclusions Alternative use of fiber optics Conclusions Alternative use of fiber optics Conclusions Ference and space charge measurements Experimental setup 6.1.1 Test object 6.1.2 PEA setup Temperature gradient Space charge accumulation	40 41 41 43 44 46 47 48 49 51 52 56 57 58 58 58 58 58 58 58 59 60 61				
5	Spa 5.1 5.2 5.3 5.4 5.5 5.6 5.7 5.8 5.9 5.10 5.11 Tem 6.1 6.2 6.3 6.4	mart use of existing technology ce charge accumulation model Smart temperature measurements Model structure Temperature gradient Capacitive field Conductivity gradient Space charge distribution Space charge field Space charge field Space charge distribution revised Space charge distribution revised Alternative use of fiber optics Conclusions Alternative use of fiber optics 6.1.1 Test object 6.1.2 PEA setup Temperature gradient Space charge accumulation	40 41 41 43 44 46 47 48 49 51 52 56 57 58 58 58 58 58 59 60 61 62				
6	Spa 5.1 5.2 5.3 5.4 5.5 5.6 5.7 5.8 5.9 5.10 5.11 Tem 6.1 6.2 6.3 6.4 6 5	mart use of existing technology ce charge accumulation model Smart temperature measurements Model structure Temperature gradient Capacitive field Conductivity gradient Space charge distribution Space charge field Space charge field Space charge distribution revised Alternative use of fiber optics Conclusions Alternative use of fiber optics 6.1.1 Test object 6.1.2 PEA setup Temperature gradient Space charge accumulation	40 41 41 43 44 46 47 48 49 51 52 56 57 58 58 58 58 58 58 59 60 61 62 64				
6	Spa 5.1 5.2 5.3 5.4 5.5 5.6 5.7 5.8 5.9 5.10 5.11 Tem 6.1 6.2 6.3 6.4 6.5	mart use of existing technology ce charge accumulation model Smart temperature measurements Model structure Temperature gradient Capacitive field Conductivity gradient Space charge distribution Space charge field Space charge field Alternative use of fiber optics Conclusions Alternative use of fiber optics 6.1.1 Test object 6.1.2 PEA setup Temperature gradient Space charge accumulation	40 41 41 43 44 46 47 48 49 51 52 56 57 58 58 58 58 58 58 59 60 61 62 64 64 64				
6	Spa 5.1 5.2 5.3 5.4 5.5 5.6 5.7 5.8 5.9 5.10 5.11 Tem 6.1 6.2 6.3 6.4 6.5	mart use of existing technology ce charge accumulation model Smart temperature measurements Model structure Temperature gradient Capacitive field Conductivity gradient Space charge distribution Space charge field Space charge distribution revised Space charge distribution revised Alternative use of fiber optics Conclusions 6.1.1 Temperature gradient Space charge accumulation 6.1.2 PEA setup Temperature gradient Space charge accumulation	40 41 41 43 44 46 47 48 49 51 52 56 57 58 58 58 58 58 59 60 61 62 64 64 64				

Bibliography

Appendices

Α	Inte	rview TenneT TSO	74
	A.1	Definitie Smart Grid	74
	A.2	Uitbreiding capaciteit	74
	A.3	Demand side response	75
	A.4	Duurzame bronnen	75
	A.5	Elektrisch vervoer	76
	A.6	Asset management	76
	A.7	Dynamic Line Rating	76
	A.8	PD-meting	77
в	Inte	erview Seitz Instruments	78
	B.1	Smart Grid and reliability	78
	B.2	Reliability and online PD measurement	78
	B.3	Online PD measurement techniques	79
	B.4	Shift towards online diagnostics	79
	B.5	Demand for online PD measurements	79
	B.6	Transmission and distribution grid	79
\mathbf{C}	Inte	rview Techimp	80
С	Inte C.1	Smart Grid and reliability	80 80
С	Inte C.1 C.2	Prview Techimp Smart Grid and reliability Reliability and online PD measurement	80 80 81
С	Inte C.1 C.2 C.3	Berview Techimp Smart Grid and reliability Reliability and online PD measurement Online PD measurement techniques	80 80 81 81
С	Inte C.1 C.2 C.3 C.4	Brview Techimp Smart Grid and reliability Reliability and online PD measurement Online PD measurement techniques Shift towards online diagnostics	80 80 81 81 82
С	Inte C.1 C.2 C.3 C.4 C.5	Prview Techimp Smart Grid and reliability Reliability and online PD measurement Online PD measurement techniques Shift towards online diagnostics Demand for online PD measurements	80 80 81 81 82 82
С	Inte C.1 C.2 C.3 C.4 C.5 C.6	erview Techimp Smart Grid and reliability Reliability and online PD measurement Online PD measurement techniques Shift towards online diagnostics Demand for online PD measurements Transmission and distribution grid	 80 80 81 81 82 82 82
D	Inte C.1 C.2 C.3 C.4 C.5 C.6 MA	Smart Grid and reliability	 80 80 81 81 82 82 82 83
C D	Inte C.1 C.2 C.3 C.4 C.5 C.6 MA D.1	Berview Techimp Smart Grid and reliability Reliability and online PD measurement Online PD measurement techniques Shift towards online diagnostics Demand for online PD measurements Transmission and distribution grid State TLAB functions Temperature gradient	 80 80 81 81 82 82 82 82 83
C D	Inte C.1 C.2 C.3 C.4 C.5 C.6 MA D.1 D.2	Berview Techimp Smart Grid and reliability Reliability and online PD measurement Online PD measurement techniques Shift towards online diagnostics Demand for online PD measurements Transmission and distribution grid State Temperature gradient Capacitive electric field	 80 80 81 82 82 82 82 83 85
C D	Inte C.1 C.2 C.3 C.4 C.5 C.6 MA D.1 D.2 D.3	Brview Techimp Smart Grid and reliability Reliability and online PD measurement Online PD measurement techniques Shift towards online diagnostics Demand for online PD measurements Transmission and distribution grid TucAB functions Temperature gradient Capacitive electric field Conductivity gradient	 80 81 81 82 82 82 83 85 85
C D	Inte C.1 C.2 C.3 C.4 C.5 C.6 MA D.1 D.2 D.3 D.4	Brview Techimp Smart Grid and reliability Reliability and online PD measurement Online PD measurement techniques Shift towards online diagnostics Demand for online PD measurements Transmission and distribution grid State TucAB functions Temperature gradient Conductivity gradient Space charge distribution	 80 81 81 82 82 82 83 85 85 86
D	Inte C.1 C.2 C.3 C.4 C.5 C.6 MA D.1 D.2 D.3 D.4 D.5	Smart Grid and reliability	80 80 81 82 82 82 83 83 85 85 86 86
D	Inte C.1 C.2 C.3 C.4 C.5 C.6 MA D.1 D.2 D.3 D.4 D.5 D.6	smart Grid and reliability	80 80 81 81 82 82 82 83 83 85 85 86 86 86
D	Inte C.1 C.2 C.3 C.4 C.5 C.6 MA D.1 D.2 D.3 D.4 D.5 D.6 D.7	smart Grid and reliability	80 80 81 81 82 82 82 83 85 85 86 86 86 87

66

Preface

Research departments focus on new trends, as for instance is the case with *smart grids*. Because these departments possess very specific knowledge, it is a challenge to translate new trends into the knowledge the departments have.

This study was done with the idea to translate the rise of smart grids into a part of the research that is performed by the research group High Voltage Technology and Management: online diagnostics. In addition, a fresh look at smart grids is given by investigating the smart use of existing technologies.

At first, my thanks go to prof. Smit, who gave me the opportunity to graduate before his summer holiday.

Then, it was a pleasure to work with my supervisor dr. ir. Morshuis. The perfect balance between constructive feedback, guidance and freedom to develop my own ideas, formed a sound basis for my graduation project.

The days working at the university would not be that nice if there were no 3 pm tea breaks. Besides their great assistance in the laboratory, ing. van Nes, Aad and Wim always ensured enjoyable conversations during the break.

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Furthermore, I am very grateful to my managers Lars and Tom at Inter IKEA Systems B.V., who supported me during my graduation project and allowed me to be completely flexible regarding my working hours.

Finally, this thesis could not have been realized without the love of my parents, brother and girlfriend.

June, 2011

Nomenclature

2-D	Two dimensional		
AC	Alternating Current		
ACSR	Aluminum Conductor Steel Reinforced		
CIM	Common Information Model		
СТО	Chief Technology Officer		
DC	Direct Current		
DEIS	IEEE Dielectrics and Electrical Insulation Society		
DER	Distributed Energy Resources		
DG	Distributed Generation		
DGA	Dissolved Gas Analysis		
DOE	Department of Energy		
DP	Degree of Polymerization		
EEGI	European Electricity Grid Initiative		
EHV	Extra High Voltage		
EM	Electromagnetic		
ESB	Electricity Supply Board (Irish utility)		
EU	European Union		
EUT	Equipment Under Test		
FFA	Furfuraldehyde or Furfural		

FFT Fast Fourier Transform

Preface

FRA	Frequency Response Analysis
GIS	Gas-Insulated Substation
$_{ m HF}$	High Frequency
HFCT High Frequency Current Transformer	
HV High Voltage	
IEC International Electrotechnical Commission	
IEEE	Institute of Electrical and Electronics Engineers
MV	Medium Voltage
OLTC	On-Load Tap Changer
PD	Partial Discharge
PEA	Pulsed Electroacoustic (space charge measurement)
RES	Renewable Energy Sources
SCADA	Supervisory Control and Data Acquisition
TSM	Thermal Step Method (space charge measurement)
TSO	Transmission System Operator
UHF	Ultra High Frequency
UV	Ultraviolet
VHF	Very High Frequency
XLPE	Cross-linked Polyethylene

CHAPTER 1

Introduction

Smart Grids, it sounds fancy, but what is it about? That question is focussed on in this study. Moreover, what role will online diagnostics play in a smart grid, which is meant to be the future power grid? By analyzing the background and meaning of smart grids and assessing the variety of online diagnostic techniques, these questions are answered.

1.1 Background of Smart Grid

The movement towards smart grids was started in different continents before the term was actually used in practice. Dominant players in this movement were the European Union and the U.S. DOE (Department of Energy).

1.1.1 European Union

Back in 2001, projects were initiated by the EU cluster IRED (Integration of Renewable Energy Sources and Distributed Generation into the European Electricity Grid), part of EU Framework Program 5, with a total budget of 34 million euro [1]. These projects aimed at exchanging information, identifying research topics and initiating strategic actions with regard to DER (Distributed Energy Resources). IRED draw the conclusion that:

- The electricity networks of the future will be based to a large extent on new power electronics and ICT applications, some of which have already been in use in other sectors of industry for decades.
- Reliability, safety and quality of power are the main issues linked to the large-scale deployment of DER. Their effect on European transmission networks, cannot be neglected and must be addressed with a comprehensive system approach.

The first step towards smart grids was made.

Two years later, in 2003 the EU proposed an alternative architecture for the future electricity systems to allow for an increasing amount of DG (Distributed Generation) as part of its Framework Program 6[2]. The so-called *internet model* transforms the electricity grid from a centralized and passive network into a distributed and active layout, in which the bidirectional interaction between supply and demand (the consumer) plays an important role.

1.1.2 United States

Also, the U.S. DOE has published numerous papers on the smart and future grid. In July 2003, the U.S. DOE published the "GRID 2030: A National Vision for Electricity's Second 100 Years" [3]. This report summarizes the outcomes of a meeting of 65 executives representing the industry, stakeholders and government. Among the major findings of this meeting are two ideas that are relevant for this study.

- There are several promising technologies on the horizon that could help modernize and expand the Nation's electric delivery system, relieve transmission congestion, and address other problems in system planning and operations. These include advanced conductors made from new composite materials and high temperature superconducting materials, advanced electric storage systems such as flow batteries or flywheels, distributed intelligence and smart controls, power electronics devices for AC-DC conversion and other purposes, and distributed energy resources including on-site generation and demand management.
- It is becoming increasingly difficult to site new conventional overhead transmission lines, particularly in urban and suburban areas experiencing the greatest load growth. Resolving this siting dilemma, by a) deploying power electronic solutions that allow more power flow through existing transmission assets and b) developing low impact grid solutions that are respectful of land use concerns, is crucial to meeting the nation's electricity needs.

Since at least 2005 the term *Smart Grid* has been used in literature [4], because at that time the North American power grid faced threats such as congestion and atypical power flows. Simultaneously, the demand for higher reliability increased. In the same year the EU (European Union) realized, a new approach to the design of electrical infrastructure is required to realize their sustainable agenda and install DER on a large scale [1].

1.1.3 IEC

As governments were already focussing on smart grids, standards organization IEC (International Electrotechnical Commission) launched the *IEC Smart Grid Strategic Group* (also known as *IEC SG3*) in 2008. This group developed a framework of standards that should facilitate interoperability between smart grid devices and systems. Once standards are in place, the development of technologies is accelerated.

1.1.4 Drivers for Smart Grid

Besides the intention from governments to pave the way for RES (Renewable Energy Sources) there are alternative drivers for grid modernization.

Overall increase in demand At first, the total electric energy consumption and generation are increasing every year. To give a feeling for these numbers, the total electricity production in the world has increased from $13.7 \cdot 10^{12}$ kWh in the year 1998 to $18.8 \cdot 10^{12}$ kWh in 2008 [5], which is a 37% increase in a 10 years time span. The Dutch TSO (Transmission System Operator) TenneT used a similar figure for its scenario calculations [6] assuming a yearly load increase of 3% ($1.03^{10} = 34\%$ in 10 years). As stated before, it is becoming increasingly difficult to site new overhead transmission lines, especially in densely populated areas (e.g. The Netherlands) and it is therefore attractive to look for solutions optimizing the usage of current assets.

Distributed generation Another advantage that may come with the transformation towards a smart grid is the possibility to allow for DG on a large scale. Private parties will be able to generate electrical energy (even on a small scale) and deliver to the grid. This will increase competitiveness in the electricity supply market. Also, dynamic pricing schemes are within the possibilities the future grid could offer. A pilot using smart meters has shown positive results, which are significant saving on electricity bills (an average of 2-39% depending on the price plan) and peak demand reductions [7].

Grid reliability To go more into technical requirements, grid reliability is an important aspect of smart grids, because an increasing number of components in the grid is operated on the edge [8]. Energy consumption and peak demand are increasing and infrastructure is aging while investments are limited. Other factors threatening grid reliability are grid congestion and an increasing number of (HVDC) long distance transfers.

1.2 Objective of this study

Nowadays, most diagnostic measurements are performed offline, but this has a large impact on the network. Components have to be isolated to perform this type of measurements. With an increasing demand for energy and reliability and the availability of new technologies, online monitoring will play an important role in the future. In the smart grid – future power grid – intelligence is integrated in the power grid. In this study is shown how important online monitoring is in the future power grid.

Moreover, studies on more reliable, cheaper and cleaner materials and online monitoring should facilitate the smart grid. This study focuses on online diagnostic techniques to better monitor the status of components in the electricity grid, to allow for an optimal utilization of these components and thereby contributing to a *smart* grid.

Introduction



Figure 1.1: A graphic representation of the thesis outline. Different chapters are closely related to each other, which is indicated by the arrows.

1.3 Outline of this study

This thesis basically exists of two parts. In part I the function of online diagnostics within smart grids is made clear. Chapter 2 deals with the definition of the smart grid from the component perspective. This explains the different facets of the smart grid determined by various institutions and translates these facets to operational requirements on component level. An outside-in approach is used in chapter 3 to identify quantities that can be measured online. At the outside, the operational requirements are used to describe failure modes in components based on existing studies. At the inside, the most important failure modes of components can be prevented by measuring important quantities. To measure these quantities, several measurement methods are available. Chapter 4 focuses on quantities related to aging phenomena and discusses different online measurement techniques.

Part II is about an example of *smartness*. Current diagnostic techniques are not yet used optimally. Fiber optics in cables are used for hotspot monitoring, but could for instance be used to calculate the space charge distribution caused by a temperature gradient across a DC cable insulation. In chapter 5 a model is developed that calculates the resistive field based on plain temperature measurements. Subsequently, this model is validated in chapter 6.

Part I

Smart grids and online diagnostics

CHAPTER 2

The component perspective

As smart grid is a buzz word, its relevant meaning must be determined with regard to the scope of this thesis; online monitoring and diagnostics. Both literature and company views are used to boil down to a more narrow description of smart grids, which can be used and applied on component level. Finally, this chapter positions the role of online diagnostics within smart grids.

2.1 Modernizing the grid

Many publications with regard to smart grids indicate that no radical changes must be expected. Here, a number of examples are given to illustrate the impact of smart grids on component level.

