

KTH Electrical Engineering

## Diagnostics of stator insulation by dielectric response and variable frequency partial discharge measurements

A study of varied low frequencies in stator insulation, with particular attention to end-winding stress-grading

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#### Abstract

Stator insulation is critical to the reliability of electrical generators and motors. It is common industrial practice to use electrical measurement of partial discharges (PD) and some form of current-voltage measurement as part of the condition assessment of stator insulation at maintenance times. Extension of these methods by the recently investigated methods of high-voltage dielectric spectroscopy (HV-DS) and variable frequency phaseresolved partial discharge analysis (VF-PRPDA) may offer usefully increased information about the condition of a stator's insulation while requiring less power from the test voltage source than with conventional power-frequency measurements.

HV-DS and VF-PRPDA have independent variables of the amplitude and frequency of a sinusoidal voltage applied to the insulation system. The dependent variables are the smooth currents of HV-DS and the discharge pulse charges of VF-PRPDA; these may be analysed in many ways, typically as complex capacitance, the harmonic spectrum of currents when there is PD activity or other non-linearities in the insulation system, and various measures of PD pulse distribution.

The methods provide complementary information and have a common need of a variable frequency high voltage driving source. This makes the simultaneous use of these methods a matter of interest, as further information can be gained without extra time and with a total equipment size and cost smaller than that of both separate systems.

In this thesis, results are presented from several directions of work relevant to the application of the low frequency diagnostic methods, HV-DS and VF-PRPDA, to machine insulation.

The contribution to measured frequency domain dielectric response from the current into the non-linear stress grading of stator end-windings has been studied from physical and numerical models. As well as the effects on the dielectric response (complex capacitance), the harmonic spectrum of the current into the grading, and the distribution and waveform of the potential along the grading is shown from the numerical models. The frequency and amplitude dependent response of the stress-grading is of importance due to its significant contribution to the measured dielectric response of a whole stator and to the harmonic currents due to other non-linear phenomena such as partial discharge currents,

Short dielectric response measurements have been made on a complete hydro-generator before and after a period of maintenance, giving a better idea of the practical limitations that time constraints and a large test-object put on possible amplitudes and frequencies for driving the test object.

Two new epoxy-mica stator coils have been studied with both DS and VF-PRPDA before and after accelerated thermal aging, as a preliminary step for seeing what changes can be detected electrically and for studying how the PD and DS methods differ in their measurement of PD.

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## Chapter 1

## Preliminaries

#### 1.1 Introduction

#### Aims of this work

The aim of this project is the assessment and development of the application of two diagnostic measurement methods to the condition assessment of stator winding insulation in large electrical generators and motors.

These methods are developments on established practices: one is high voltage dielectric spectroscopy (HV-DS) which has been developed for power cables in earlier work at this department; the other is variable frequency phase-resolved partial discharge analysis (VF-PRPDA) which has been investigated at this department on laboratory test objects and old stator bars.

There are several potential advantages of these developments. "Extra dimensions" are given to the independent variables — voltage amplitude in the case of the spectroscopy, and frequency in the case of the partial discharge measurement — and to the dependent variables by considering the harmonic content in the current measured by spectroscopy. The information from the two methods is largely complementary. There is also the possibility of running all measurements at a lower frequency than the normal power frequency, thereby permitting smaller testing power supplies.

#### Contributions of this work

The main results reported here have to do with the interaction of varied low frequency high voltage stresses with the non-linear resistive "stress-grading" found at the ends of the stator bars or coils on most high-voltage machines. This stress grading is known to have a significant effect on dielectric measurements at power frequency, and has a still stronger effect at low frequency. Results from measurements on physical models, simulations of numerical models, and some measurements on some real stator coils are presented and discussed. Some of the results of the models have earlier been published in [TE04] and [TE05].

Working towards an assessment of what changes in insulation condition can be seen with these techniques, and how they are manifested, some new stator coils have had measurements performed before and after accelerated thermal aging. This has given an opportunity to study the stress-grading currents of a real stator coil before the aging, and to compare the currents measured by the HV-DS and VF-PRPDA methods. These measurements on real coils are recent and are only in the initial stages. Some results are presented here as they have a relevance to questions raised from the modelling of stress-grading and the measurement of partial discharge currents in machine insulation. Some field measurements have been performed on a small hydro-generator, giving a better idea of practical requirements for diagnostic methods.

#### Structure of this report

The first chapters give some background detail about the very broad subjects of stator insulation (chapter 2), and the theory and practice of the measurement techniques (chapter 3) used in this work. These chapters are quite long and and are only a summary of some points that have been thought useful background to the later chapters and the several possible ways in which this work on combined HV-DS and VF-PRPDA measurements may go. Please skip these chapters if mainly interested in the results of the work done so far.

The reporting of new results starts with the analysis of stress-grading systems (chapter 4), which follows as a detailed study of one aspect of the previous chapter. Some results from the recently started aging tests on real stator coils (chapter 5) are presented and are used to compare the PD currents measured by the HV-DS and VF-PRPDA methods.