2.1.1 Smart Grid values and characteristics

The U.S. DOE published "A Vision for the Smart Grid" that shortly describes the smart grid values and characteristics in order to answer the question how a smart grid should look like [9]. The values mentioned are reliability, security, economy, efficiency, environmental friendliness and safety. Therefore, its functionality is described by 7 characteristics:

- 1. enable active participation by customers,
- 2. accommodate all generation and storage options,
- 3. enable new products, services and markets,
- 4. provide power quality for the digital economy,
- 5. optimize asset utilization and operate efficiently,
- 6. anticipate and respond to system disturbances and
- 7. operate resiliently against attack and natural disaster.

Five out of the six smart grid values defined by the U.S. DOE will be used to connect the component's operational requirements to the definition of smart grid. These values are depicted in figure 2.1.

- **Efficient** Efficiency leads to optimal usage of assets, minimization of transport losses and minimization of costs.
- **Reliable** Reliable energy transmission includes the minimization of failures and hence the reduction of power outages. Therefore, power is available to users when and of the quality they need it.
- **Safe** The value *safe* indicates that the grid is safe and will not harm users and workers in the proximity of a high voltage conductor.
- **Secure** Security of the grid means that the electricity supply is not vulnerable to external influences, such as natural disasters, weather conditions and human attacks. A secure grid recovers quickly after it is disturbed by external influences.
- **Economic** The basic laws of supply and demand apply to the grid. This will automatically result in an energy price that is good for the users, utilities and the TSO. Investment strategies will lead to low-cost solutions that benefit all parties involved and also obey the other smart grid values.

A similar set of values is embraced by the EU's *European Smart Grids Tech*nology Platform: flexible, accessible, reliable and economic [10]. Flexible refers to the flexibility to fulfill the need of customers and the ability to respond to challenges in the future. The value *accessible* indicates that (especially renewable) power sources should be available to all network users. The smart grid values proposed by the U.S. DOE are technically more explicit, and are therefore used in the analysis below.

The previously mentioned set of values is not sufficient in order to describe the smart grid on component level. Values are part of an abstract believe of what a smart grid could look like, but do not give enough clarity about the difference between our current power grid and the so-called smart grid in terms of functionality. For that reason relevant smart grid characteristics mentioned in the introduction are linked to the smart grid values in figure 2.1. Only the relevant characteristics are used, which are 4, 5, 6 and 7. These characteristics are related to the technical requirements of the grid:

- provide power quality for the digital economy,
- optimize asset utilization and operate efficiently,
- anticipate and respond to system disturbances and
- operate resiliently against attack and natural disaster.

In addition, the following characteristic can be added:

• allow for Distributed Generation (DG) on a large scale.

As can be seen in figure 2.2 all smart grid characteristics can be linked to the values depicted in figure 2.1. Striking in this figure is that two isolated groups



Figure 2.1: The five smart grid values defined by the U.S. DOE can be used to describe smart grids from a component perspective.

of links exist. One group (including the values *secure* and *reliable*) is focussed on robustness and reliability of the power grid. The other group deals with asset management. This implies that the concept smart grid technically exists of two important concepts: reliability and asset management, which are already important matters in today's power grid. Proper asset management will result in a reliable electricity supply. Therefore, the relation between the two concepts is of a causal character.

In what sense is a smart grid different from the current power grid with regard to the components in the grid? The power grid today is already equipped with a large amount of technology and thus one may call it *smart*; fiber optics in cables, demand and supply forecasting, weather models used for maximizing cable load etc.

In conclusion, the concept *smart grid* has to do with the modernization and extension of the power grid in such a way that it meets future needs: efficient and reliable power transmission while capacity increases.

2.1.2 Asset management

Smart grids is often related to intelligence and communication between different systems within the power grid. Using intelligence and online diagnostic systems condition-based asset management can be implemented, which can be used to reduce maintenance and investment costs. Also, condition-based asset management is useful to identify risky components in the network and hence increase the reliability of the electricity supply [11]. In the EEGI (European Electricity Grid Initiative) "Roadmap 2010-18 and Detailed Implementation Plan 2010-12"



Figure 2.2: The five smart grid values (blue) are linked to the smart grid characteristics (green). Two groups result: one that focuses on reliability and one that deals with asset management. The arrow between the two groups demonstrate the causal relationship.

it is mentioned that "A better understanding of asset aging mechanisms: new ICT tools need to be developed to face smartly the end of life of the different network components" is part of the implementation plan [12, p. 35]. This emphasizes the importance of online diagnostics to repair or replace components timely and minimize costs of maintenance and inspection.

To share all diagnostic data among systems, standards are required. It is proposed to extend the CIM (Common Information Model) (IEC 61970, 61968) that describes the power systems equipment and network [13]. The extension exist of maintenance and monitoring classes that enable condition-based asset management. To introduce new diagnostic techniques in the future power grid, such a standardized information model is required.

Furthermore, the IEC states on its website¹ that the aging infrastructure of today is one of the main drivers behind smart grids. To manage the aging infrastructure diagnostic techniques are required to assess the aging state of components.

2.2 Company views on Smart Grids

If a new concept as smart grids is introduced, it is extremely important what the industry thinks of it. The view of the industry determines the willingness

¹http://www.iec.ch/smartgrid/background/

to implement the concept and the way the concept is finally realized. For that reason, interviews were conducted with three companies that have a relevant connection (i.e. TSO and technology developers) with smart grids.

2.2.1 The view of TenneT TSO

TenneT is the TSO in The Netherlands. As TenneT develops and maintains the transmission grid, it is important to know what their view is on Smart Grid, especially on online diagnostics. An interview conducted with M. van der Meijden [14], innovation manager at TenneT, gave insights about his ideas and the position of TenneT toward the Smart Grid. A full report of the interview can be found in appendix A. However, this report is written in Dutch as the interview was conducted in Dutch too.

Section 2.2.1 elaborates on the definition of Smart Grid according to TenneT TSO. Thereafter, in section 2.2.1 a few examples of smart solutions are mentioned, which gives an impression of TenneT's approach toward the Smart Grid.

Definition of Smart Grid

Smart Grid is a buzz word. A Smart Grid is not a goal but the means to find a balance between the following goals: (1) reliable power delivery, (2) environmental responsibility and (3) affordability.

One side of Smart Grid deals with the adjustment of transport capacity when changes occur in supply and demand. For instance, it is planned that power generation facilities will move to the coastal areas of The Netherlands. This will lead to a change in power flow to other areas. The capacity of the transport grid should be adjusted accordingly.

On the other side Smart Grid refers to intelligence that is applied in the grid where necessary and beneficial. Both users and production are actively involved in the Smart Grid. Accordingly, a Smart Grid can better be referred to as a Smart Energy System. One must keep in mind that careless addition of intelligent systems only increases the probability of failure. The current transmission grid is already smart: many intelligent systems are integrated and the capacity is large.

Examples of Smartness

According to TenneT one can make a grid smart by thinking about the problems we are faced with. A few examples are stipulated in this section.

Increasing capacity In stead of increasing the capacity of the grid one can plan and predict the power to be delivered. With regard to wind/solar power the production can be predicted a day in advance. Consequently, conventional production facilities can balance the mismatch between production and load.

If the distance between production and load increases, the transmission grid must be expanded.

Demand side response The energy price should be an incentive for users to increase or decrease energy consumption. Likewise, the price steers production facilities to balance production and load. Regarding electric cars, this will encourage users to spread the load during the day.

Dynamic line rating Using sufficiently accurate weather models, one can determine the capacity of an overhead line. This way assets are used more efficient in case weather dependent production facilities are connected to the grid having the same correlation between production and weather. For wind power this is the case: an increasing wind speed means an increasing energy production and a larger line capacity – enhanced line cooling.

Asset management Based on past experience and component use (e.g. number of switching cycles of a circuit breaker) preventive measures are performed. Visual inspection and measurement are subsequent actions. In case online measurement is inexpensive, condition-based management is preferred.

Maintenance actions are triggered by data measured in the grid. Depending on the quantities that are measured and the component that is monitored measurements are carried out in varying time intervals. For instance, PD (partial discharge) is measured offline and once a year per cable. This interval is short enough to identify a trend. Online PD measurement is a new development, which can be favorable in case of lower measurement costs.

2.2.2 The view of Seitz Instruments

Seitz Instruments is a Swiss company that develops and sells diagnostic equipment for HV power systems. CTO (chief technology officer) of Seitz Instruments dr. ir. B. Quak answered a few questions by e-mail [15]. A hardcopy of the correspondence can be found in appendix B.

Improving reliability

It is not always the case that online diagnostics improve the grid reliability. Adding measuring and sensing systems with a low reliability might decrease the total grid reliability. For instance, internal sensors can reduce the breakdown voltage of a component or false positives (the monitoring system indicates a defect in case no defect exists) cause unavailability of a component.

Moreover, PD is only a symptom of a defect and can serve in some cases as a predictor for defects. However, there is no direct relationship between PD activity and the reliability of components.

Demand for online PD measurements

Offline PD detection is still most popular, because of its application during testing of components. On the other hand, online PD detection and monitoring are under development. A lot of research is done in this field, but more research is required to come to a robust solution. Nevertheless, an increasing demand for online PD monitoring is expected in the coming 10 years.

2.2.3 The view of Techimp

The Italian company Techimp is specialized in diagnostic equipment applied to electrical engineering. By answering a number of questions, project manager M. Tozzi gave an overview of their vision on smart grids and online diagnostics. The complete interview can be found in appendix C.

Power flow and reliability

In smart grids it is important to combine techniques that control the power flow with techniques that prevent failures. This enables the system to schedule the power flow using realistic reliability figures.

Diagnostic markers (e.g. PD activity) that are related to the degradation state of components have to be identified and monitored. Diagnostic tools should be integrated with proper communication tools to meet the smart grid approach. Consequently, a bidirectional flow of information is established between the grid and SCADA (supervisory control and data acquisition) centers to minimize power outages. This approach improves power quality, reliability of power delivery and the efficiency of components.

Online PD measurement

Online PD monitoring is one of the most suitable solutions to control degradation mechanisms in all electrical apparatuses. The most important parameter is *not* the magnitude of the PD activity, but the trend. Online PD measurement is most appropriate for this purpose compared to periodic measurements, because external conditions change continuously. Also, intermittent PD and fast degradation processes can only be detected by permanent systems.

However, PD diagnostic systems are expensive compared to other systems. In addition, the analysis of PD data is complex and needs expertise. As a result, the total costs of failure of the equipment under test should be high enough to justify the investment. This is generally true for the transmission grid, but not for the distribution grid (MV systems).

Future developments

Online diagnostic equipment becomes slowly more popular, but customers underestimate the complexity of these systems. Three major challanges during the coming 10 years can be identified. At first, the market needs integrated intelligence and cost reduction. To attain this, intelligence from the expert must be programmed into the diagnostic equipment. Secondly, the reliability of these systems has a large margin for improvement. At last, integration of diagnostic equipment in existing systems and communication between systems is the base to fully fit the smart grid approach.

2.3 Comment on online diagnostics

Online diagnostics can be beneficial for the reliability of the grid, but there are still some issues that prevent grid operators from applying these techniques on a wide scale. There are several reasons for this. At first, all measured data should be collected and analyzed efficiently [16]. If online diagnostics is applied on a wide scale, a massive data flow must be analyzed. To prevent false alarm, improve these processes and draw conclusions from the outcome employees should be dedicated to the data analysis. This adds to the measurement costs.

Secondly, measurements should become cheaper [14, 17]. It is not yet clear for the business whether extensive online monitoring outweigh the costs of failure. Will online diagnostics really prevent failures?

Another issue is the reliability of the electronics used in the measurement system. High voltage components are designed for a lifetime of several decades. Electronics on the other hand consist of semiconductor technologies that are subject to failures more frequently. The question is whether the grid reliability will improve using relatively unreliable electronics.

2.4 Transmission and distribution grid

In this thesis the focus is on the application of online diagnostics in the transmission grid. There are major differences between the transmission (voltages $\geq 110 \text{ kV}^2$) and distribution grid (voltages $< 110 \text{ kV}^2$) that make it difficult to compare diagnostic techniques in both networks. This is emphasized by Seitz Instruments in section B.6.

This section formulates the differences between diagnostic equipment in the transmission and distribution grid in a number of areas.

Voltage level The voltage level is lower in the distribution grid, which requires other specifications for diagnostic and monitoring systems. Measurement transformers and insulation systems for the transmission grid are larger and more expensive than for the distribution grid counterpart.

Impact Failure of the diagnostic system (false-positive and false-negative) has a larger impact in the transmission grid. A false-positive result will lead to further inspection and thereby unavailability of a component for a certain period of time. This is very expensive and, when no redundancy is applied, has an impact on a large number of users. On the other hand, a false-negative result can lead to a defect when no other monitoring or maintenance is performed. A defect in the transmission grid can cause a power cut for many users. For the distribution grid the number of affected users rarely exceeds 10.000³.

Density of components Distances between components in the distribution grid are smaller and, hence, the network has a higher density. Monitoring all components requires a large number of monitoring systems and is thus very costly. Therefore, monitoring and diagnostic systems should be cheaper to offer a feasible solution [17].

²Voltage level applies to the power grid in The Netherlands.

³Number originates from power outage information on the website of grid operator Stedin.

The component perspective



Figure 2.3: The abstract values and characteristics of smart grids are reduced to online diagnostics via asset management and reliability. Expert systems support online diagnostics where necessary.

Data analysis An increasing number of components means more data that needs to be processed. This requires more computer power and expert reviews. Especially the experts who make decisions based on the information from the data, are very expensive for a grid operator.

PD activity Components in the distribution grid are generally allowed to withstand higher PD amplitude than components in the transmission grid [17].

2.5 Conclusions

Smart Grid is a very broad term, defined in literature by many institutions and approached from different perspectives. It is hardly possible to work with this matter without narrowing down to a more explicit and tangible description. Abstract values and characteristics are used to approach smart grid from a component perspective; the connection between *smart grids* and *online diagnostics*.

Values and characteristics A broad set of values and characteristics based on governmental publications (see figure 2.2) is chosen as a starting point to work toward online diagnostics. All values and characteristics lead to two concepts: reliability and asset management. Proper asset management will finally result in a reliable transmission grid.

Asset management Both governments and standard organizations refer to asset management in their implementation plans. In addition, TSO TenneT states that condition-based asset management is preferred if affordable. Clearly, asset management and in particular *condition-based asset management* is an important tool to maintain and perhaps improve the reliability in the future.

Online diagnostics Technology companies state that the popularity of online diagnostics is expected to increase during the coming 10 years. However, there is no direct relationship between the application of online diagnostics and the grid reliability. It should therefore be assessed in each case whether online diagnostics is a beneficial and economically feasible solution. Chapter 3 further

elaborates on the quantities that can be measured. Subsequently, chapter 4 deals with the different online diagnostic techniques.

Expert systems A major drawback of online diagnostics is the interpretation of measurement results. This is in particular true for online PD measurements (see chapter 4). Experts are expensive to hire and for that reason online PD measurements are not always feasible, especially for the distribution grid where diagnostics tools should be less costly. Expert systems with embedded knowledge rules can overcome this problem in the future.

CHAPTER 3

The outside-in approach

Chapter 2 elaborated on the need for online diagnostics to increase the reliability, efficiency, safety, security and economic feasibility of the transmission grid as is required for a smart grid. It has been shown that online diagnostics play an important role within a smart grid.

In this chapter it is determined what quantities should be measured in order to fulfill the need for online diagnostics. For that reason this chapter refers to the *outside-in approach* (see figure 3.1). At first, the need for online diagnostics is described from an overview – outside – perspective; *what data is actually needed to assess the aging state and operational condition of components.* Afterwards, the answer to this question can be used to investigate what measurement techniques are suitable to obtain the data from the grid. This will be presented in chapter 4.

Currently the power grid, especially the transmission grid, exists of three main areas:

- substations (section 3.1),
- underground cables (section 3.2) and
- overhead lines (section 3.3).

The smart grid can be defined taking each of these areas as a starting point.

In the following sections the most frequent failure modes for each component are listed and it is explained how to optimally operate this component using diagnostics in the future power grid. A distinction is made between the aging state and operational conditions of each component. In section 2.2.1 it is mentioned that measurement costs are an important factor determining the feasibility of the application of an online diagnostic method. These costs are not taken into account here, because the scope of this report is to identify online diagnostic techniques that play an important role in future power systems. From an innovation point of view, further development of these techniques can reduce the costs for future application.



Figure 3.1: The outside-in approach starts at the overview perspective, the smart grid. Reliability is positioned in the smart grid framework. More to the inside, the need for data is investigated by assessing failure modes of different components. Finally, a need for online diagnostic techniques is established.