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#### 1.2 Acknowledgments

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It seems common in theses and reports to thank one's family for enduring somewhat longer than usual hours close to the time when laboratory equipment, test objects, and computers have to be coaxed into producing the final sets of results for a writing-up deadline. In spite of confidence that the few remaining parts would be finished quickly, since "they are so small, there is nothing really to go wrong", there were in fact several small delays — so, I too feel need of such a line to thank Malin, Nicholas, Philip and William for putting up so very well with some rather extended working times of late!

### Chapter 2

## Stator insulation systems

Rotating electrical machines, i.e. motors and generators, here on often referred to simply as 'machines', cover a vast range of ratings and constructions. This work is focused solely on the stator windings of three phase alternating current synchronous or induction machines with a rated line voltage of at least several kilovolts; 5 kV r.m.s. rated line voltage ( $U_{\rm N} = 5 {\rm kV}$ ) is about the level where the construction and working stress make this work relevant.

Machines of this voltage rating — high voltage (HV) machines — have power ratings in the order of hundreds of kilowatts to hundreds of megawatts, and usually have mica-based insulation systems of well defined geometry. Such machines are responsible for almost all electricity generation and for much industrial consumption, so there is already a lot of interest in on-line and off-line condition assessment of critical parts. Note that this work is directly relevant only to off-line measurements, since the use of varied, low, frequency of the electric field in the insulation is fundamental to the methods considered.

This chapter gives a description of the major variations in the stator insulation system of the relevant set of machines, then an overview of current industrial practice in condition assessment methods.

#### 2.1 Construction of stator insulation systems

The construction of HV machines and particularly their stator insulation is described here in order to assist understanding of the various diagnostic methods treated later. Much of the insulation-specific detail here has come from [SBCD04]. Beware of taking too literally such generalisations as "in the range 200–1000 MW" — such bounds are approximate and there will probably be an exception.

#### Geometry and variants of HV machines

Large AC machines consist of a cylindrical iron rotor moving within the bore of an iron stator. Both of these parts have electrical windings of insulated conductors arranged to produce a magnetic field linking the turns of the rotor and stator windings. The stator winding is formed by conductors within slots in the surface that faces the rotor. In these windings the working power of the machine is generated or dissipated. The rotor winding is of similar slotted construction to the stator in high-speed machines, or has windings around protruding pole-pieces on lower speed machines. The rotor conductors are excited by a DC supply, and have a maximum voltage to earth of only a few kilovolts even on large machines.

The number of magnetic pole-pairs around the stator or rotor is an important feature of a machine: this determines the ratio of the (fixed) electrical supply frequency to the frequency of mechanical rotation. Gearing of the huge powers involved in electrical generation is hugely impractical compared to adapting the electrical machine, by adjusting the number of pole-pairs, to interface different angular speeds of electrical system and mechanical power-source.

Hydro-turbines move at quite low speeds and their attached generators therefore often have many pairs of poles and rotate at low speeds of a few revolutions per second. To allow such a large number of pole-pairs to be accommodated the diameter of the machine is very large. The rotors of such machines are of the "salient pole" type, with mushroom-shaped iron pole-pieces protruding from a central rotor core. The rotor windings are then around the sides of the pole-pieces.

Steam-turbines and gas-turbines operate at higher speeds, often sufficiently fast — 3000 rpm on a 50 Hz system — for their attached generators to have just one pair of poles. The rotors are then of modest diameter and considerable length, and are of slotted cylindrical construction, often called "round rotors".

Through the power-range of interest, about 1 MW to over 1000 MW, there are various differences in design of windings depending on power-rating, age and the mechanical power source or load: the winding construction and cooling methods are of particular relevance to the stator insulation system.

#### **Cooling systems**

To remove heat from the windings and iron, several methods may be used. These fall into two main groups: indirect cooling, which removes heat from conductors after it has passed through the insulation, and direct cooling, which removes heat from by circulation of a fluid within the windings.



Figure 2.1: Cross section of one of the many poles of a large ( $\approx 150$ MVA) hydrogenerator, showing stator (top) and salient-pole rotor (bottom) with some stator slots occupied by sections of stator bar. Thanks to NTNU Trondheim on whose wall this example hangs.

Indirect cooling is used in three variants: open-ventilated indirect-cooled machines have air from the environment passed through the machine; recirculated air or recirculated hydrogen cooling uses enclosed air or hydrogen circulated within the machine and cooled by a heat-exchanger with air or water on the other side. When using recirculated gas, it is possible to pressurise the machine's containment, improving the (volumetric) heat capacity of the gas. Hydrogen has a particularly good heat capacity.

Direct cooling uses either purified water or hydrogen, circulated either through hollow conductors or through separate ducts alongside the conductors. This is used as a supplement rather than as an alternative to indirect cooling, for cases where the advantages of better cooling outweigh the considerable cost and complexity of the inclusion of ducts, connection of ducts in the end-winding region, and external apparatus for treating and cooling the fluid.

Only small machines use open-ventilated indirect cooling. Modern turbo-generators up to a few hundred MW are indirectly-cooled by recirculated air, and larger ones by recirculated hydrogen, while before the 1990s cooling by recirculated hydrogen was sometimes used even at such low ratings as 50 MW. Direct water-cooling is used in hydro-generators at ratings above about 500 MW. Modern turbo-generators have direct hydrogen or water cooling of stator-windings at ratings above about 200 MW, though older designs (1950s) use direct cooling of machines as small as 100 MW.