Aging and degradation In this chapter the term *aging state* is used. Aging is a global process that occurs in all insulation materials. This process is accelerated under high thermal and electric stress. Due to aging local defects grow in the insulation material and material properties change. *Degradation* occurs at places with enhanced electric stresses and consequently, aging accelerates. Finally, degraded insulation material can cause *breakdown* locally. Hence, *aging* is a global phenomenon and *degradation* is a local process of accelerated *aging* usually caused by enhanced field strengths and hotspots.

3.1 Substations

A substation usually consist of multiple components depending on the layout of the substation. Important components are the high voltage transformer including the tap changer, external insulation (bushing and post insulator), switchgear (circuit breakers and disconnectors), instrument (current and potential) transformers. Switchgear and instrument transformers are not included in the analysis.

3.1.1 Transformers

Power transformers are installed at the supply side to bring the voltage to transmission voltage level (in The Netherlands ≥ 110 kV). At the load side the voltage is transformed down to distribution level. These components are usually very reliable and designed for a lifetime of several decades, but can last over 60 years. Important sources of failure are the on-load tap changers (OLTC), windings, insulation aging and oil contamination [18]. Therefore, the

data obtained from transformers must focus on these areas. This section focusses on the traditional oil-filled transformers.

Aging state

OLTC OLTC are a frequent source of failures in transformers. A study [11] focussing on 51 failures in a real population of 500 transformers shows that 60%of the failures is caused by OLTC faults. This number is higher than the 41%mentioned in an earlier study from CIGRÉ [18]. Regardless the differences, these numbers indicate that OLTC faults have to be taken serious. For transformers without an on-load tap changer, but equipped with a de-energized tap changer, hardly 5% of the failures was due to the tap changer. This illustrates the vulnerability of an OLTC. Common causes of OLTC faults are contact wear, weak springs and defects in the driving mechanism. Studies show that the aging of tap changers can be monitored by measuring acoustic vibrations, dynamic and static contact resistance, winding resistance, tap changer driving motor current/power, dissolved gas analysis and diverter oil temperature [11, 18–23]. The latter two measurements have been evaluated using ESB's (Electricity Supply Board) transformer failure history [24]. According to the evaluation these measurements are effective in preventing major failures and transforming those into minor failures by detecting the failures in a premature stage.

Insulation Secondly, insulation degradation is a well-known source of power transformer failure. A frequently applied method to detect developing faults in the insulation is Dissolved Gas Analysis (DGA). Using this method, transformer oil is checked on by-products from PD and overheating. The gasses involved are generally CO, CO₂, H₂ and CH₄ – typically indicating cellulosic decomposition – and C₂H₂, C₂H₄ (ethylene is typical for oil decomposition) and C₂H₆ [25]. However, a study including 82 transformer failures in ESB's history of transformer failures in service [24] shows that dissolved gas monitoring would not have prevented minor failures (i.e. faults that can be repaired on-site, outage typically < 1 month). Instead, major failures could have been detected and transformed into minor failures.

Another method to describe the aging of the transformer insulation is to assess the paper insulation condition [26, 27]. The thermal degradation of paper can be measured by the furfuraldehyde (FFA) content in transformer oil. Unlike the production of the gasses carbon monoxide and carbon dioxide – which is often measured – in oil, the formation of FFA is specific to the paper degradation process. From the FFA content in oil the degree of polymerization (DP) of the paper is estimated. To prevent accelerated insulation aging, the transformer must be operated at a lower temperature and the water-in-oil content should be minimized. Therefore, the water-in-oil content and oil temperature should be measured too.

Besides the chemical analysis, PD can be measured at a transformer. PD often indicate a fault or weak spot in the insulation and contribute to further deterioration of the insulating material. Faults can occur in the windings and main dielectric insulation due to mechanical and electrical stresses. Many methods have been realized to measure PD including optical, electrical, chemical and acoustic methods. Chapter 4 will further elaborate on the different methods to measure PD activity.

In addition, a measurement that is performed on the insulation construction is the tangent δ measurement (also called dielectric loss measurement), which measures the dielectric losses in the insulation. The calculation of the tangent δ is depicted in equation 3.1, in which I_R is the resistive/real component of the current ad I_C the capacitive/imaginary component.

$$\tan \delta = \frac{I_R}{I_C} \tag{3.1}$$

Increasing losses indicate a decreasing resistance and hence, degradation of the dielectric [18, 28]. The power factor of the insulation material is expressed in cosine θ (see equation 3.2, I_T is the vector sum of the resistive and capacitive component of the current).

$$\cos \theta = \frac{I_R}{I_T} \tag{3.2}$$

The tan δ and cos θ have a mutual relationship. For convention, the tan δ (i.e. dielectric loss factor) is used. Depending on the frequency at which the measurement is performed, different aging mechanisms can be detected [18].

A last method that is used to assess the condition of the winding insulation, is measuring the winding hotspot temperature [28]. The paper insulation loses its mechanical strength by exposure to excessive heat, which can lead to tearing and displacement.

Windings Also, transformer windings are a major cause of failures. Reference [18] reports that according to a CIGRÉ study 19% of transformer failures is caused by the windings. Therefore it is important to gain information about the condition of the windings. Several quantities can be measured to assess the condition of the windings. To check whether there are open or short-circuited windings, the windings ratio is measured at all tap positions and phases [18]. Thereby, the winding resistance is measured together with the oil temperature. The resistance of the windings vary with the oil temperature and thus, both should be measured simultaneously to be able to compare measurements.

Another approach is the frequency response analysis (FRA). Using the FRA winding movements are detected by measuring the transfer function of the transformer. Changes in internal capacitances of the transformer affect the transfer function. These movements can be caused by short-circuit currents and loosened winding clamping [18].

An alternative method to assess the winding condition is to measure the stray reactance of the transformer [29]. Using this method the core and winding losses, short-circuit reactance, but also the winding tightness can be assessed.

Operational conditions

Besides monitoring aging symptoms in a transformer, the operational conditions are monitored to verify the condition of the transformer in the short run. Aging processes are often slow processes that can degrade several parts of the transformer over many years, while operational conditions can change depending on the currents and voltages.

Firstly, losses occur in the transformer that increase the temperature of the insulating oil. For that reason, the oil is pumped and often cooled by fans. The

pump and fan operation should be monitored at all times. Furthermore, the oil – often measured at the top of the transformer – and ambient temperature are measured, because overheating can cause transformer failure.

Secondly, high oil temperatures are caused by high transformer loading. Therefore, load currents and voltages per phase are measured. These figures play also an important role in the operations of the power grid and dynamic loading of the transformer. Besides, the position of the tap changer should be monitored during operation of the transformer.

3.1.2 External insulation

Bushings and station post insulators serve to insulate the high voltage from surrounding equipment and support the high voltage conductor.

Bushings are used to guide the conductor inside a transformer and prevent flashovers to the grounded transformer tank wall. Due to the high dielectric and thermal stress, bushings are an important cause of transformer failures [30]. Several studies showed that bushings cause 20-33% of large power transformer failures [31].

Other important components in substations are the ceramic insulators that support the HV busbars.

Aging state

Bushings Typical defects originate in the condenser core and are caused by oil contamination with moisture and discharge across the inner porcelain or overheated conductor contacts [28, 31].

Oil contamination in the bushing results in increasing dielectric losses. To detect this, the tan δ or the current imbalance for the three phases can be measured. The current imbalance is calculated by the sum current measurement. If all three bushings are in balance, the sum of the currents would result in zero. In reality, the sum is always a non-zero value. Furthermore, surface discharge across the porcelain or discharges in oil can be detected by PD measurements. Another parameter that gives information about the condition of the bushing, is the capacitance [28]. The capacitance is, however, related to the tan δ by means of the leakage current I_R . Ideally, the busing is a perfect capacitance and no leakage current exists (tan $\delta = 0$).

Post insulators Insulators are often situated outside in the open air and are prone to contamination and fog, which are common causes for failures – leakage currents and flashovers [32, 33]. To diagnose aging and deterioration of the insulator the same method can be applied as for most insulation systems; PD measurement [34]. Contamination will cause PD on the surface of the insulator that deteriorates the insulator properties.

Another method to assess the condition of composite insulators is to analyze the electric field distribution along the insulator [35]. Conductive defects can be detected using this method.



Figure 3.2: The layout of an ABB ELK-14 GIS rated for voltages up to 300 kV. Source: ABB Group Website

Operational conditions

Bushings It is known that the effect of the heat of the transformer and the electric stress on the bushings is of high importance [31]. Therefore, the operational condition of the transformer already gives sufficient information to determine the operational status of the bushings. Top oil temperature, voltages and currents are key parameters to be measured.

Post insulators A method to measure the contamination on the insulator surface is to measure the leakage current [36]. Using this method strategies for cleaning can be determined. In addition, the electrical stress on the insulator should be measured to see whether the insulator is operating safely. The voltage of the high voltage conductor should therefore be measured.

In some countries (e.g. China) seismic stresses can cause cracks in ceramic insulators, but in The Netherlands this does not play an important role.

3.1.3 Gas-Insulated Substation

Gas-insulated substations (GIS) are reliable components [37] that are compact in comparison to their air-insulated counterparts. The substation consists of a metal enclosure filled with SF_6 gas that has excellent insulating properties. As indicated in figure 3.2 the high voltage conductor is floating in the metal structure and entirely surrounded by SF_6 .

Aging state

Despite the high reliability of GIS, failures occurred in the past. A CIGRÉ study among 2115 GIS reported a total of 161 failures in voltage class 300 - 500 kV. In this voltage class the 380 kV GIS operate in the Netherlands. Having 161 failures over 6371 circuit-breaker-bay-years the average breakdown frequency equals 2.53 (contrary to the 2.58 reported) per 100 circuit-breaker-bay-years [37]. However, these numbers originate from 2000.

A recent study was performed among the entire GIS population in Norway, which consists of 111 GIS [38]. This study shows a failure rate of 2.8 per 100 circuit-breaker-years for 300 kV GIS and 1.5 per 100 circuit-breaker-years for 420 kV. Hence, the failure rate of GIS in the aforementioned voltage class is about 2 failures per 100 circuit-breakers-years. An overview of failure rates is depicted in table 3.1.

Table 3.1: Failure rates of GIS.

Voltage class	Failure rate ¹	Source
300 - 500 kV	2.53	[37]
300 kV	2.8	[38]
420 kV	1.5	[38]

Here, the focus is on aging phenomena and therefore it is interesting to look at the failure modes in addition to the failure rates. In [37] 66% of the failures occurred in the voltage class 300 - 500 kV due to insulation breakdown. In addition, 43% of the total (including the more reliable 145 kV GIS) Norwegian population failed due to internal breakdown [38]. As insulation failure is often preceded by PD activity, it is useful to measure PD in GIS.

Operational conditions

As the SF_6 gas is under pressure, leakages can cause failure in GIS. The survey mentioned in the previous section [38] reported that 23% of the failures occurred due to SF_6 leakage. Accordingly, this is the second most frequently occurring failure mode in GIS. Therefore, SF_6 pressure and density are important parameters to be measured.

According to the design of an intelligent system for GIS [39] there are numerous parameters that can be measured to assess the operational condition. The parameters that are relevant – monitoring of circuit breakers and other mechanical parts is excluded – here, are:

- Ambient air temperature,
- air humidity,
- SF₆ temperature,
- SF₆ pressure and
- SF₆ density.

Furthermore, voltages and currents are measured at various points in the GIS to assess the status of different components.

¹Failure rate expressed in failures per 100 circuit-breaker-years.

3.2 Underground cables

In case overhead lines are difficult to place, underground HV cables are an ideal solution. An additional paragraph is added for HVDC cables, because specific data are only relevant to the monitoring of HVDC cables.

Aging state

Most likely, defects in underground cables occur in cable joints and terminations [40]. In the cable itself faults are likely to occur by voids, impurities and protrusions on the semi-conductive layer of the cable [41]. In addition, the installation and the laying of the underground cable can result in defects and consequently, accelerated aging mechanisms in the insulation. The IEEE Dielectrics and Electrical Insulation Society (DEIS) searches for a fit between its research and the smart grid developments [42], which demonstrates that insulation is an important topic in the future power grid.

Developing defects in the cable insulation can be detected by PD and dielectric loss measurements. As with the preceding components, dielectric losses can be represented as the tan δ .

HVDC cables Different from AC, DC cables do not show regular 50 Hz cycle PD patterns during constant voltage operation. Moreover, the PD pattern depends on the stage – resistive, capacitive or transient stage – of the cable operation. Whereas AC has a clearly defined PD inception voltage, this is not the case for DC, which has an effect on the analysis of the PD pattern and not on the actual measurement [43, p. 89, 93].

Dielectric loss measurements are measured at AC voltage and do not relate to DC operation. However, dielectric loss measurements can be beneficial to identify cavities in the insulation material [43, p. 169].

Operational conditions

A limitation with regard to the operation of underground cables is the thermal capacity [44]. Hence, temperature is an important parameter to be measured. Using fibre optics that is usually integrated in the cable, hotspots can be detected. At critical points (i.e. joints and terminations) the outer temperature can be measured. Using mathematical models, the conductor temperature can be estimated based on the load, ambient temperature and outer insulation temperature.

Other data with regard to operational conditions are the voltage across the insulation and current through the conductor.

HVDC cables The electric field around the HV conductor is influenced by space charges that accumulate in the insulation material. Moreover, the space charge distribution depends on the temperature gradient across the cable insulation and the stage of operation. Therefore, it is important to measure temperature. Using a proper mathematical model, the temperature gradient can be calculated. Chapter 5 focuses on online temperature measurements on HVDC cables. In addition, the space charge and electric field distribution can be measured.

3.3 Overhead lines

The major part of the HV transmission network consists of overhead lines. Overhead lines are prone to a large number of environmental conditions, such as lightning, snow, rain and wind. Lightning strokes in the vicinity of an overhead line can cause overvoltages on the line, which can also affect other equipment in the transmission/distribution network (e.g. transformers) [45]. Snow, rain and wind can cause line galloping, which might result in dangerous situations [46]. Online diagnostics can detect faults and overvoltages. Consequently, adequate actions can be taken automatically.

Besides the faults that can occur due to weather conditions mentioned above, the current carrying capacity of a line is based on assumptions about the ambient temperature, wind speed and other weather-related variables [47]. To maximize the capacity based on weather conditions overhead lines should be monitored. This increases the efficiency – in terms of use and not in terms of power loss – of the asset.

Aging state

As an overhead conductor itself is not equipped with insulation, but insulated by the air, insulation defects cannot occur at the conductor. However, bottlenecks in overhead line systems are the porcelain insulators, spacers and compression splices [48]. Defects on these components cause corona and arcing. Consequently, corona (i.e. PD) should be measured to assess the condition of the weaker components in the overhead line system.

Some utilities suffer from corrosion in the steel core of ACSR (Aluminum Conductor Steel Reinforced) conductors. Hence, corrosion should be detected in areas where corrosive agents are present in the air.

Also, the contact resistance of splices can be measured to monitor aging. Degradation mechanisms cause the resistance to increase over time. An alternative method to determine degradation of splices is to identify temperature differences along components. Losses in components will cause a local temperature rise.

Insulator As mentioned before, porcelain (and non-ceramic) insulators are weak spots in the system. Similar to post insulators found in substations (section 3.1.2) contamination can be formed, which in return decreases the dielectric capacity of the insulator. The same data (i.e. PD and electric field distribution) can be measured to assess the condition of the insulator.

In addition, conductive defects and thus, excessive losses in the insulator can be identified using local temperature measurements as used to detect degradation in compression splices [48].

Operational conditions

The thermal condition is the most important parameter of an overhead line. Therefore, the temperature and the current-carrying capacity should be known. To detect line sagging by excessive heating the height of the high voltage conductor must be determined. Another method to measure movements – including galloping – of the overhead line is to measure the tensile stress [49]. Moreover, the cooling of the conductor depends on weather parameters – wind speed, wind direction, ambient temperature and global radiation – that can also be measured. In chapter 4, several measurement techniques are given to obtain these parameters.

In addition, the common parameters – voltage and current – are measured as well to determine losses in the overhead line, phase shifting and to assist in dynamic operation of the power grid.

3.4 Overview of data required

In table 3.2 the previously mentioned data that can be used for monitoring purposes, is summarized. Chapter 4 will elaborate on the online measurement techniques that can be used to obtain the data depicted in the table.

 Table 3.2: An overview of all data that can be obtained from the grid to assess the aging and operational condition of components in the transmission grid.

Area	Component	\mathbf{Type}^{1}	Data
Subst.	Transformer	A	PD, DGA (CO, CO ₂ , H ₂ , CH ₄ , C ₂ H ₂ , C ₂ H ₄ and C ₂ H ₆), FFA in oil, water in oil, tan δ , hotspot temperature windings ratio, winding resistance oil temperature FBA stray reactance
	"	0	Oil pump and fan operation, oil and ambient temperature, load currents and voltages, tap changer position
Subst.	OLTC	А	Acoustic vibrations, dynamic and static contact resistance, winding resistance, tap changer driving motor current/power, DGA, diverter oil temperature
Subst.	Bushing "	A O	Tan δ , sum current, PD, capacitance See transformer operational conditions
Subst.	Insulator	А	PD, E-field distribution
	"	0	Leakage current, voltage
	GIS	А	PD
	"	0	Ambient air humidity and temperature, SF ₆ pressure, density and temperature, voltages and currents
Cable	AC/DC	А	PD, $\tan \delta$
	"	0	Voltage, current, conductor/ambient temperature
	DC	0	Space charge, temperature gradient
Line	Conductor	A	Corrosion
	Spacer	A	PD
	Splice	A	PD, contact resistance, temperature
	Insulator	A	PD, temperature, E-field distribution
	_	0	Voltage, current, conductor and
			ambient temperature, conductor height
			and movements, wind speed and
			direction, global radiation

 $^{1}A = Aging / O = Operational condition$
CHAPTER 4

Online measurement techniques

In the previous chapter all data are listed that can be used to assess the aging state and operational condition of particular components. The next step is to identify electric *online* measurement techniques that are currently available to measure the data. Several steps are taken in this chapter to ensure that the measurement techniques are selected carefully. An overview of these steps is given in figure 4.1. The focus of this study and selection of required data from table 3.2 (step 1) is elaborated in section 4.1. In step 2 (sections 4.2 and 4.3) existing measurement techniques are listed that are able to obtain the data selected in step 1. This includes a brief description of the measurement technique, the advantages and drawbacks of each technique and the suitability for different components. Finally, in step 3 (section 4.4) an overview is presented of all measurement techniques that were mentioned in step 2.

4.1 Focus and selection of required data

At first, table 3.2 shows that extensive data can be measured to assess the operational condition or aging state of high voltage components in the transmission



Figure 4.1: Graphical representation of the approach applied in chapter 4.



Figure 4.2: An overview of the data selection process (step 1 in figure 4.1). Table 3.2 represents the input. The selection criteria are explained in section 4.1. Subsequently, the output is focussed on in the remaining part of the chapter as described in figure 4.1.

grid. With regard to the topic of this study grid reliability is very important. In addition, chapter 3 indicates that insulation aging is a frequently occurring cause of failures. Therefore, this chapter focusses on *measurement techniques* for aging phenomena.

Secondly, some data can only be measured by offline measurements (e.g. tan δ). As the study elaborates on online diagnostics in future power grids, these offline techniques are excluded in the following.

With regard to the different components, the focus is on *transformers, cables and GIS*. These are critical components in the power grid with specific aging mechanisms in insulation materials. Nowadays, developments in insulation materials play an important role in research into aging of HV components. Most transformers are insulated with paper and oil and cables with paper/oil or paper/mass. These insulation materials are gradually being replaced by alternatives as for instance XLPE (cross-linked polyethylene) or epoxy. In addition, GIS are insulated by SF₆ gas. Also, alternatives for SF₆ are investigated. Different insulation materials show aging mechanisms with different characteristics. Therefore, the importance is stressed to continuously develop diagnostic techniques to gain knowledge about aging mechanisms that contribute to degradation of dielectrics.

Finally, the remaining promising diagnostic techniques that fit the preceding requirements are PD measurement (section 4.2) and *Space Charge* measurement (section 4.3).

4.2 Partial Discharge measurement

Partial discharge (PD) measurement is a common method to assess aging processes and weak spots in insulation material. There are several measurement techniques suitable for online measurement of PD and are referred to as unconventional PD detection techniques. The conventional PD detection technique described in IEC 60270 is only used in offline measurements and is therefore not covered here. The unconventional methods will be classified in this section based on a number of criteria:

- Basic description of measurement technique
- Advantages and drawbacks
- Experiences with components

Sensitivity check Most unconventional PD measurement techniques cannot be calibrated to display the apparent charge. Only the HF and VHF method in section 4.2.1 can be calibrated. The sensitivity of other techniques are verified by means of a sensitivity check. An artificial electric pulse is injected in the test apparatus to simulate a real defect. Consequently, the pulse is detected by the sensors. By means of this measurement the minimum detectable apparent charge in pC (picocoulomb) is determined, which is called the sensitivity of the PD detection setup [50].

4.2.1 HF/VHF/UHF measurement

By means of couplers, high frequency (HF, 3 MHz – 30 MHz), very high frequency (VHF, 30 MHz – 300 MHz) or ultra high frequency (UHF, 300 MHz – 3 GHz) electromagnetic (EM) signals are detected. PD pulses propagate through the conductor, but also induce EM transients in the surrounding media, unless the component is electrically shielded. The coupler receives the HF/VH-F/UHF signals that are often amplified and finally displayed on an oscilloscope or spectrum analyzer. The frequency range of the PD signals depends on the type of defect and the component (medium and geometry). An overview of the applicability of HF/VHF/UHF measurements is found in table 4.1. From the table it can be concluded that PD in cable accessories result in lower frequency EM signals. On the other hand, PD in transformers and GIS have a shorter rise time and thus emit higher frequency signals. The VHF/UHF method can be applied to most components. For that reason, an emphasis is put on the UHF method in this section.

Table 4.1: An overview of the applicability of HF/VH/UHF PD measurement [50].

	Cables	Transformers	GIS
HF	+	-	-
VHF	+/-	+	+
UHF	+/-	+	+

Advantages and drawbacks

Advantages:

• The high attenuation of UHF EM signals results in a proper location selectivity [51, 52]. When a PD measurement is performed on different locations, an increasing signal amplitude indicates the proximity of the PD source.

- Only a few known discrete interferences exist in the UHF frequency band [51]. For instance, corona discharges in air do not interfere with measurements in the UHF range and can be suppressed using a 500 MHz high pass filter. Other high frequency disturbances (e.g. TV and mobile telephone signals) can be eliminated using narrow band UHF PD detection [53, 54].
- High signal-to-noise-ratio compared to conventional detection [55].
- High propagation speed of EM waves allows for phase-resolved measurements. Travel times are extremely low compared to the 50 Hz power cycle. PD patterns can easily be synchronized with the power frequency without large time errors that occur with acoustic measurements. The resulting phase-resolved measurement shows whether PD occurs at the positive or negative slope of the power frequency.
- The HF and VHF method can be calibrated to display the apparent charge magnitude [50].

Drawbacks:

- Due to the spatial signal attenuation less suitable for distributed measurements (e.g. at cables) [51]. Multiple couplers should be used to monitor a larger area.
- The UHF method cannot be calibrated to measure the apparent charge of PD activity. In contrast, a voltage signal is measured that is related to the size of a discharge [52].

Experiences with components

Application of the UHF method has been reported for several components: GIS, transformers and cables. In this section experience with the UHF method for these specific components will be listed.

Experiences with GIS UHF measurements can be carried out on GIS apparatus with high sensitivities due the shielding properties of the enclosure. However, the sensitivity is slightly less compared to the conventional PD detection method. To attain this sensitivity, well-designed sensors should be used and no interference should be present [53]. Different antenna designs will not be covered here. If the intensity of disturbances is large, sensitive measurements using broadband UHF PD detection are impossible [53].

Various types of defects can be detected. Using narrowband detection, four types of defects can be detected: a fixed protrusion on the inner conductor, a free particle on the enclosure surface, a fixed particle on a spacer, and a spacer with delamination at the spacer conductor insert [53].

To ensure a high sensitivity in the entire GIS multiple couplers should be mounted. The location of multiple couplers can be determined in such a way that a sensitivity of 5 pC to protrusions and free moving particles is ensured. As free moving particles are the most frequent cause of breakdown it is recommended to optimize the location of the couplers for this particular defect [56]. The overall signal attenuation depends on the position of the defect. The worst case attenuation (10 meters and seven spacers between defect and sensor) was about 20 dB [53].

Both internal and external couplers can be used for UHF PD detection in GIS [57]. Sensitivity checks on external UHF couplers mounted on graphite bursting plates and glass inspection windows resulted in sensitivities of 8 pC and 4 pC respectively [58].

Experiences with transformers A sensitivity check in a laboratory environment resulted in a sensitivity of at least 100 pC [55]. Despite the complex internal structure of a transformer, barriers in the transformer have a small influence on the sensitivity of the UHF PD measurement. In a 220 kV test tank a PD magnitude of 10 pC was detected [59]. For a fixed PD location there is a linear relation between the measured UHF signal and the apparent charge in pC [50, 55].

If multiple acoustic sensors are used, the location of the PD source can be estimated. Using two UHF sensors the intersection of two parabolic surfaces shows the plane in which the PD is located. Three sensors or more will make 3D localization possible [54]. The location selectivity is reported as 1% of the distance between two UHF sensors [60]. The signal attenuation in transformers is estimated at 6 dB per 10 m travelled [60].

Antennas can be positioned inside and outside the transformer tank. External antennas are placed on dielectric windows, which are pre-installed during the production of the transformer. Internal sensors can be installed in the oildrain valve. These have a sufficient sensitivity that is comparable with external sensors [61].

Experiences with cables As mentioned in table 4.1 the UHF method is less suitable for PD detection in cables than HF and VHF, but it can be used to detect weak spots in cable insulation systems [11]. UHF sensors can be used to assess the condition of XLPE cable joints [62]. A cable rod antenna is used on-site to distinguish background noise from PD activity. Four different types of PD – cavity, floating, sliding and protrusion discharge – can be detected with high detection sensitivity [63]. A Rogowski coil VHF sensor can be used in addition for PD calibration purposes. To assess PD in cables the HF/VHF PD measurement technique is more effective. A sensitivity of 200 pC is reported for a VHF setup with a 3 meter long 10 kV XLPE distribution cable to detect faults in cable terminations [64]. The rather low sensitivity is probably caused by the signal processing technique or sensor type. Also, PD in an oil-filled joint located at 120 m from a 840 m long 10 kV PILC cable could be detected by VHF PD detection [64]. The sensor is a high frequency split-core current transformer that is clamped around the earth wire.

UHF PD measurement has good noise discriminating properties. Mobile phone signals can be suppressed using narrowband UHF techniques. If mobile phone signals are emitted strongly, the signal-noise ratio of UHF PD measurement is optimal between 1.2 and 1.6 GHz. The sensitivity to protrusion typical UHF PD signals can attain 48 pC in this case [65]. These measurements were performed on-site on a 220 kV power cable terminal and joint. However, the location of external UHF sensors has a large effect on the detectability of PD. Above 80 MHz the effects of signal attenuation are clearly visible [66].

4.2.2 Acoustic measurement

A small part of the energy (less than 1% [40]) in a PD will be converted into heat and subsequently movement of the surrounding medium. This causes an acoustic wave that can be measured. Depending on the medium the acoustic wave travels in, the characteristics of the wave will be different. The shape of the detected wave depends on various parameters: the source, detector and the sensor [67]. However, the relationship between the amplitude of the acoustic wave and the discharge magnitude is commonly linear [68].

Acoustic signals can be measured by electro-acoustic sensors, acousto-optic sensors [69] or the human ear. Using an amplifier or stethoscope the sensitivity of the human ear to acoustic signals can be improved [68]. The human ear is able to detect acoustic signals from a 40 pC air discharge at a 1 m distance [70, p. 330]. However, in a noisy environment (e.g. onsite) the sensitivity decreases to 1000 to 10,000 pC for air discharges. Furthermore, if the discharge source is located inside an apparatus, the sensitivity of the human ear is very poor. Hence, electro-acoustic sensors have a great advantage for onsite measurements.

Advantages and drawbacks [67, 68]

Advantages:

- Acoustic PD detection is immune to electromagnetic interference.
- Measurement of PD is possible from the enclosure of the component. No couplers need be installed.
- The sensitivity of acoustic PD detection does not depend on the capacitance of the test object.
- Acoustic PD detection allows PD source localization. Using two or more sensors a time-of-flight measurement can be performed. Based on the difference in arrival time of the signals at the different sensors the location of the PD can be determined.
- Acoustic PD detection is non-invasive.
- Investment costs for an acoustic PD measurement system are moderate [71].

Drawbacks:

- The velocity of the acoustic wave depends strongly on the medium. This mechanism is rather complex for different materials (gases, liquids and solids).
- Acoustic waves are prone to various types of influences that reduce the intensity of the wave. *Reflection and refraction* occur at boundaries of media with a different acoustic impedance. In addition, *spatial attenuation* occurs when the wave spreads over a larger volume or area when the distance to the source increases. A part of the wave energy is converted into heat by *acoustic absorption*.

- In real media, the wave velocity also depends on the frequency, which is called dispersion. This makes it more difficult to predict the wave velocity and source location. However, in the relevant frequency range (< 1 MHz) dispersion can be neglected.
- In solids the absorption coefficient can vary over decades. Therefore, the PD measurement sensitivity is strongly influenced by thick layers of solids.
- If the structure of the test object is complex the relationship between the RMS value of the signal and the PD energy becomes complex. Consequently, absolute measurements are considered impossible in this case.
- Acoustic PD measurements cannot be calibrated with regard to the apparent discharge magnitude.

Experiences with components

Experiences with GIS Acoustic PD measurements can attain a sensitivity of approximately 2 pC [68], but show less sensitivity than UHF detection. PD originating from floating particles, protrusions on the inner shell and HV electrode faults can be detected by acoustic measurements [72, 73]. However, the sensitivity of acoustic PD detection is insufficient for fixed metallic particles on spacers [72, 74]. In addition, free conducting particles cause PD that is not in phase with the 50 Hz power frequency. It is therefore more difficult to distinguish this type of PD from noise [68]. The optimal sensor bandwidth for acoustic PD measurement appears to be 10 kHz to 80 kHz [68].

The absorption of pressure wave energy is significant in SF₆ gas [67, 73]. As a result, the high frequency components of PD signals are suppressed. Acoustic absorption increases with the square of the frequency and is inversely proportional to the static pressure. In air, humidity plays an important role too. The absorption in air (50 % relative humidity) equals 1.6 dB/m at 50 kHz, 20°C and 1 atm (\approx 1 bar). For SF₆ this is 80 dB/m under the same conditions [67]. Besides, the metal GIS enclosure causes dispersion of the signal and flanges produce extensive echoing and ringing [68]. These effects impede proper data analysis.

Experiences with transformers In case of an internal PD in the windings or barriers the wave propagation is complex and the sensitivity can be reduced [59, 68]. A sensitivity drop of 32% was observed with three pressboard barriers in a 220 kV test tank compared to a situation without barriers [59]. In this case the minimum detectable apparent charge was 210 pC. Another study reported a sensitivity of 10 pC on a 1.3 MVA transformer [71]. The PD source was located 1.20 m from the sensor including a barrier and 4 layer HV-winding in between. This high sensitivity was reached using an adapted FFT (Fast Fourier Transform) signal processing algorithm to distinguish noise from PD activity.

Fiber optic sensors can be used to measure the acoustic waves with a high signal-to-noise ratio. This type of sensors show a better sensitivity than the favored piezoelectric sensors and can be positioned inside the transformer tank [69, 75]. Noise from the transformer core is the major disturbance and ranges from 50 kHz to 60 kHz [68].



Figure 4.3: Corona and surface discharges emit EM radiation in the optical spectrum. This radiation can be captured with an optical sensor or seen with the human eye.

When the transformer is in-service a single acoustic sensor is sufficient to detect and roughly localize PD [68]. When the sensor is moved around the transformer, an increasing signal strength indicates the proximity of a PD source.

Experiences with cables Acoustic PD measurements are less suitable for cables. Absorption in the cable insulation deteriorates the measurement sensitivity [40, 68]. A sensitivity of 100 pC for XLPE cables is mentioned [68]. It is, however, possible to measure PD activity by moving the acoustic sensor along the cable. In the proximity of PD activity the acoustic signal level increases [68]. To monitor PD online continuously acoustic PD measurement are preferably used at cable accessories (e.g. joints and terminations) [40, 68].

4.2.3 Optical measurement

During PD activity several processes (i.e. ionization, excitation and recombination) produce EM waves in and beyond the optical wavelength. Similar to acoustic PD detection the amount of energy radiated in the optical spectrum is approximately 1% of the total discharge energy in low pressure gases [76]. In solids and liquids this amount is even smaller.

For ages it has been known that electrical discharges can be sensed by the human eye (see figure 4.3). With regard to PD detection the eye is able to see light originating from a discharge magnitude of 20 pC with a rate of 100 pulses per second [70, p. 329]. To establish this sensitivity the environment should be shielded from external light sources. Thereby, 95% of the light from a corona discharge is in the ultraviolet (UV) area [76]. This explains why corona is difficult to see in a light environment. In order to (1) analyze PD, (2) detect discharges inside enclosures and (3) detect light beyond the wavelengths the eye is sensitive to, opto-electronics should be used.