#### Electrical consequences of cooling systems

Use of hydrogen at greater than atmospheric pressure has further positive effects on the electrical insulation. The breakdown strength of the higher-pressure gas is greater than for atmospheric air, resulting in reduced risk of PD in the slots and end-windings. The absence of oxygen means that oxidative thermal deterioration of the insulation is reduced, which is relevant both to the deterioration due to operating temperature and to that due to PD. Ozone detection systems, mentioned later, will not be of use in hydrogen-cooled machines since there is not significant oxygen present to form the ozone.

#### Stator insulation requirements

A high-power machine must have a large product of stator-terminal current and voltage. Making either of these quantities large is however undesirable since high voltage puts greater demands on the insulation, while high currents necessitate thick conductors (bending problem, skin effect, eddy current losses) or many parallel connections (circulating currents, complex connections in the end-windings) and makes harder the matter of transferring current from the terminals (losses, magnetic forces). The compromise position chosen as optimal, changing little over the years, is that the voltage used in the stator is up to around 30 kV line-voltage on the largest ratings, and is indeed about half this value even for very much lower powers of tens of megawatts.

A particularly strong constraint imposed by machine design is that every bit of space around the conductor area is very valuable: all electromagnetic machines are a compromise between "iron" and "copper" (magnetic and electrical conductors) and to the electromagnetic designer any insulation is just an unfortunate necessity that must be kept into as small a cross-sectional area as possible.

The windings operate at high temperature, due to the need to use space efficiently and therefore to economise on the area of conductors. The conductor temperature of indirectly-cooled windings is determined by the insulation's thermal properties, with thinner and more thermally conductive insulation being desirable. The temperature also affects the insulation's deterioration, since for an air-cooled machine a reaction with oxygen is responsible for some of the aging of the organic insulation material and this reaction is thermally activated.

#### Coil or bar stator windings

Machines of more than about 1 kV (at which voltage there is a maximum practical power of some hundreds of kilowatts) always have "form-wound" stators: the windings are carefully prepared with conductors and insulation before being inserted in the stator.





Up to about 50 MW a "coil-type" form-winding is used, in which a multiturn loop of conductors with insulation is prefabricated ready to be inserted so that the two long parallel sections (legs) fit into two stator slots and the remainder protrudes from the ends of the stator. This is quite simple to construct as one end of the stator then has no extra connections needed; the connections are just continuations of the coils.

For larger ratings it is impracticable to fit so thick and rigid a coil into the stator, and it is desirable to have transposition of the subconductors of each turn (described in the next paragraph) to reduce losses. The windings for machines of such high power rating are therefore fabricated in single bars for insertion in the stator: this is a "bar-type" or "Roebels-bar" construction. It is then necessary at each end to make connections between individual conductors, which is complicated still further if channels for direct cooling are present.

#### Stator conductors

Within a coil or bar, there are several mutually insulated conductors — about ten, as a very rough idea. A high-power machine has high currents: if each winding turn were a single copper wire, this wire's cross-section would be so great as to



(a) Cross-section looking axially, of the insulation system within the slot of a quite low-power machine (no stranding, indirect cooling). There would typically be two separate coils in the slot, stacked vertically. (b) Cross-section looking radially, of insulation around the slot to end transition region. The insulation itself continues in the slot, but the slot semiconductor changes to the higher-resistivity non-linear end-winding stress-grading, with some overlap

Figure 2.3: Diagrams of the construction of a simple stator insulation system

cause unacceptable skin effect and eddy current losses. Several smaller conductors, the "strands" or sub-conductors, are therefore connected in parallel to form a larger conductor. The strands in a bar-type winding are arranged to change position regularly (transposition) in order to minimise differences in the induced voltages that could arise from different magnetic conditions in different parts of the slot. Strands in a coil-type winding usually do not need this transposition as the smaller machine size results in less distance between different strands; an inverted turn at the end-winding can be used to swap inner and outer parts between the two slots that a coil occupies. "Turns" of parallel strands are then connected in series to form whole coils, which are themselves connected to form whole windings.

The set of conductors and insulation that is put in each stator slot is conventionally of rectangular cross-section with rounded edges, constrained by cross-section demands of the iron between the slots and by the practicalities of making the winding. Often a stator slot contains an arm of each of two coils, stacked radially. The open top of the slot cannot be closed by metal on account of electric shorting between laminations and induced voltage along such a metal strip. To hold the bars or coils in place, insulating slot-wedges are slid along the outside of the slot.

The corners of conventional bars result in a non-uniform electric field in and

around the insulation and therefore in some over- or under-stressed regions. Some recent development has been made of fundamentally different insulation systems, based on circular-section conductors of cable-insulation design, but this has not become at all widely used.

#### Stator insulation geometry

Strand insulation can be very thin, as the expected voltages between strands in the same turn are small ( $\approx 10$ V). It must however be mechanically strong against erosion, and able to withstand high temperatures. At points where the strands have a transposition, extra insulation is often needed to fill the gaps.