The optical spectrum of PD depends on the surrounding medium and the discharge intensity. Pressure, temperature and the insulation material influence the spectrum that ranges from UV until the infrared area.

Advantages and drawbacks

Advantages:

- Optical techniques are immune to most electromagnetic and acoustic disturbances [76]. However, all electrical parts should be shielded properly. Also, light is a electromagnetic phenomenon that can influence the optical measurement. Using proper shielding from external light sources disturbances are minimized.
- Optical PD detection potentially has a higher sensitivity than conventional PD detection [77]. However, these experiments were conducted in a laboratory environment with little environmental noise.
- Under fast voltage transients PD can be measured using optical techniques [77].
- A linear relation is found between the partial discharge magnitude and the output voltage of the optical sensor [76, 78].
- PD can be localized using several optical detectors [77, 78].

Disadvantages:

- In liquids and solids light is easily absorbed. Hence, PD detection from a large distance is not possible [76].
- Optical PD detection can not be calibrated. The same holds for UHF and acoustic PD detection [76].
- Internal discharges in cavities can not be observed with optical PD detection. All optical signals are absorbed in the surrounding solid.

Experiences with components

Experiences with GIS PD from protrusions and floating particles can be measured using optical detection [77].

Experiences with transformers Experiments with an optical PD detection system were conducted on a point-plane configuration in oil [78]. Results show a high sensitivity and very fast time response. The response of the optical system is comparable to a high bandwidth conventional detection system. The point-plane configuration demonstrates how optical measurements behave in transformer oil, but do not meet the complexity and size of a transformer. Further investigation is required on this topic.

4.2.4 Combination of acoustic and UHF measurement

All previously mentioned PD measurement techniques have different properties. It could therefore be beneficial to apply multiple techniques simultaneously. An example of a proper combination of techniques is acoustic and UHF PD measurement. Because EM signals travel faster than acoustic signals, these can be used as a time reference in PD source localization. This method has been applied to a transformer. Unfortunately, this technique appeared to be



infrared camera, the polymer absorption film and high voltage electrodes.



Figure 4.4: An experimental setup of the 2-D EM field intensity imaging technique [82].

very sensitive to errors in the measured arrival times [79]. Another reason to combine acoustic and UHF PD measurement is to distinguish noise from PD signals [68, 80, 81], because these techniques have different noise sources. Common signals are likely to originate from the PD source. Consequently, the probability of false indications of PD activity is reduced.

Also, for GIS it is recommended to use UHF PD detection as a major detection technique supplemented with for example acoustic PD measurements [72].

4.2.52-D EM field imaging technique

An alternative method for detecting PD is the two dimensional (2-D) EM field intensity imaging technique. This technique uses an organic polymer film with carbon powders to convert EM field energy into heat. EM waves induce currents in the conducting film that heat the film locally. An infrared camera is used to capture the temperature changes in the film. Using a lock-in amplifier temperature changes of several mK can be observed. Figure 4.4(a) shows an experimental setup for this technique with a 15 kV HV electrode initiating PD activity. The measurement result is depicted in figure 4.4(b), which shows the temperature change compared with the 'cold' (i.e. non-energized) situation.

The 2-D map of the EM field makes it convenient to find the PD source location. It is expected that the system is successful in localizing PD activity in cable insulation [82]. However, this technique is still under development.

4.3Space charge measurement

Most electric infrastructure is based on 50 Hz or 60 Hz AC (alternating current). For longer distances (more than 30-50 km for sea-crossings [83]) the use of DC (direct current) can be beneficial. The reason for this is that AC connections consume a lot of reactive power. HVDC (high voltage DC) connections overcome this problem.

When HVDC cables are used, different phenomena occur in the cable insulation, especially when modern polymeric insulation materials (e.g. XLPE) are applied. While at AC voltage the electric field strength in the insulation is rather constant, the electric field strength at DC voltage varies over time. This is caused by (1) the buildup of space charge at inhomogeneities in the cable insulation and (2) a temperature gradient in the insulation material. At AC voltage the quick polarity changes do not allow charge accumulation.

Local inhomogeneities and a temperature drop in the insulation material cause differences in resistivity. When DC voltage is applied, space charges are allowed to accumulate at these inhomogeneities. The charges induce an electric field (i.e. space charge field \vec{E}_{ρ}) that is superposed on the capacitive field \vec{E}_0 (see equation 4.1). When the capacitive field changes during transients (e.g. polarity reversal, switch off), the resistive electric field \vec{E} (the sum of the capacitive and space charge field) can be twice the capacitive field strength.

$$\vec{E} = \vec{E_0} + \vec{E_\rho} \tag{4.1}$$

4.3.1 Space charge and electric field

The main driver for space charge measurements is the electric field distribution in a cable. When the space charge distribution is known, the electric field distribution can be derived.

Although space charge measurements give information about a small part of cable (several centimeters), it can be representative for the entire cable. By mounting the sensor at a weak spot in the cable, for instance a cable joint, the electric field in this area can be kept at a safe value. The maximum electric field can be used to control the operating conditions. Thereby, a trend in changing electric fields indicates that the insulation material is changing. Consequently, this might be associated with the remaining life of a cable.

4.3.2 Space charge and insulation aging

There is still discussion on the relation between space charge and insulation aging. It is expected that thorough analysis of the space charge distribution gives information about the aging state of the insulation material [83]. Investigation has shown that for polycarbonate space charge information – homo or hetero charge formation – can be used as an aging indicator [84]. Also, there is evidence that the presence of space charge has an influence on the remaining life [85].

Yet, there is no agreement about the causality between space charge and aging. Some theories state that space accelerates aging and others explain the opposite relationship. However, it is proposed that from the onset electric field strength for space charge accumulation on, aging mechanisms related to space charge are significant [86].

4.3.3 Online space charge measurement

Several techniques are available for space charge measurements. The TSM (thermal step method) appears unfavorable for online measurements, because (1) the HV source should be disconnected during the measurement and (2) a compensation sample is required that is identical to the cable under test [87]. This has the following explanation.

- 1. During online measurements the HV source cannot be disconnected. This implies that the power transmission should be shut during the measurement, which is unrealistic.
- 2. In real life situations the capacitance of cables is high. This will lead to large compensation capacitors to compensate for the test object. These capacitors make the measurement unpractical and expensive, especially when the measurement is performed on multiple locations.

It is shown that the PEA (pulsed electroacoustic) method is theoretically suitable for online application [83]. This technique is based on the principle that an electric pulse exerts a force on a charged particle. As a consequence, acoustic signals are induced that can be measured by a sensor (PEA cell). The time delay of an acoustic signal is translated into the location where movement was induced by the space charge. However, the setup should be placed in an isolated compartment, because the outer semicon must be exposed to the PEA cell. The pulse is applied via the PEA cell, because the earth screen should be kept at earth potential.

4.4 Overview of measurement techniques

In this chapter various measurement techniques are mentioned. An overview of advantages and drawbacks of different measurement techniques is depicted in table 4.2. However, it is hard to compare measurement techniques, because different test objects and environments show a large deviation on measurement performance. Therefore, the table should be interpreted with care.

Technique	Advantages	Drawbacks
UHF PD	Location selectivity	Signal attenuation
	Selective interference	No calibration
	High SNR	Invasive coupler
Acoustic PD	No electric interference	Wave velocity varies
	Non-invasive	Signal attenuation
	Capacitance not relevant	PD not related to signal
	Easy localization	No calibration
	Moderate costs	
Optical PD	Low EM interference	Light absorption
	Low acoustic interference	No calibration
	Immune to transients	No internal PD visible
	Output linear to PD	
	Easy localization	
Acoustic+UHF PD	Localization	Errors in arrival times
	Noise reduction	
2-D EM PD	Easy localization	Experimental
		Not suitable onsite
Space charge PEA	Field distribution	Experimental
	DC phenomena	Complex setup

 Table 4.2: An overview of online measurement techniques.

Part II

Smart use of existing technology

CHAPTER 5

Space charge accumulation model

Grid operators are not waiting for expensive monitoring technologies while it remains unclear whether monitoring systems pay off in terms of an increased security of power delivery and lower operating costs. This is confirmed by the view of TenneT TSO in appendix A.8. Therefore, it might be interesting to use existing technologies in a *smarter* way.

5.1 Smart temperature measurements

An increasing number of high voltage cables are equipped with a fiber optic cable in the bundle (see figure 5.1). The fiber can be used for data transmission, but also for hot spot detection. In addition, more information could be extracted from the temperature measurements performed using fiber optics. Section 4.3 elaborates on space charge accumulation in high voltage DC cables with polymeric insulation materials. In the case of polymeric HVDC cables the temperature distribution in the cable plays a major role in the electric field distribution.

In this chapter it is investigated whether and to what extent information extracted from fiber optics is useful to predict space charge accumulation and field enhancement in the polymeric insulation material.

A number of purposes where smart temperature measurements could be used for, are mentioned below.

Accelerated aging As will be demonstrated in section 5.8 the steady state resistive electric field in a loaded HVDC cable is strongest at the outside of the insulation. In the case of an AC voltage, however, the maximum electric field is located at the inside of the cable insulation. This implies that most insulation aging takes place at another location inside the cable insulation. If the electric field could be derived from temperature measurements, experience could be gained regarding the aging processes and deterioration of the insulation. Ultimately, time-exposure characteristics (lifetime curve) can be used to define Fiber optic cable

Figure 5.1: A typical design of a polymeric HVDC cable in which the optical fiber is clearly marked. This design originates from the Trans Bay Cable Project lead by the city of Pittsburg, California, USA. Prysmian designed this 200 kV XLPE cable. Source: City of Pittsburg

the aging state and reliability based on the exposure to a certain electric field strength for a period of time.

Ambient temperature Underground cables are usually buried in soil or laying in sea water. As a consequence, the ambient temperature is rather constant compared to overhead lines that are exposed to the air. It is possible that temperatures vary due to changing ambient conditions (e.g. weather, water flow). Subsequently, a changing ambient temperature influences the temperature gradient across the cable insulation and the space charge and electric field distribution are influenced. The stress on the polymeric insulation can be determined and the reliability is derived from the aforementioned lifetime curve.

Overloading Overloading a cable changes the temperature from the inside of the insulation due to ohmic losses. Thereby, the temperature distribution will converge toward a new steady state situation. If the current is known, the new temperature and electric field distribution can be predicted using the temperature data from the optical fiber.

When the current through the conductor is increased, the temperature across the insulation changes gradually due to the thermal capacitance of the cable insulation. If the thermal time constant is known, the overloading allowance can be determined based on the temperature measurements and predicted field enhancement.

Polarity reversal Dangerous situations occur when the polarity is suddenly reversed after space charge has been accumulated in the cable insulation. The effect of a polarity reversal on the electric field distribution is demonstrated in section 5.8.

Using temperature measurements the amount of space charge accumulation due to interfacial polarization in the cable, can be estimated. Having this knowledge, one can determine whether a polarity reversal is safe. In case of an unsafe situation it is possible to estimate the time between switching off the voltage and changing polarity. After switching off the voltage the space charge is slowly removed from the cable insulation, after which the polarity can be reversed safely.

Maintenance Before maintenance can be performed on cables or connected equipment, the voltage on the system must often be switched off. After the voltage has been switched off the space charges remain in the cable insulation for a period of time (from hours up to days). As a consequence, the electric field also remains present across the insulation. Once the space charge distribution and the characteristics of the cable insulation material are known, it can be calculated when the electric field has decayed towards a safe magnitude.

5.2 Model structure

In this chapter, a static model is developed that predicts the space charge accumulation in the cable insulation assuming that the temperature dependency of the insulation conductivity is the main cause of space charge. In addition, the model will show the electric field enhancement due to the presence of space charge. Next, in chapter 6 the model is validated by simultaneous temperature and space charge measurements.

The model consists of several interconnected parts that are depicted in figure 5.2. In the first model block, the temperature gradient is calculated based on the load current that heats the cable and the measured outer temperature from the optical fiber. Hence, any dielectric losses in the insulation are neglected. The calculation is explained in section 5.3.

Secondly, the conductivity gradient (section 5.5) in the cable insulation is calculated using the temperature gradient and the capacitive field, which is induced by the voltage applied to the high voltage conductor in the cable.

Subsequently, the space charge accumulation, or, more precisely, the interfacial polarization charge (section 5.6) and its space charge field (section 5.7) are calculated. The space charge field finally adds up to the capacitive field to form a resistive field (section 5.8).



Figure 5.2: Graphical representation of the different steps and input parameters in the space charge accumulation model.

All calculations in this section are based on the XLPE MV (medium voltage) cable used in [83]. Relevant parameters of this cable are depicted in table 5.1.

Value Parameter XLPE Insulation material Inner radius r_{in} 4.5 mmOuter radius r_{out} 9.0 mm Conductor radius 4.0 mm Conductor material Aluminum Current 220 A $45 \ ^{\circ}C$ Outer temperature Applied voltage 30 kV

Table 5.1: MV XLPE cable and model input parameters.

5.3 Temperature gradient

Due to the load current in the cable conductor, joule losses heat the cable from the inside. The heat transfers through the insulation material and is released into the surrounding medium. As a result the inner part of the insulation has a higher temperature than the outside. The losses per unit cable length are calculated as

$$P_{loss} = I^2 R \tag{5.1}$$

where I is the current through the conductor and R the conductor resistance per unit cable length. Here, we neglect the losses in the cable insulation and the semicon layers.

The outside temperature of the insulation is measured by the optical fiber. It is assumed that the optical fiber is at the same temperature as the outside of the insulation. To calculate the conductor temperature the thermal resistance R_{th} of the insulation must be determined. The thermal resistance is calculated in equation (5.2) as a function of the inner (r_{in}) and outer (r_{out}) radius of the cable insulation and thermal conductivity k.

$$R_{th} = \frac{1}{2\pi k} \ln\left(\frac{r_{out}}{r_{in}}\right) \tag{5.2}$$

In reference [83] the thermal conductivity k is assumed to be 0.3. However, the thermal conductivity itself depends on the actual temperature. Experimental results of [88] can be used to establish an empirical relationship between the temperature and the thermal conductivity of XLPE. The values of k are shown in table 5.2. In [88] results are supported with a power law fitting curve. In addition, a polynomial fit predicts a maximum value of k just before the 90°C point, which is not confirmed by the authors. Therefore, the data is fit using the power law $k = aT^b + c$ (see figure 5.3). The empirical formula in equation (5.3) shows the same relationship between the temperature (in Kelvin) and the



Figure 5.3: Power law fit of thermal conductivity measurements as a function of the absolute temperature. Data obtained from [88].

$T \ [^{\circ}C]$	$k \; [{\rm Wm^{-1}K^{-1}}]$
25	0.223
55	0.267
90	0.280

Table 5.2: Thermal conductivity of XLPE as a function of temperature [88].

thermal conductivity including the coefficients. This relationship is used in the model to estimate the thermal conductivity. An initial value of 0.3 is taken.

 $k = -3.579 \cdot 10^{13} \cdot T^{-5.911} + 0.3098 \tag{5.3}$

Once the thermal resistance is determined the relation between the outer temperature and the inner temperature is known. The initial value for the static conductor resistance $\rho_{e0} = 28.2 \cdot 10^{-9} \Omega m$ is characteristic for an aluminum conductor at a temperature of 20 °C.

$$T_{in} = T_{out} + R_{th} \cdot P_{loss} = T_{out} + R_{th} \cdot I^2 \frac{\rho_e}{A_c}$$
(5.4)

Because both the thermal conductivity of the cable insulation and electric resistance (and thus the losses) of the conductor depend on the temperature, an iteration procedure is used to converge to a solution. For each iteration the average temperature between the inner and outer temperature is chosen to calculate a new value of the thermal conductivity k. Afterwards, the inner temperature



Figure 5.4: Steady state temperature distribution across the cable insulation.

is calculated and finally, the electric resistance and the induced losses are recalculated. Equation (5.5) adjusts the static resistance of the conductor material for differences in temperature. Parameter α is the temperature coefficient.

$$\Delta \rho_e = \alpha \Delta T \rho_{e0} \tag{5.5}$$

This procedure is repeated until the change in electric resistance is lower than 1 % of the total electric resistance. The full temperature distribution is calculated by equation (5.6).

$$T(r) = T_{in} - \frac{\ln\left(\frac{r}{r_{in}}\right)(T_{in} - T_{out})}{\ln\left(\frac{r_{out}}{r_{in}}\right)}$$
(5.6)

The result of the calculation is shown in figure 5.4, which is produced by means of the MATLAB function shown in appendix D.1.