Turn insulation must be able to withstand the voltage of some hundreds of volts between turns in normal operation. It must be also to withstand the much higher voltages that can result from transients coming to the generator terminals from outside; a high frequency signal is distributed very disproportionately much over the first turns of the winding next to the terminals, due to the high inductance of the slot part of the windings.

Since the 1970s many manufacturers have used a strengthened strand insulation to obviate the need for turn insulation.

To insulate the outside of the turn insulation from the stator-core's earth potential a further layer, the "groundwall" or "main" insulation, is used. This is the thickest insulation layer, as near the phase terminals it must be able to insulate the full phase to earth voltage, often many kilovolts.

Although the groundwall thickness could be varied along a winding from a small amount at the neutral point to the necessarily greater thickness near the phase terminal, this is avoided for simplicity of geometry; a life-lenght prolongation trick facilitated by this is the reversal of the connection of a winding so that the previously higher-stressed parts of groundwall are stressed less than the other end, so prolonging the insulation's life.

For machines operating at more than about 6 kV the groundwall insulation in the slot region is covered with a semiconductive (poor conductor, 0.1-10 k $\Omega/sq^1$ ) compound, usually with carbon-black as the conductive component. This is sufficiently conductive to ensure that cavities between the bar and the stator will not be exposed to high enough electric fields to cause partial discharges (PDs) but sufficiently resistive that the laminations of the stator iron will not be shorted out. The laminations are the thin sheets of iron that are stacked together along the axis of the machine, to form the magnetic circuit; they are electrically insulated from each other by a thin layer, to prevent the induced electric field within the machine from driving large eddy currents through the iron. Although the voltages between

 $<sup>^{1}</sup>$ The surface resistivity of a layer of material is the resistance between two opposite edges of any square of that material, independent of the size of the square

laminations are small, the potential currents if laminations get shorted together in several places are large enough to cause significant heating and sparking with bad effect on the surface of the windings' insulation.

The end-winding region is the part of the winding outside the stator-core, where the bars or coils through the stator are connected to each other to form windings.

With the zero-potential surrounding of the stator core removed, the outer surface of the insulation has a potential due to the conductors inside. In the part of this region close to the stator the electric field in the surrounding medium (air or hydrogen) on the groundwall's surface would be particularly high due to concentration of the electric field from the end-windings, as described in more detail in section 4.1. This may lead to PDs on the surface, with damaging effect. As the end-winding of large machines is a mass of connections and is therefore sensitive from an insulation perspective, it is preferred that the end-windings should be allowed to be remote from earth potential. It is therefore not desirable to coat the end-windings with a quite conductive semiconducting compound such as that used within the slot.

Instead, a semi-conducting coating with much higher resistivity, usually including Silicon Carbide (SiC) to give it a non-linear current/voltage-gradient relation, is applied for several centimetres from the end of the winding's outer semiconducting coating of relatively low resistivity. The surface potential then falls off quite smoothly along the end-winding insulation surface towards the stator, and surface discharges are avoided. The grading and semiconductor materials are applied as paint or, in more modern designs, as tapes. SiC-based materials are returned to in section 4.1.

#### Stator insulation materials

In [BS04] a detailed description of the development of the mica (or its forerunners), binding resins and impregnation processes is given. [SBCD04] is more extensive, and has more industrial detail, e.g. about some of the large number of trade-names used by generator manufacturers for their variations on the general themes of the materials and processing methods that are outlined below. [Rux04] has a short and practical descriptions of characteristics of the main types of binding resins.

The following summary of materials and processing methods is primarily aimed at relevant dielectric features of the insulation systems in machines that are still in widespread use.

Since the end of the days of organic cloths with oils or resins on them (late 1800s and first decade of 1900s) stator insulation has been based on mica. Mica is a mineral occurring in thin lamina, chemically very inert and consequently favoured for many high-temperature insulation applications. It is enduring of moderate partial discharges and has very high resistivity.

#### 2.1. CONSTRUCTION OF STATOR INSULATION SYSTEMS

The mica is now usually applied as a 'paper' of small flakes, on a thin glass fibre backing tape, wound onto the conductors. A further impregnating or 'binding' substance is needed between the mica flakes, to provide mechanical strength and to fill the gaps that would otherwise have a low dielectric strength. This material is generally a bitumen or synthetic resin.

In older machines still widely used, manufactured between about 1920 and 1960. asphaltic bitumen was used as the binding material. This is often called either bitumen or asphalt, in relation to machine insulation. This substance is a residue of the distillation of crude oil. It contains a wide variety of molecular sizes of predominantly long, straight chain hydrocarbons with a high degree of saturation and with some sulphur, nitrogen and oxygen. The non-hydrocarbon elements give rise to dipole moments, e.g. from attachment of oxygen to carbon in the unsaturated chain, leading to a slow-moving dipolar component in the dielectric response. Bitumen has also a higher conductivity than the modern replacements, and is more prone to adsorb water. It has the risk of softening or even running out of the windings at high temperature. High temperatures can also cause the removal of more volatile components, and oxidation or cracking of remaining molecules, which leads to reduction in bonding strength and embrittlement at room temperature. Voids in the insulation can be formed due to cycles of softening of the bitumen. Bitumen is therefore limited to temperature class B ( $130^{\circ}$ C), and the working electric stress is usually designed to be less than 2 kV/mm, which avoids significant discharge activity in such voids.