5.4 Capacitive field

An external power supply applies a DC voltage to the cable, which initially establishes a radial capacitive electric field. The electric field influences the conductivity of the insulation. Equation (5.7) is used to determine the capacitive



Figure 5.5: Conductivity gradient across the cable insulation.

electric field distribution in a radial geometry.

$$E(r) = \frac{1}{r} \cdot \frac{V_{DC}}{\ln\left(\frac{r_{out}}{r_{in}}\right)}$$
(5.7)

This equation is processed in MATLAB using the code in appendix D.2.

5.5 Conductivity gradient

As displayed in figure 5.2 the conductivity gradient is calculated using the temperature gradient and the electric field. The resistive field is not known yet and therefore the capacitive field is used as an initial approximation. In [83] two formulas are presented to calculate the conductivity. The two equations do not show significant differences, but the empirical variant (5.8) is more accurate at lower field strengths. Therefore, this equation is used.

$$\sigma(T, E) = \sigma_{ref} \left(\frac{E}{E_{ref}}\right)^{\nu} e^{\alpha \cdot (T - T_{ref})}$$
(5.8)

The constants are adopted from [83] and are depicted in table 5.3. Finally, the model results are presented in figure 5.5. These results originate from the MATLAB code in appendix D.3.

Parameter	Value	
α	0.15	$^{\circ}\mathrm{C}^{-1}$
u	1.8	
σ_{ref}	$3\cdot 10^{-18}$	$\Omega^{-1} \mathrm{m}^{-1}$
E_{ref}	13	kV/mm
T_{ref}	20	$^{\circ}\mathrm{C}$

Table 5.3: Parameters in equation 5.8.



Figure 5.6: Space charge distribution across the cable insulation. Close to the conductor the highest space charge density is found.

5.6 Space charge distribution

Once the conductivity gradient is known the space charge profile due to the temperature gradient can be calculated. Combining Ohm's law (5.9) and Gauss' law (5.10) results in (5.11).

$$\vec{J} = \sigma \vec{E} \tag{5.9}$$

$$\rho = \nabla \cdot (\epsilon_0 \epsilon_r \vec{E}) \tag{5.10}$$

$$\rho = \nabla \cdot \left(\frac{\epsilon_0 \epsilon_r}{\sigma} \vec{J}\right) \tag{5.11}$$

This can be rewritten¹ as equation (5.12).

$$\rho = \frac{\epsilon_0 \epsilon_r}{\sigma} \nabla \cdot \vec{J} + \vec{J} \cdot \left(\nabla \frac{\epsilon_0 \epsilon_r}{\sigma} \right)$$
(5.12)

¹The product rule for divergence of a scalar f and vector \vec{v} : $\nabla \cdot (f\vec{v}) = f \nabla \cdot \vec{v} + \vec{v} \cdot \nabla f$



Figure 5.7: The space charge induced electric field across the cable. A strongly negative electric field is present near the conductor and a positive electric field at the outside of the insulation.

Equation (5.12) is rewritten as (5.14) using the current continuity equation (5.13) derived from Maxwell's equations.

$$\nabla \cdot \vec{J} = -\frac{\partial \rho}{\partial t} \tag{5.13}$$

$$\rho = -\frac{\epsilon_0 \epsilon_r}{\sigma} \frac{\partial \rho}{\partial t} + \vec{J} \cdot \left(\nabla \frac{\epsilon_0 \epsilon_r}{\sigma} \right) \tag{5.14}$$

In this chapter the dynamics are not taken into account. Therefore, the first term of (5.14) including the time derivative equals zero. Finally, the space charge distribution can be calculated using equation (5.15). For that purpose the MATLAB code in appendix D.4 is used.

$$\rho = \vec{J} \cdot \left(\nabla \frac{\epsilon_0 \epsilon_r}{\sigma}\right) = \sigma \vec{E} \cdot \left(\nabla \frac{\epsilon_0 \epsilon_r}{\sigma}\right) \tag{5.15}$$

Figure 5.6 shows the result of this calculation. It is obvious that the space charge is concentrated at the inner radius of the cable insulation, near the conductor.

5.7 Space charge field

Space charges establish an electric field that adds up to the initial capacitive electric field that is calculated in section 5.4. From Poisson's equation the following relation is established for the space charge induced electric field E_{ρ} in



Figure 5.8: The space charge field adds to the capacitive field. As result the initial capacitive field is weakened at the inside of the cable and enhanced at the outside of the cable. Consequently, the outside of the insulation material needs to withstand a higher stress and suffers from accelerated aging.

a cylindric geometry [83].

$$E_{\rho}(r) = \frac{1}{r}C + \frac{1}{r}\int_{r_{in}}^{r} \frac{\rho(r)r}{\epsilon} \mathrm{d}r$$
(5.16)

The integration constant C can be derived from the boundary condition that the space charge induced electric field does not change the voltage across the cable insulation. Therefore, the integral over the space charge induced electric field equals zero (see equation (5.17)).

$$\int_{r_{in}}^{r_{out}} E_{\rho}(r) \mathrm{d}r = 0 \tag{5.17}$$

Inserting (5.16) in (5.17) results in (5.18).

$$\int_{r_{in}}^{r_{out}} \frac{C}{r} dr + \int_{r_{in}}^{r_{out}} \left(\frac{1}{r} \int_{r_{in}}^{r} \frac{\rho(r)r}{\epsilon} dr \right) dr = 0$$
(5.18)



Figure 5.9: After a polarity reversal the space charge field adds to the reversed capacitive field. As result the the capacitive field at the inside of the insulation is severely enhanced.

At last, integration constant C can be isolated.

$$C = -\frac{\int_{r_{in}}^{r_{out}} \left(\frac{1}{r} \int_{r_{in}}^{r} \frac{\rho(r)r}{\epsilon} dr\right) dr}{\ln\left(\frac{r_{out}}{r_{in}}\right)}$$
(5.19)

Using the function in appendix D.5 equations (5.16) and (5.19) are computed. Subsequently, the model results are displayed in figure 5.7, which shows a negative space charge induced electric field at the inside of the cable insulation. At the outside of the cable a moderate positive electric field is found.

5.8 Resistive field

If a DC field is applied space charge gradually builds up in the polymer cable insulation. The applied field E_0 (also called Laplacian field) and the space charge field E_{ρ} add and result in a resistive field E.

$$E = E_0 + E_\rho \tag{5.20}$$

The resistive field distribution is displayed in figure 5.8. At the inside of the insulation, the electric field is weakened while at the outside the electric field is

enhanced. This effect has consequences for the stress of the insulation. As the integral over the space charge field equals zero the voltage across the insulation is not affected. However, the distribution of the electric field has drastically changed. The highest field strength is increased by approximately 30 % and the location of the highest field strength is moved to the outside.

Polarity reversal However, the largest effect of space charges occurs if the polarity is reversed. The capacitive field changes polarity, but the space charge field cannot change instantaneously. It takes several hours before the space charge distribution has stabilized after the polarity reversal of the capacitive field [83]. The resulting resistive field immediately after the polarity reversal has taken place, is depicted in figure 5.9. A critical situation occurs at the inside of the cable insulation. The field enhancement equals 160 %, just from under -10 kV/mm to -25 kV/mm, which could harm the dielectric upon frequent occurrence.

5.9 Space charge distribution revised

To calculate the conductivity gradient, the capacitive field was used as an approximation for the total (i.e. resistive) field in section 5.5. The resistive field should be entered in equation (5.8) to recalculate the conductivity gradient and, subsequently, the space charge distribution. An improved model is depicted in figure 5.10. However, equation (5.8) is not valid for electric field strengths below zero. In that case the conductivity would then be negative as well, which is not possible. As the initially calculated resistive field crosses zero (see figure 5.8), the iteration cannot be performed.

In [83] another equation is given for the calculation of the conductivity, which



Figure 5.10: Graphical representation of the different steps and input parameters in the space charge accumulation model. An iteration feedback loop is added to account for the effect of the resistive field on the conductivity and the space charge distribution.



Figure 5.11: The capacitive, space charge and resistive electric field after fifteen iterations. At the right side of the figure information is missing due to the iterations.

is based on the hopping theory of conduction in amorphous dielectrics.

$$\sigma(T, E) = A \cdot e^{-\frac{E_a}{kT}} \cdot \frac{\sinh(B|E|)}{|E|}$$
(5.21)

The constants in this equation are shown in table 5.4. Absolute value operators account for a negative value of the electric field strength. When the iteration procedure is repeated fourteen times, the difference in space charge near the conductor between two subsequent iterations is less than 1 %. Figure 5.11 shows the result of the calculation. One should note that each iteration removes information due to the gradient in equation (5.15). The space charge field is clearly less dominant as in the previous calculations. However, the iteration is not converging to a stable space charge distribution. Each iteration influences the space charge density is approximately 0.05 C/m^3 , which is equal to the minimum value in figure 5.6. However, it is found that the parameters in table 5.4 depend on condition of the material [89]. Therefore, it remains complex to estimate the conductivity distribution on temperature and electric field data. The MATLAB code related to this alternative model can be found in appendix D.7.

An alternative approach is proposed in [90], where the conductivity only depends on the temperature and activation energy. Equation (5.22) shows a similar relationship as in (5.21), but not depending on the electric field strength.



Figure 5.12: The capacitive, space charge and resistive electric field after three iterations according to equation (5.25).

$$\sigma(T) = \sigma_0 \cdot e^{\frac{-E_a}{kT}} \tag{5.22}$$

The space charge density is calculated using equation (5.23), which is derived from (5.15) by solving the gradient in one direction.

$$\rho(r) = -\epsilon_0 \epsilon_r E(r) \frac{1}{\sigma(r)} \frac{\mathrm{d}\sigma(r)}{\mathrm{d}T(r)} \frac{\mathrm{d}T(r)}{\mathrm{d}r}$$
(5.23)

Since it is difficult to determine the variation of the local charge carrier concentration and mobility with local temperature, the authors assume an isothermal sample. The temperature does not depend on the position r.

$$\frac{1}{\sigma(r)}\frac{\mathrm{d}\sigma(r)}{\mathrm{d}T(r)} = \frac{1}{\sigma(T)}\frac{\mathrm{d}\sigma(T)}{\mathrm{d}T}$$
(5.24)

Table 5.4: Parameters in equation 5.21.

Parameter	Value	
A	$1 \cdot 10^{1}4$	$V^{-1}\Omega^{-1}$
B	$2\cdot 10^{-7}$	$V^{-1}m$
E_a	1.48	eV



Figure 5.13: The space charge distribution obtained after three iterations using equation (5.25).

Combining (5.22), (5.23) and (5.24) results in (5.25).

$$\rho(r) = -\epsilon_0 \epsilon_r E(r) \frac{E_a}{kT^2(r)} \frac{\mathrm{d}T(r)}{\mathrm{d}r}$$
(5.25)

This equation allows us to calculate the space charge distribution directly from temperature data using $E_a = 1.1 \text{ eV}$ [90]. Figure 5.12 displays the resistive field obtained after three iterations (change of space charge density near conductor ; 1%). This figure is almost similar to figure 5.11, except the missing information at the right side of the graph. This shows that the influence of the electric field on the conductivity is not significant in this case. Contrary to the previous calculation, the space charge distribution converges properly after three iterations. The space charge distribution is shown in figure 5.13 and the MATLAB code that contains this model, can be found in appendix D.8.

Compared to the initial space charge distribution (figure 5.6), the shape of the distribution has reversed and its magnitude has decreased by a decade. Also, the amount of space charge is rather constant across the cable insulation. Initially, the spread of the space charge density with regard to the average value is 150 % ($(\rho_{max} - \rho_{min})/\rho_{mean}$). Here, a spread of only 30 % is observed.

Activation energy It is found that the measured space charge density in reality is considerably lower than the calculated distribution [90]. The authors attribute this difference to the simplification made in equation (5.24). If the mean activation energy is replaced with the activation energy associated with the



Figure 5.14: An example of a distributed strain measurement performed by a specially designed optical fiber. Landslides can be easily detected using this system. Source: [91]

hopping transport of mobile charge carriers through the bulk of the insulation, $E_{hop} \approx 0.09 \text{ eV}$ is calculated, much lower than the 1.1 eV assumed in model. The higher activation energies are associated with the charge injection at the electrodes. Values in the range of 0.9–1.3 eV have been measured. The question remains what the activation energies depend on and which value to use in the model.

5.10 Alternative use of fiber optics

In the oil and gas industry fiber optics have been used for many years to monitor pipelines. Remote optically amplification results in an extended measurement range up to 100 km [91]. Optical amplifiers are distributed along the cable. These amplifiers obtain their power from a separate non-sensing fiber. Currently, a monitoring system is installed at the commercial BritNed cable from The Netherlands to the United Kingdom that does not use this system. This limits the measurement range to approximately 30 km from both ends of the cable. Improvements can thus be made by implementing distributed amplifiers.

Except using fiber optics for temperature measurements, other quantities can also be derived from the signals through fiber optics [91]. At first, vibrations along the cable can be measured. This can be used to detect changes in the soil (e.g. landslides and subsidence) or third-party events (e.g. digging and vehicle movement) that could harm the cable. Secondly, strain can be measured using a specially designed fiber optic cable. The earth's surface is moving continuously, which could impose forces on a cable from various directions and at various magnitudes. Consequently, a typical strain profile occurs along the cable. Premature detection of hazardous strains could prevent damage at the cable insulation. An example of such strain measurements (figure 5.14) demonstrates the detection of landslides.

5.11 Conclusions

In this chapter it is investigated whether fiber optic cables, preinstalled in power cables, can be used in a smarter way than for the purpose of hotspot detection.

Field enhancement caused by space charge accumulation Distributed temperature measurements in HVDC power cables can be used to determine the space charge distribution across the power cable insulation along the full length of the cable. From this distribution the resistive electric field can be calculated, which shows where field enhancements and, thus most aging occurs. Eventually, such calculations could be used for the optimization of maintenance schedules and planning of polarity reversals. However, it is assumed that space charge accumulates mainly by interfacial polarization, which implies that space charge injection at the electrodes is neglected. This is valid provided that the electric field strength is below the threshold for space injection.

Cable insulation properties From sections 5.5 and 5.9 can be concluded that it is very difficult to model the conductivity gradient across the insulation based on temperature and electric field data. This is mainly caused by the complex conduction processes on micro and macro scale in polymeric insulation materials. In addition, the relation between the temperature, electric field and the conductivity depends on the aging state of the insulation material. Therefore, it is hard to derive the aging state of the cable insulation from temperature data.

A sophisticated model from the insulation material's properties could significantly improve the accuracy and usability of the models proposed in this chapter. Hence, it is recommended to carefully characterize the insulation material in advance and investigate the relation between the conductivity, space charge distribution and aging phenomena.

Expert systems Chapter 2 clearly shows the criticism related to the data analysis of online diagnostics. Changes in measured patterns must be detected by expert systems, which could warn asset managers in case of a potential hazard. This saves excessive costs of expertise to analyze the data originating from the online diagnostic systems. To design such an expert system, knowledge rules are required that are based on extensive research into the physical mechanisms influencing the space charge accumulation in polymeric insulation materials.

CHAPTER 6

Temperature and space charge measurements

Previously in chapter 5, a model was developed to predict the space charge accumulation and the resistive electric field in polymeric cable insulation material due to a temperature gradient. Here, the model is validated using data from a space charge measurement setup.

In section 6.1 the experimental setup is described briefly, because the focus here is on the validation of the model and not on the setup. Subsequently, the temperatures during the measurements are verified with the model calculations (section 6.2). Furthermore, the measured space charge distribution across the cable insulation (section 6.3) and the electric field enhancement (section 6.4) are compared with the calculated distributions.

6.1 Experimental setup

It is proposed to use the PEA technique for online space charge measurements (section 4.3.3). However, it was not possible to develop such a setup within the scope of this study. For that reason, the setup for space charge measurements on a cable geometry test object described in [92], is used (section 6.1.2). In section 6.1.1 the test object is described.

6.1.1 Test object

For the test a mini cable was used. A scale model of the cable layout is depicted in figure 6.1. Striking is that no earth screen and armor are present. The PEA cell is directly mounted on the outer semicon and the measurement equipment is connected to earth.

The cable consists of a copper conductor surrounded by a semicon layer. Important is the XLPE insulation, in which the space charge will probably accumulate. Furthermore, another semicon layer on the outside of the cable ensures a proper interface between the cable and the PEA cell. The cable dimensions can be found in table 6.1.



Figure 6.1: A scale model of the test object. The different layers of the cable are labeled. An earth screen is not required due to the measurement equipment that is connected to earth.

Diameter	Value
Conductor	$1.63 \mathrm{~mm}$
Inner semicon	$2.64~\mathrm{mm}$
XLPE insulation	$5.69~\mathrm{mm}$
Outer semicon	$7.21~\mathrm{mm}$

Table 6.1: Test object dimensions.

6.1.2 PEA setup

The setup used for the space charge measurements is schematically shown in figure 6.2. A cable holder fixes the cable on the PEA cell that consists of an acoustic sensor and absorption block with a similar acoustic impedance in order to prevent acoustic reflections. Consequently, the signal is amplified and fed into a scope, where the raw measurement data is stored.

A pulse generator applies the HV pulse on the cable semicon using a separate electrode close to the PEA cell. A voltage is applied on the cable conductor by an HVDC source. For the purpose of this study a temperature gradient is applied across the cable insulation. The cable is heated using a current transformer that induces a current in the cable loop. A thermocouple on the outside of the cable is used for temperature measurements. To estimate the conductor temperature a dummy loop is used carrying the same current, but no voltage is applied to allow for an interruption in the cable insulation, where the temperature is measured by a thermocouple. Furthermore, current measurements are performed by means of a Rogowski coil with a ratio between the primary current and secondary current of 120:1.

Temperature and voltage

Depending on the availability of measurement data, combinations of various temperatures and voltages are chosen to compare with the model [92]. Measurements were performed on a 20°C (isothermal), 40°C and 60°C conductor temperature. However, the isothermal measurements are not useful here due to the zero temperature gradient. The model returns zero space charge accordingly. Nevertheless, measurements on 40°C and 60°C are used in the analysis.

With regard to the high voltage applied, many choices are available. The most important requirement is that differences between space charge measure-



Figure 6.2: Graphical representation of the PEA setup for cable geometry samples. The PEA sensor is placed under the cable holder. A signal amplifiers connects the PEA sensor to the scope.

ments should be clearly visible to see whether the model is valid under multiple conditions. Therefore, it was chosen to use a low (3 kV for 40°C and 3.5 kV for 60°C) and high (20 kV) voltage for both temperatures. The corresponding average electric field strengths are 2.0 kV/mm at 3 kV, 2.3 kV/mm at 3.5 kV and 13.1 kV/mm at 20 kV. Hence, four data sets are compared to the model predictions.

6.2 Temperature gradient

Thermocouples at multiple locations are used. Two thermocouples are placed on the outer semicon of the test object, of which one is placed near the current transformer and the other away from it. Likewise, on the dummy loop two pair of thermocouples are mounted, one on the conductor and one on the outside. All measured temperatures are displayed in table 6.2. The average temperatures are averages of the thermocouple pairs. Finally, the estimates of the conductor temperature are calculated by correcting the dummy conductor temperature for the difference in outside temperature between the test object and the dummy loop.

Another parameter that is required to calculate the temperature distribution, is the current through the cable conductor. For the 40°C and 60°C measurements current of respectively 27 A and 38.4 A were calculated from the Rogowski coil readings.

Accordingly, the results of the model are displayed in figure 6.3. The measured distributions have been determined using equation (5.6). Although the accuracy of the thermocouples is about 0.5° C, from the figures is concluded that the real inner temperature is higher than the calculated inner temperature. This

40°C	$T_{40,3\mathrm{kV},1}$	$T_{40,3\mathrm{kV},2}$	$T_{40,20\mathrm{kV},1}$	$T_{\rm 40,20kV,2}$
Outside test object	34.3	35.2	36.5	36.2
Outside dummy loop	37.4	36.2	38.4	37.8
Inside dummy loop	43.4	41.6	44.6	43.5
60°C	$T_{60,3.5\rm kV,1}$	$T_{60,3.5\rm kV,2}$	$T_{60,20\rm kV,1}$	$T_{60,20\rm kV,2}$
Outside test object	50.6	49.4	50.1	49.2
Outside dummy loop	52.1	51.4	51.9	51.2
Inside dummy loop	65.3	62.9	64.8	63.0
Averages	$T_{40,3\rm kV,av}$	$T_{40,20\mathrm{kV,av}}$	$T_{\rm 60,3.5kV,av}$	$T_{\rm 60,20 kV,av}$
Outside test object	34.8	36.4	50.0	49.7
Outside dummy loop	36.8	38.1	51.8	51.6
Inside dummy loop	42.5	44.1	64.1	63.9
Estimates	$T_{40,3\rm kV,c}$	$T_{40,20 \mathrm{kV,c}}$	$T_{\rm 60,3.5kV,c}$	$T_{\rm 60,20kV,c}$
Inside test object	40.1	42.0	61.9	61.5

Table 6.2: Temperature data. All values are expressed in °C.

can mainly be attributed to the semicon layers, which is not accounted for in the model. The semicon layers have a higher thermal resistance than the copper, which leads to a better thermal isolation of the conductor. As a consequence, the inner temperature is higher than expected. The outer semicon is not included at all in the model. Obviously, this isolates the cable too.

6.3 Space charge accumulation

To draw conclusions about the space charge distribution, the data originating from the PEA setup have to be processed. Most complex operations have already been applied in [92] (deconvolution, filtering etc.). The raw data contain 24 to 26 traces per measurement. These traces are stored over time and are shown the space charge accumulation as a function time. Each trace contains over 2000 measurement points across the cable insulation.

At first, the first trace is subtracted from the other traces. This removes the surface charge on the electrodes and the charge that is initially in the cable. It is assumed that no or an insignificant amount of charge is present upon the start of the measurement. Therefore, the first trace is the reference trace.

Secondly, as we are not interested in the accumulation of space charge over time, but in the stead-state situation when the accumulation has stopped, the focus is on the last five traces. Therefore, an average trace of the last five traces is calculated to reduce the effect of disturbances.

As proposed in section 5.9, an activation energy of 0.09 eV is used for low electric field strengths and a slightly higher energy of 0.13 eV is chosen for far higher field strengths. The comparison between the measurements and the model is displayed in figure 6.4. It should be noted that the detection limit of the PEA setup is approximately 0.006 Cm⁻³.

In case of a low electric field strength (figures 6.4(a) and 6.4(c)) both the measured and the modeled distributions are mainly below the threshold of



Figure 6.3: Measured temperatures compared with the calculated temperature distributions.

 0.006 Cm^{-3} . The space charge density in the bulk insulation can therefore be taken as zero. Figure 6.4(a) shows a peak of 0.03 Cm^{-3} around 2.4 mm. The average space charge density in that region is however very low due to the strong oscillation, which is shown by the model that indicates a very low space density in both graphs. Little mirror charge is shown at the earth electrode, which is caused by subtraction of the first trace.

Striking is the strong negative peak of -0.08 Cm^{-3} around 1.6 mm in figure 6.4(b). This peak is also caused by the subtraction of the first trace. The measurement at 60°C and 20 kV voltage (figure 6.4(d)) shows a similar peak at the inner side of the cable radius, but its magnitude is much lower. Mirror charge is also formed at the outer side of the electrode at the 20 kV measurements. The model predicts a higher space charge density in the case of a high electric field, but it appeared that the sign (plus or minus) of the space charge accumulation is not always positive.

6.4 Electric field enhancement

At last, it can be investigated how the model predicts the space charge induced electric field compared to calculations from the PEA data. The same procedure as with the space charge data has been applied to the electric field data. The first trace is used as the reference trace and subtracted from the other traces. As a consequence, only the field enhancement is taken into account. Then, the last five are averaged and compared to the model calculations.

The space charge induced electric field distributions are shown in figure 6.5.


Figure 6.4: Measured space charge distributions compared with the calculated space charge distributions. The dotted red line indicates the detection limit of the PEA setup.

It should be noted that the order of magnitude of the space charge induced electric field strengths are a decade smaller than the capacitive electric field. Hence, the influence of the space charge field on the resistive electric field is relatively small.

In three cases (figures 6.5(a), 6.5(c) and 6.5(d)) the predicted electric field enhancement caused by the presence of space charge, is close to the distribution calculated from the PEA measurements. At low voltage, a small field enhancement is induced by space charges, while at higher voltages field enhancements up to 1 kV/mm are shown.

In figure 6.5(b) the drop in the electric field caused by the mirror charge, is not calculated, because mirror charge is just an artifact caused by the subtraction of the first trace. Moreover, figure 6.5(d) shows differences between the two lines at the inner part and the outside of the insulation, also caused by mirror charge. A decrease in space charge density was predicted across the full cable insulation layer, but the space charge density increase near the outer semicon. Most likely the outer semicon influences the space charge distribution. No clear differences are observed between the different temperature gradients. The applied voltage appeared to be much more influential than the temperature gradient.



Figure 6.5: Comparison of the space charge induced electric field calculated from space charge data, originating from PEA measurements and model predictions.

6.5 Conclusions and recommendations

A space charge accumulation model has been compared with data from PEA space charge measurements. The conclusions and recommendations resulting from this comparison are summarized here.

6.5.1 Conclusions

Temperature distribution It is possible to accurately determine the static temperature gradient across the cable insulation using temperature measurements on the outside of the cable. These measurements can be performed by means of the optical fiber in cables. However, it is not possible to neglect the semicon layers and, if applicable, the earth screen and armor.

Interfacial polarization and space charge injection The assumption was made that space charge accumulation was solely caused by interfacial polarization. Space charge measurements have demonstrated that at high electric field strengths (13 kV/mm) the space charge distribution deviates strongly from the model, which indicates that space charge injection is likely to take place at the electrodes. Hence, the model is only valid under the threshold for space charge injection.

Fiber optics Initially, the space charge accumulation model was intended to make smart use of fiber optics integrated in high voltage cables. Temperature

measurements could then be used to predict the space charge accumulation and the electric field enhancement. This is possible if the HVDC cable is operated below the threshold for space charge injection. Otherwise, a more complex model is required that takes space charge injection into account.

6.5.2 Recommendations

Space charge accumulation To be able to predict space charge accumulation in polymeric cable insulation without measuring the space charge itself, the threshold for space charge injection should be determined in advance. Then, the model should be verified below and above the threshold concerned. In case that the cable is operated below the threshold, this model fulfills the basic needs of the system.

Full size cable Due to time constraints space charge measurements have been performed on an existing PEA setup suitable for mini cables. The temperature gradient across a mini cable is very small. Larger temperature gradients make the effect on the space charge distribution more visible. Also, because the measured space charge densities were very close to the detection threshold of the PEA setup, it was hard to compare the space charge distribution at low voltages to the model. Thus, it is recommended to perform PEA measurements on larger cables (at least MV) to compare results with this space charge model.

Conduction current measurements It is difficult to model the conductivity of the cable insulation as a function of temperature and electric field. A conduction current measurement setup was built, but time constraints did not allow any measurements, which would strengthen the model. For that reason it is recommended to investigate the conductivity characteristics of polymeric insulation materials in a cable geometry.

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APPENDIX A

Interview TenneT TSO

4 October 2010

Ir. M.A.M.M. (Mart) van der Meijden Innovation manager, TenneT TSO B.V. Utrechtseweg 310, Arnhem, The Netherlands

Interview was conducted in Dutch. Therefore, this interview report is written in Dutch.

A.1 Definitie Smart Grid

Doelen van TenneT: (1) leveringszekerheid, (2) milieu verantwoord en (3) betaalbaar. In deze driehoek moet altijd naar het optimum gezocht worden.

Smart Grid is een containerbegrip. Smart Grid geen doel maar middel. Het is beter om te praten over oplossingen in plaats van over Smart Grids. Investeren en onderhoud zijn geen doel, maar een middel. Smart Grid is het toevoegen (en wegnemen) van capaciteit (technologie) en intelligentie waar dat nodig is. Bij Smart Grid roep je zowel de hulp in van de productie als van de gebruikers. Dit kan dus een Smart Energy System genoemd worden.

Onderscheid moet gemaakt worden tussen innovatie en bedrijfsvoering. Bij bedrijfsvoering wordt slechts het noodzakelijke geïmplementeerd in het net. Meer complexiteit in het net verhoogt ook de kans op storingen. Het hoogspanningsnet is al smart: zit veel intelligentie in verwerkt en heeft al een grote capaciteit.

A.2 Uitbreiding capaciteit

Door nieuwe en alternatieve productie-eenheden is er behoefte aan twee zaken in het net: (1) meer capaciteit en (2) meer dynamiek. Het kan ook slimmer dan sec uitbreiding van capaciteit. Je kunt voorspellen wanneer het waait. De nauwkeurigheid van deze voorspelling is afhankelijk van de tijd tussen het maken van de voorspelling en het voorspelde moment.

Aangeslotenen van TenneT hebben de programmaverantwoordelijkheid: balanshandhaving betekent dat er een dag van te voren bekend moet zijn wat er geleverd en afgenomen gaat worden. Productie moet gepland worden en vooral flexibel ingezet worden. Indien er grote afstanden tussen vraag en aanbod zijn, is er meer net nodig. Het transportnet overbrugt afstanden en dus moet er geïnvesteerd worden in nieuwe netten.

In Nederland zit de belasting in het midden en westen van het land. Nieuwe centrales verplaatsen naar de kust vanwege koelwater en goedkoper aanvoeren van brandstof, dus de opwekking en belasting gaan steeds verder uit elkaar. Daarom moet het net steeds versterkt worden. Er moet altijd gekeken worden naar de kosten van de verbinding tussen opwekking en belasting. De kortste weg van opwekking naar belasting is bedrijfseconomisch de goedkoopste oplossing. Soms is het goedkoper om een productie-eenheid niet te laten leveren en hiervoor te compenseren, dan een nieuwe lijn aan te leggen.

A.3 Demand side response

Demand side response: het gedrag van de klant door middel van prijsprikkels sturen. Dit is een van de elementen van een Smart Grid. De klant moet dus betrokken worden bij het hele proces en intelligentie moet gericht toegepast worden. Je maakt dan de belasting flexibeler. Er zijn twee methoden voor. Allereerst smart home/industrial systems: het automatisch uitschakelen van apparatuur. Er ontstaat een evenwicht als belasting afgeschakeld wordt en/of productie bijgeschakeld wordt. Ten tweede, TenneT gaat uit van het marktmechanisme en gelooft dat prijsprikkels geschikt zijn om het gedrag van een gebruiker te beïnvloeden; het principe van vraag en aanbod. Het voordeel hiervan is dat onverwachte partijen meewerken met het systeem.

Smart metering aanleggen kost geld. Prijzen van de meters worden geschat tussen 70 en 150 excl. installatiekosten. Het gaat niet om de Smart Meter, maar om (1) de prijsprikkel moet bekend zijn bij gebruikers en (2) er moet bekend zijn waar geschakeld moet worden; welke apparatuur kan worden afgeschakeld. Hoe kun je dat dan goedkoop automatiseren? De historie van energieverbruik in een huishouden moet bekend zijn en deze moet geregistreerd worden. Dit kan in de toekomst via internet opgestuurd worden naar energieleveranciers. De kern is om te registreren en dan is er geen smart meter nodig. Dit is heel goedkoop. De energieprijs kan via internet van de APX gehaald worden. Er zullen nieuwe providers komen die deze informatie op een slimme manier verwerken. Dan is privacy ook geen probleem, zodra de klant toestemming geeft voor het versturen van de informatie. De klant blijft eigenaar van de gegevens. De dienstverlener kan een slim prijsplan samenstellen op basis van gegevens.

A.4 Duurzame bronnen

We voorspellen dat er meer duurzame bronnen komen; dus meer zonnepanelen en windmolens. Vervolgens moet er veel geïnvesteerd worden, want het n-1 criterium (leveringszekerheid) moet gehandhaafd worden. De bedrijfstijd van een windmolen is 2500 uur op land en op zee 3500 uur. Voor zonne-energie is dit 800 uur. Als je een 5 kW aansluiting hebt en over 10 kW aan vermogen beschikt, moet je een zwaardere aansluiting hebben. Het is beter om je energie binnenshuis slim te gebruiken, bijvoorbeeld door de diepvriezer te voeden met zonnepanelen op dagen waarop veel zon schijnt. Je kunt ook een accu in huis zetten om energie in op te slaan. Oude accu's van elektrische autos zijn voor deze toepassing uitermate geschikt. Stel dat er een miljoen huishoudens met zonnepanelen zijn, dan hoef je een miljoen keer geen aansluiting te versterken. Mensen gaan geen systemen aanschaffen als het niet gestandaardiseerd is en tegen lage kosten aan te schaffen is.

A.5 Elektrisch vervoer

Als er ooit 200.000 elektrische auto's in Nederland rijden en iedereen komt tegelijk thuis om vervolgens de auto opgeladen wordt, gaat het mis. Indien slim omgegaan wordt met de laadtijdstippen, kunnen 5.000.000 autos worden opgeladen.

A.6 Asset management

TenneT doet aan risk-based asset management. Er wordt gekeken of er risico dreigt voor de drie doelstellingen van TenneT. Er worden tevens preventieve maatregelen genomen aan de hand van het gebruik van een component (bv. het aantal schakelingen van een vermogensschakelaar). Daarna hebben er visuele inspectie en metingen plaats. Het liefst voert TenneT condition-based onderhoud uit indien de benodigde data goedkoop meetbaar is. Er wordt meer gemeten indien de metingen zeer goedkoop zijn t.o.v. de schade die gelopen wordt als een component defect raakt.