The next generation of insulation materials, from the 1940s on used synthetic polymers as the binding material. Polyester and epoxy resins are thermosetting (crosslinked) polymers that have had wide use in machine insulation. Polyester resins formed by condensation have oxygen atoms double-bonded to some parts of the carbon chain, forming permanent dipoles which increase the permittivity and the absorption of water. Epoxy resins have superior properties: they are non-polar, mechanically strong, highly resistant to chemical attack, well adhesive to most materials, and they have no by-products of formation. They are, however, more expensive than polyester resins, and require more careful control of the curing process in which the cross-linking is formed. Nevertheless, epoxy resins are the currently preferred type for high voltage stator insulation. The working stresses of modern synthetic resin insulation systems can be as high as 5 kV/mm [BS04]

There are several ways of forming the final system of mica flakes bonded within a cross-linked resin binding material. Some modern resin insulation systems use a tape that consists of a backing fabric for strength during winding, on which are mica flakes already in an incompletely cured resin; these are called 'B-stage' tapes, and curing at elevated temperature e.g. 160°C is then needed to cross-link the resin. Vacuum-pressure impregnation (VPI) is instead used when the mica tapes have no resin in them. The taped bars or coils are put in a chamber which is evacuated to a low vacuum, removing the air from the spaces within the insulation. The impregnating material is introduced as a liquid, and the pressure in the chamber is increased to much more than atmospheric pressure, forcing the impregnating material into the spaces. Global VPI is the VPI treatment of an entire assembled stator, with all windings and the iron core. This forms a strong bond between the core and the bars or coils.

#### 2.2 Condition Assessment

Condition Assessment, often abbreviated to CA, is the process of estimating the state of a piece of equipment in order to estimate probabilities of failures and thereby to make a good choice of maintenance tasks and times. Stator insulation is arguably among the more difficult components for condition assessment in highvoltage engineering: much of it is hidden, there are many interacting factors that affect aging, and one small problem area is needed in a long winding to fail the entire machine.

Condition monitoring (CM) is the part of condition assessment concerned with measuring some property of a component. Some widely used forms of condition monitoring for stator insulation are here described, and the two electrical off-line methods of interest for this work are covered in more detail in later chapters.

#### **Reliability of generators: components**

The main parts of a machine that are most susceptible to aging and consequent failure are the insulation systems of the two windings, and the bearings that support the rotor.

There are many parties interested in statistics on the frequency and severity of failures of machine components; these details are of interest to machine owners, government regulators of electricity supply, reliability councils and insurance companies. Comparison of such data, and indeed interpretation even of a particular source, is complicated by large differences in relative failure probabilities and costs for different types, sizes and ages of machines and the various ways in which the components of the machine may be divided. There is also the problem that the root cause of a fault and the most obvious manifestation of the fault may be in different components; some faults manifested as stator insulation breakdown may have come quite rapidly from mechanical damage due to defects in the stator core or loose particles from the rotor. Unless the damage progresses slowly up to breakdown then regular off-line measurements of the stator insulation's electrical properties will not help to predict such faults.

If interested in the relative importances of difference parts of the machine for reliability, i.e. for which component a certain investment in effective monitoring and maintenance is most profitable, then attention should be given to how severe each type of failure is in terms of repair costs and expectation of time out of service.

#### 2.2. CONDITION ASSESSMENT

High-voltage stator insulation tends to win in this product of frequency and severity, compared to the other major parts!

In [vBGS04] a table is presented, compiled from failure data from nearly a thousand gas- or steam-turbine driven turbo-generators in North America. For the air-cooled gas-turbine driven machines of mean rating 50 MVA the high-voltage insulation has the longest down-time per outage and is responsible for about four times as much down-time per year than all the other failures combined. For the hydrogen-cooled steam-turbine driven machines of mean rating 160 MVA the other failures in the groups 'mechanical' and 'rotor winding' account together for more mean down-time per year than the high-voltage insulation, but each of these groups is smaller on its own. A survey of hydro-generators in North America cited in [SBCD04] has suggested around 40% of outage-causing faults to be due to stator insulation, and fewer to the rotor (the remainder are mainly mechanical).

The bearings of large or critical machines are monitored on-line for vibration and temperature, and even quite small machines of a few MW often have regular scheduled measurements. Bearing problems can even arise due to winding problems if an asymmetry in the magnetic field is caused by for example turn-shorts.

The rotor insulation has lower voltages to insulate, since 1 kV (DC) is about the maximum normal excitation voltage, but has less direct cooling in the larger machines and has to operate with large forces on it due to the rotation. The thermal conditions under highly excited conditions can also be very severe.

On-line electrical monitoring of rotor insulation is hard with many designs of excitation system (rotating exciter or DC machine), since there is not direct electrical connection from the stationary part of the machine to the rotor winding. A short-circuited turn in the rotor only results in a less effective field, in contrast to the case of the stator where the alternating magnetic field would cause a huge current to flow in that turn; the rotor turn insulation is therefore not as critical a candidate for continual monitoring. A rotor earth-fault can also be mitigated by systems that use an excitation source that is not solidly earthed, i.e. a single earth fault causes no immediate electromagnetic change, so can be tolerated for a period until a suitable maintenance time arises.