Voor de bedrijfsvoering wordt er niet meer gemeten dan stromen, spanningen, fase en frequentie. Onderhoudsploegen verkrijgen meer informatie uit het net. Vaak wordt deze informatie op afstand gemeten en verstuurd via internet. PD-metingen in kabels worden regelmatig gemeten; bijvoorbeeld 1 keer per jaar. Op basis van veranderingen in het gemeten patroon wordt een onderhoudsstrategie vastgesteld.

A.7 Dynamic Line Rating

Een overhead lijn wordt ontworpen op basis van bepaalde weersomstandigheden. Indien omstandigheden gunstiger zijn, zou een lijn meer belast kunnen worden. TenneT past een zomerrating en een winterrating toe om onderscheid te maken tussen verschillende weersomstandigheden. In de zomer is de belasting vaak lager (behalve met airconditioning) dan in de winter, hetgeen past bij de verschillende ratings.

In Duitsland wordt een pilot gedraaid met dynamic line rating, waarbij onder gunstige omstandigheden een lijn 50% meer belast kan worden. In het noorden van het land zijn veel kolencentrales. Deze centrales willen de productie afstemmen op de markt, onafhankelijk van het seizoen of de weersomstandigheden. Met dynamic line rating valt hier weinig voordeel te behalen. DLR heeft alleen zin als de productie van een bepaalde faciliteit dezelfde correlatie heeft met de weersomstandigheden als de lijn waarover het vermogen getransporteerd wordt (bv. bij windenergie en de koeling van de lijn). Soms kan er 700 MW meer over een lijn transporteerd worden bij een toename in capaciteit van 50%. Dit vergt wel investering in metingen, observatie en communicatie met de bedrijfsvoering. Indien dit systematisch wordt toegepast, kan dit systeem in het hele net uitgerold worden. De pilot in Duitsland heeft als bedoeling dat het in de toekomst een standaard wordt.

In ondergrondse kabels zit een glasfiber datakabel waarmee de temperatuur in de kabel wordt gemeten. Voor de toepassing is een model nodig dat de relatie beschrijft tussen de traagheid van het opwarmen van de kabel, de geschiedenis van de belasting en de huidige belasting. In de randstad kan een kabel met 3000 A belast worden. Vanwege leveringszekerheid zijn er altijd 2 lijnen/kabels die maximaal met 50% belast worden. Er is nu een proef waarbij de temperatuur van overhead lijnen wordt gemeten. Dit is niet perse nodig. In Duitsland wordt de temperatuur zelf niet gemeten, maar op basis van weersomstandigheden is een model gemaakt voor de temperatuur. Het model is voldoende nauwkeurig. Dit is een voorbeeld van Smart Grid; op een slimme wijze gebruik maken van je elektriciteitsnet.

A.8 PD-meting

Continu PD meten in een kabel is niet nodig om een trend over de jaren heen te herkennen. Het continu meten, registreren en analyseren kost geld. Het gaat erom dat een goed meetinterval wordt gekozen. Vaak wordt een jaar gekozen als meetinterval. PD wordt offline gemeten. Hiervoor moet de kabel buiten gebruik worden genomen. Dan wordt een 1/10 Hz-signaal op de kabel gezet. Er zijn daarentegen nieuwe ontwikkelingen om online te meten. Intelligentie is nodig om online de data te analyseren.

Appendix B

Interview Seitz Instruments

12 March 2011

Dr. ir. Ben Quak CTO, Seitz Instruments AG Mellingerstrasse 12, Niederrohrdorf, Switzerland

B.1 Smart Grid and reliability

In Smart Grids, grid reliability is an important subject. To what extent will online diagnostics improve grid reliability according to your experience? It depends on the particular definition of reliability, the type of processes to be monitored and the implementation of the monitoring (the technology used). Adding to a grid additional systems (e.g. measuring or sensing systems) with lower level of reliability might reduce the total grid reliability. For instance, applying internal sensors inside a HV system might reduce the breakdown voltage, or, even worse, the monitoring systems themselves might trigger false positives, causing unnecessary unavailability of the monitored grid components.

B.2 Reliability and online PD measurement

To what extent will online PD measurement equipment improve the reliability of components? In other words, is it effective to apply online PD measurements? Can you name examples from your experience?

PD itself is only a symptom of existing discharging defects. Depending on the type of defect and differences in stress factors it both can or can not be used as an early warning of a upcoming breakdown. As a result there cannot be a direct relationship between reliability of components and PD monitoring.

B.3 Online PD measurement techniques

There are many techniques for PD measurement. What ONLINE measurement technique (HF/VHF/UHF, acoustic, optical or combination of methods) is most effective and for what component (transformer, GIS or cable)?

It has only be demonstrated that online PD monitoring is successful for continuous monitoring in rotating machines (PD accepted and trending is of interest) and GIS (no PD at all is accepted). Regarding power cables and transformers the experiences are very different. Due to large diversity of different constructions, materials used the PD activity is more complex. In particular with false-positive and false-negative outcomes regarding partial discharges no combination can be defined.

B.4 Shift towards online diagnostics

Seitz Instruments is specialized in diagnostic equipment. How in the industry is the demand for online diagnostic equipment developing? Is a shift observed from conventional towards online measurement techniques?

The use of conventional technology so called offline has a different application (quality testing, diagnostic testing) than the online monitoring. As a result, conventional testing remains the actual issue and a systematic increase can be observed in the requests from the power industry. Online monitoring however, is still a relative new trend and mainly due to the issues listed in section B.3, still under development.

B.5 Demand for online PD measurements

What developments do you expect in the market for online (PD) measurement techniques during the coming 10 years?

Depending on the type of components (i.e. transformers, cables, generators, switchgear) and the successfulness of field applications (no false-positive or false-negative) online PD monitoring will obtain more and more attention. A lot of academic research has already been performed at this moment, of course as other manufacturers around the world Seitz Instruments works also seriously on a robust and devoted solution but we see that a vast amount of research still has to be executed in the future.

B.6 Transmission and distribution grid

How do the effectivity and attractiveness of online diagnostics in transmission relate to those in the distribution grid? Are there differences in the application of methods?

MV and HV are complete different types of networks, not only with different configurations and objectives, but also with different stresses and therefore monitoring systems for MV will need complete different specifications than those for HV. As such no direct comparison can be made.

Appendix C

Interview Techimp

1 April 2011

M. (Marco) Tozzi Project manager, Techimp S.p.A. Via Toscana 11/c, Zola Predosa, Italy

C.1 Smart Grid and reliability

In the future power grid (Smart Grid), grid reliability is an important subject. To what extent will online diagnostics improve grid reliability according to your experience?

A smart grid should be able to support optimal power flow control strategies accounting for transmission links limits and reliability levels. Smart meters, wide area monitoring systems, dynamic line rating, digital protective relays enable optimization of the power flow. However, these techniques need to be integrated with those able to prevent failures in order to schedule power flows using realistic reliability figures.

In this framework, diagnostic markers, directly related to the degradation state of these electrical apparatuses, have to be identified and monitored. For instance, in case of systems with organic insulation (typically present in cables and transformers) Partial Discharges (PD) are, in most cases, the predominant cause of failure. Indeed, PD detection and analysis has been widely recognized, over the last twenty years, as a powerful tool to highlight the presence of electrical degradation processes in all the HV and MV electrical systems, including not only transformers and cables, but also GIS and rotating machines.

Resorting to the analysis of Partial Discharges in all the network assets, it is thus possible to plan corrective actions only when required, minimizing maintenance costs and reducing unexpected failure risk. This capabilities, if integrated with proper communication tools, fully fit the smart grid approach. In fact, a bidirectional flow of information is established between grid apparatus and SCADA centers to minimize power outages, thus improving power quality, reliability, and efficiency.

For this purpose, on-line PD permanent monitoring can be considered one of the most suitable solutions to control the degradation mechanisms in all electrical apparatuses. However, massive implementation of a PD detection system over a network consisting of several devices implies substantial capital investments. For this reason, permanent monitoring may be suitable when either the direct cost of the Equipment Under Test (EUT) or the indirect costs associated with its failure are high enough to justify such an investment, which is generally true for EHV and HV applications. For MV apparatuses, which direct costs are orders of magnitude lower than those in HV, another approach can be used based on setting up a network of permanently-installed sensors covering all the MV assets in the grid (transformers, cables, switchgear), and allowing PD measurements to be carried out by means of a portable detection system online, without any outage.

C.2 Reliability and online PD measurement

To what extent will online PD measurement equipment improve the reliability of components? In other words, is it effective to apply online PD measurements? Can you name examples from your experience?

There are many arguments that can be considered. Anyway, the alternative to a permanent system is to carry out periodic sampling and this alternative fails when PD are intermittent and when the degradation rate is fast. Intermittent PD can be detected and evaluated using permanent systems only.

Furthermore, the most important marker is not the magnitude of the discharges, but their trend. To evaluate the trend you need to repeat the measurements always in the same conditions and this is difficult with periodic measurements (environmental conditions change, sensor position may change, operator may change etc.).

C.3 Online PD measurement techniques

There are many techniques for PD measurement. What online measurement technique (UHF, acoustic, optical or combination of methods) is most effective and for what component (transformer, GIS or cable)?

This depends on the asset of course. This is a short overview:

- GIS: UHF using both internal and external sensors and a HFCT (high frequency current transformer) on cable terminations.
- Transformers: electrical sensors (tap adapters) and UHF sensors (external or internal). Acoustic sensors are useful for localization, but only for large PD magnitudes (which may not be harmful).
- Cables: HFCT sensors in each accessory. Embedded joints capacitive sensors are strongly recommended.
- Rotating machines: capacitive couplers.

C.4 Shift towards online diagnostics

Techimp is specialized in diagnostic equipment. How in the industry is the demand for online diagnostic equipment developing? Is a shift observed from conventional towards online measurement techniques?

The demand for online diagnostic equipment is high, because the potential is great and it is slowly being known to everyone. But customers think that such systems can be managed similarly to an online DGA. But this is not the case. PD systems are complex and need expertise and continuous support. In addition they are also expensive compared to other diagnostic systems. So, in the end, the market definitely wants such systems, but they are waiting for improved integrated intelligence and cost reduction.

C.5 Demand for online PD measurements

What developments do you expect in the market for online (PD) measurement techniques during the next 10 years?

The intelligence should pass from the expert's mind into the diagnostic systems. This is really challenging, but this should be the future.False alarms shall be avoided. The system shall be independent, working in autonomy and the expert can be contacted only in very difficult cases.

On the other side, mechanical and electronic reliability of such systems have a large margin of improvement.

At last, *communication and integration* in existing systems is the base to fully fit the smart grid approach, i.e. the future.

C.6 Transmission and distribution grid

How do the effectivity and attractiveness of online diagnostics in transmission relate to those in the distribution grid? Are there differences in the application of methods?

Well, ideally the method should be the same, but there is a huge difference in costs. Distribution can not afford the same cost of the transmission. For this reason a compromise between the optimal technical solution and the optimal economical solution should be found.

Starting from the fact that permanent monitoring is the optimal technical (but too expensive) solution it can be acceptable, for MV systems, to carry out periodic tests and then run short monitoring sessions only if something critical is detected. It must be considered that, in general, MV systems may withstand higher amplitude PD compared to transmission systems.

APPENDIX D

MATLAB functions

The model developed to predict the space charge distribution in cable insulation material caused by a temperature gradient is based on the MATLAB functions described here. Every function can be used autonomously using its specified inputs and outputs.

D.1 Temperature gradient

```
2 %%%File that initiates temperature calculations%%%%%%%%%%%%%%%
4
5 function [r, T_r] = \dots
6
   temperature(I_input,T_input,delta_r,r_in,r_out,A_c)
7
9
11
12 %Current through cable
13 I=I_input;
14
15 %Static conductor resistance (at 20 C)
16 rho=28.2*10^-9;
17
18 %Temperature coefficient resistance
19 alpha=0.0039;
20
24
25 %Outer shield temperature
26 T_out=T_input+273.15;
^{27}
```

```
28 %Thermal conductivity insulation (initial guess)
29 k=0.3;
30
34
35 %Radius from inner conductor to outer shield
36 r=r_in:delta_r:r_out;
37
41
42 %Cable electric resistance
43 R=rho/A_c;
44
45 %Insulation thermal resistance
46 R_th=1/(2*pi*k)*log(r_out/r_in);
47
48 %Losses in cable
49 P=I^2*R;
50
51 %Temperature
52 T_in=T_out+P*R_th;
53
54
56 %%%Calculte temp dependent resistance%
58
59 %Initiate variables
60 delta=rho;
61 rho_old=rho;
62
63 %Initiate loop until 1% change in resistance
64 while (delta>(rho_old/100))
65
     %Calculate change in static resistance
66
67
     %With regard to resistance at 20 degrees Celsius
     delta_rho=alpha*(T_in-(20+273.15))*rho;
68
69
     %New static resestance
70
     rho_new=rho+delta_rho;
71
72
     %Change in static resistance
73
     delta=rho_new-rho_old;
74
75
     %Calculate resistance per unit meter
76
     R=rho_new/A_c;
77
78
     %Calculate Joule losses
79
80
     P=I^2*R;
81
     %Recalculate thermal resistance
82
     k=-3.579*10^{13}*((T_in+T_out)/2).^{-5.911+0.3098};
83
     R_th=1/(2*pi*k)*log(r_out/r_in);
84
85
86
     %Calculate conductor temperature
     T_in=T_out+P*R_th;
87
88
     %Set calculated resistance to rho_old
89
```

D.2 Capacitive electric field

D.3 Conductivity gradient

```
4
5 function [sigma] = conduction(E_input, T_input)
6
10
11 %Convert Celsius to Kelvin
12 T_input=T_input+273.15;
13
14 %Conductivity reference
15 sigma_ref=3*10^-18;
16
17 %Electric field reference (V/m)
18 E_ref=13*10^6;
19
20 %Constants
21 alpha=0.15;
22 nu=1.8;
23
24 %Reference temperature (K)
25 T_ref=20+273.13;
26
30
31 sigma=sigma_ref*(E_input./E_ref).^nu.*...
```

32 exp(alpha*(T_input-T_ref));

D.4 Space charge distribution

```
1
4
5 function [rho]=spacecharge(sigma_input,E_input,delta_r)
6
8
10
11 e_0=8.854187817*10^-12;
12 e_r=2.3;
13
17
18 J=sigma_input.*E_input;
19
23
24 gradient=diff(e_0*e_r./sigma_input)/delta_r;
25
26 rho=J(1:length(gradient)).*gradient;
```

D.5 Space charge induced electric field

```
4
5 function [E_rho] = chargefield(rho, delta_r, r_in, r_out)
6
7 %Electric parameters
8 e_0=8.854187817*10^-12;
9 e_r=2.3;
10 e=e_0*e_r;
11
12 %Vector for radius
13 r=r_in:delta_r:r_out;
14
15 %Calculate integration constant
16 C=-sum(1./r(1:length(rho)).*...
    cumsum(rho.*r(1:length(rho))*delta_r/e)*delta_r)...
17
     /log(r_out/r_in);
18
19
20 %Integration of spacecharges
21 E_rho=1./r(1:length(rho)).*...
     (C+cumsum(rho.*r(1:length(rho))*delta_r./e));
22
```

D.6 Resistive electric field

D.7 Conductivity gradient revised

```
1 \qquad \stackrel{\circ}{\circ} 
      4
      5 function [sigma] = conduction_alt(E_input, T_input)
      6
      10
  11 %Convert Celsius to Kelvin
  12 T_input=T_input+273.15;
  13
  14 %Constants
  15 A=1 * 10 ^ 14;
  16 B=2★10<sup>^</sup>-7;
 17
  18 %Activation energy
  19 E_a=1.48;
20
  21 %Bolzmann constant
  22 k=8.61734315*10<sup>-5</sup>;
 23
  27
 28 sigma=A*exp(-E_a./(k*T_input(1:length(E_input))))...
                                                                .*sinh(B*abs(E_input))./abs(E_input);
  29
```

D.8 Space charge distribution revised

```
4
5 function [rho]=spacecharge_tg(E,delta_r,T)
6
10
11 T=T+273.15;
12
13 e_0=8.854187817*10^-12;
14 e_r=2.3;
15
16 %Activation energy
```

17 E_a=1.1;
18
19 %Bolzmann constant
20 k=8.61734315*10^-5;
21
22 %Equations
23 d=diff(T)/delta_r;

24 rho=-e_0*e_r*E(1:length(d)).*E_a./(k*T(1:length(d)).^2).*d;