Stator insulation on almost any machine of the power ratings of interest in this work undergoes periodic off-line inspections and diagnostic measurements. The more critical machines also have various degrees of on-line monitoring of stator insulation, generally seen as complementary to the off-line methods. The remainder of this chapter outlines some common on-line and off-line methods.

#### Stator insulation aging mechanisms

A common description of the mechanisms causing aging of stator insulation groups them as "Thermal, Electrical, Ambient and Mechanical". This order leads to the acronym TEAM, which apparently is preferred to the four other English words that permutations of the mechanisms' names could otherwise have produced. These TEAM stresses are widely mentioned in dicussions and analyses of aging. Ambient refers to several factors such as attack by chemicals or by photons of ultraviolet and in some cases (e.g. nuclear power stations) higher energies. There is large interaction of these mechanisms: for example, mechanical formation of voids which together with high electric stress can cause partial discharges (PD); these in turn generates heat, ultraviolet light and chemicals such as ozone, and thereby encourages mechanical wear at the attacked insulation surface by thermal and ambient stresses.

Thermal deterioration of the organic binding component of the insulation, particularly in air-cooled machines, is a continual process, often simply modelled with an Arrhenius-rate reaction, i.e. an exponential relation of rate to temperature above a minimum value. The deterioration leads to more brittle insulation material, which in turn can increase the effect of vibrational aging.

Thermal cycling may cause stresses and movement of whole bars (complete with groundwall insulation) axially relative to their slot, or for quick changes in load the forces from differential expansion may cause internal movement in the bar, between conductors and insulation. The copper windings are the main heat-source when at high load, so these warm up faster than the surrounding iron and reach a much higher temperature, besides having different coefficients of thermal expansion. Mechanical stress and/or movement occurs therefore during changes of load.

There are large forces between conductors even with the currents of normal operation; separate conductors within a bar, separate bars within a slot, and nearby connections in the end-winding region all experience forces that alternate at twice the power frequency and that can damage the insulation in regions where there is looseness that allows movement. During a short circuit the forces can be many times greater, possibly causing internal damage that initiates longer-term degradation; the bars must be very firmly held in place particularly in the end-winding regions where they do not have the stator iron and slot-wedges to constrain them.

Electrical stress can cause electrical treeing, a change in the insulation material along channels in the field, which may grow enough to cause a breakdown of the insulation.

Partial Discharge activity, although not rapidly damaging to mica insulation when discharges are small, wears the binding material by the effects of local heating, ultra-violet light and production of reactive chemicals such as acids and ozone. [Mor05] gives an introduction to, and further references about, wear effects caused by PD.

The semi-conducting coating of the stator bars may wear out, due to the chafing

#### 2.2. CONDITION ASSESSMENT

from vibration in the slot and from thermal expansion, or due to arcing from lamination short-circuits. The end-winding stress-grading materials may also become less effective with time, leading to surface PD. Tape-applied grading is found to be more durable than paints. Stress between windings in the end-winding region, due to bad design or to movement, can also cause PDs. Conductive dirt on the surfaces of the end-windings, in the high surface field, may cause PDs that wear the surface. In all these cases of PDs against the outside of the stator insulation, wear will be caused, possibly leading to a proper breakdown.

#### Off-line measurements on stator insulation

Off-line tests were used even with the earliest machines, before the technology and demands for availability caused on-line monitoring to be of interest. Off-line tests are still used at maintenance times, and allow measurements to be made that give possibly better or just complementary information to that of on-line measurements. Many popular off-line tests are very simple, and application of more sophisticated tests, while of great interest if able to improve diagnoses, has the problem of how their more detailed information should be interpreted to determine the relevant condition details.

Manual and visual inspection of the machine, possibly requiring disassembly of some parts, can detect looseness of bars in slots, wear and residues on surfaces due to repeated PD, signs of overheating and more. The need for internal access rather than, for example, electrical measurements on the terminals or from the endwindings does make direct-inspection methods less convenient in cases where the maintenance is not otherwise requiring disassembly. The risk of making worse the state of a working machine by movement of parts or an oversight during disassembly or reassembly should be borne in mind. It is claimed in [SBCD04] that when conducted by an expert such inspection is the best form; but this surely neglects voids causing PD well within the insulation layers.

When a voltage is applied between the HV conductor and the earthed stator core, some current flows due to material conductivity, free-space capacitance, material polarisation and surface conduction. Chapter 3 describes some methods based on measuring these quantities, and the references [Sto05] and [Eme04] give an industrially oriented view of such measurements.

Insulation Resistance (IR) tests just measure the current flowing after the application of a constant voltage, typically several measurements over several minutes. The IR at a particular time, often denoted  $IR_{time}$  is then defined as the quotient of the applied voltage and the current at that time, although for healthy insulation this so-called resistance will be largely due to polarisation. Healthy modern insulation can be expected to have  $IR_{60s}$  values of of hundreds of megohms, rising to several thousands of megohms for  $IR_{600s}$ . The general increase of winding length and insulation thickness with higher-rated machines makes these values a quite good approximation for a wide range of machines.

Polarisation Index (PI) is a ratio of IR at two different times, typically 10 minutes and 1 minute. This ratio prevents the very high sensitivity of measured resistance to temperature from having so powerful an effect on results wanted for comparison of machines or of a machine over time. It also cancels the effect of the size of the insulation system. An IEEE standard for insulation resistance testing of rotating machines is [Std00b], which tries to give some rationale for the use of this method. Among the dissenters, opining that currently used measurement apparatus and critera are unsuitable for modern insulation, is [GO94], albeit largely about machines with lower voltage rating than of interest here. It is well accepted that a very bad IR result need not at all mean a high probability of insulation failure, and that a very good IR result may be obtained when failure is imminent.

Capacitance and loss measurements of a winding with an applied AC voltage usually at power frequency are widely used. The ratio of dielectric loss to capacitance — the loss tangent  $(\tan \delta)$  — is an important index that cancels the size-dependent terms to give a material property rather than an object property. It is common to take such a measurement with voltage varied from low values to rather over the working value, and to observe the voltage dependence. A gradual increase in capacitance and loss is expected from the stress-grading of end-windings, but a sharp increase in loss beyond a certain voltage implies the inception of PD activity (the tan  $\delta$  tip-up test).

More detailed information about insulation can be found from Dielectric Spectroscopy as described further in section 3.1. The effects of the insulation's free-space capacitance, polarisation and conduction can be seen in different ways by for example long-time measurements of current with a constant or constantly ramped applied voltage, or with a sinusoidal alternating voltage.

"Hi-pot" (high potential) tests are more endurance tests for the insulation than diagnostic methods. This is different from the above methods, all of which can be applied at modest voltages such as rated line voltage applied from phase to earth. A DC or AC source drives the coils with a potential much higher than the rated one, often increased in steps. If a certain over-voltage level (typically 2V + 1, with V being rated voltage in kV) is withstood than the winding passes the test. If the voltage is not withstood, the winding may need to be repaired even though it may have survived for a long time in normal operation. Whether this test is performed, and what voltage is used for it, depend then on the balance between how critical an in-service insulation fault would be and how expensive it would be to repair insulation damaged by the test itself.

Generator insulation is much more tolerant of PD than is the insulation of most other HV apparatus. Some PD activity is acceptable in long-term service of micabased insulation systems, but in tests it may be useful to know some measure of the PD in order to distinguish the pulse sizes and the likely locations and concen-

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#### trations of PD activity.

There are several ways of detecting PD, some of them very crude. Sometimes PD activity is perceptible by sight (the "blackout test") which is of use when interested in PD activity in exposed places such as end-windings, and which allows location of the PD source. An extended method mentioned in [Eme05] uses detection of ultraviolet light from PD, which may be of use when a proper blackout is not possible; "coronascope" is the trade-name of the particular instrument in this reference. Sound can also be used for detection, and ultrasound methods can avoid disturbance by nearby industrial noise sources that lack the high frequency components of sharp PD pulses. Radio-frequency detectors may be used with a probe to locate regions of PD by the signal transmitted through the air.

A machine that can only easily be accessed at its terminals is more suited to electrical methods, with the current pulses into the whole winding as a result of PD being measured. These methods are further described in section 3.2 and in a common industrial implementation allow the number of each of many magnitudes levels of PDs to be seen resolved to the phase-angle of applied voltage at which they occurred, over many cycles of an applied sinusoidal voltage.

#### On-line monitoring of stator insulation

On-line monitoring is clearly highly desirable if its results can be used to keep a machine running for longer between maintenance shut-downs while still detecting problems before they cause severe damage. Electrical measurement of partial discharges can be done on-line, as can measurement of other effects of partial discharges. Further on-line parameters such as temperature are commonly monitored. Monitoring of other factors such as temperature can give a guide to insulation condition. [Sto02] and [KLG04] give a short and wide description of on-line machine insulation monitoring, and [SBCD04] goes into more detail.

Thermal monitoring of the stator windings is used for practically all machines of the sizes under discussion here. Temperature sensors are included in the stator core, or between stator bars or to measure the temperature of a cooling fluid. A large machine may have many sensors and have maintenance personnel make more use of trends over short and long periods than in the case of a less important machine where temperature sensing is mainly for a short-term warning of severe malfunction. Cooling problems, shorts between laminations of the stator core and shorts between strands are among the causes of excess temperature. The exponential effect of temperature on reaction rate for binding resins around operating temperature makes thermal aging due to hot-spots significant.

Generator Condition Monitoring (GCM), is the rather broad name often used for the specific method of detection of chemical products of hot insulation material. It is implemented as a sophisticated smoke detection system relying on the removal of ions from a chamber by their binding to smoke particles. In some machines a tracer paint may be used on critical areas, to release easily detectable chemicals at a well-defined temperature. Use of different paints in different parts of the machine allows still better location of a problem. An extreme GCM reading can be used as a warning to operations staff, but in most cases the GCM is of interest to maintenance staff; a long-term analysis is useful to spot problems such as the sporadic burning due to shorted laminations burning insulation in small areas.

Ozone  $(O_3)$  monitoring of enclosed (recirculated cooling) machines may be acheived by a sensor inside the machine enclosure, for continuous monitoring. An openventilated machine may instead have ozone measurement by simple manual exposure of a test chemical that reacts with ozone. Ozone is produced by electrical discharges, so ozone detection methods are sensitive only to PDs that are not internal to the insulation, i.e. they may be slot discharges between the groundwall insulation and the stator core due to deterioration of the semiconducting layer or to loose bars, or may be discharges in the end-windings due to wearing of the stressgrading semiconductive layer or to excessive proximity in the end region. Single PD sites are unlikely to produce measurable quantities of ozone, and general wear in poorly represented areas, e.g. the stress-grading of the end-winding rather than the semiconductive layer all along the slots, will show only weakly even if the localised activity is strong. Trends, even over a long time, are important as with GCM, if the measurements are to be usefully interpreted for phenomena other than severe declines in condition.

Radio frequency or inductive coupler methods can be used to detect PD signals emitted from the windings, using several receivers. Some ambitious schemes have used large numbers of such receivers to provide on-line localisation of PD to a quite accurate determination of the affected slot.

Monitoring of PD on-line may be acheived by direct electrical methods with a coupling capacitor, or by radio frequency or inductive coupler methods. By the use of several measurement points some location of the PD signal may also be made. Implementations of the multiple sensor method range from capacitive couplers on diametrically opposed parts of the end rings connecting windings around a largediameter hydro-generator, to inductive couplers on the ends of individual bars. The PD measurements are then made at realistic (actual!) operating conditions of three-phase voltages between the windings, and actual operating temperature and vibration. This may not be as effective as off-line variation of the voltage and frequency for identifying particular properties of PD sources, but it does mean that the actual amount of PD within the insulation during service can be known, as a guide to the wear it is causing. It is widely considered that a few large PDs are more worrying than the same charge in more smaller PDs. PD is very sensitive to voltage, gas pressure, temperature and cavity size, so to compare PD measurements throughout a machine's operation requires quite close matching of operating

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conditions if trending is be used.

Although not a direct means of measuring the state of the insulation, on-line voltage surge monitoring may be useful in recording times when the external network has introduced a transient voltage to the machine terminals. Since the inductive stator coils are a high impedance to high frequency signals there is a large voltage drop over the first turns in the winding, which may even cause a breakdown in the turn insulation, causing it to be weakened.

### Chapter 3

# Dielectric Spectroscopy and Variable Frequency Partial Discharge Analysis

Dielectric Spectroscopy (DS) and measurement of Partial Discharges (PD) have long been used in various forms for diagnostic measurements on high-voltage apparatus. Use of high voltage for DS and of varied frequency for PD measurements have been investigated in this division over at least the last decade, as novel enhancements of the industrial practices. In this chapter both methods are described, considering first the phenomena they measure, then measurement systems and the application of the methods to stator insulation. The beginnings of the sections may seem a little laboured over matters of for example polarisation. The reason is that consideration at this lower level than just macroscopic bulk properties has struck me as useful when thinking about more complex systems and geometries. Far less work has been done so far in this project on PD than on DS methods, so the details about the PD system and measurements are less extensive.

#### 3.1 Dielectric Spectroscopy

Dielectric Spectroscopy (DS) is a name for a group of methods for measuring time or frequency dependent properties of the polarisation of charges in materials. These properties are the material's Dielectric Response (DR). DS methods are widely used in chemistry, and have recently received renewed interest for condition assessment of some HV apparatus. In HV equipment, DS often measures some further effects not arising directly from polarisation of molecules, which limits the use of DS as a measurement of material properties but may still allow DS to give useful information about changes and defects in insulation system as a whole.

In this section a description is given of the sources of DR currents, some common DS methods, and some approaches to treatment of non-linear responses. The develop-

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ment of practical application of DS methods, and the functioning of the equipment used for DS measurements in this work are then described. Jonscher's Dielectric Relaxation in Solids [Jon83] is quite the best reference that can be offered for covering the theory of this subject in a way that makes it immediately useful. It covers acquisition, analysis and presentation of dielectric response data, and emphasises the virtues and limitations of difference measurement and presentation methods. It then presents a lot of experimental data to make the point that power-law models give a very good description of solid dielectrics. [Zae03] is a recent summary of the application of DS methods to HV equipment, following a line of developments in power applications that are referenced later in this chapter.

#### Dielectric materials and relaxation

Any material consists of atoms and therefore of positive and negative charges. When an electric field is applied to a material (canonically by putting excess positive and negative charges next to two opposite sides of a volume of the material, by means of conducting plates), the charges in the material experience forces pulling the positive and negative charges in opposite directions. The electrical properties of the material depend on how the charges are able to move under this imposed force.

In a good conductor, e.g. copper which has a resistivity  $\rho = 1.7 \times 10^{-8}\Omega m$ , there are so many free charges that even a weak electric field (in the order of millivolts per metre) causes a large current density of the moving charges. The maximum field is then limited by the source of the initial electric field being able to maintain the field while carrying the conduction current, or by the material becoming too hot from the losses! There is therefore no practical interest in the dynamics of charge in good conductors, at the low frequencies of interest with HV equipment; conduction current is dominant and practically instantaneous.

In a good insulator, e.g. XLPE which has a resistivity  $\rho \approx 10^{16}\Omega m$ , there is little free charge: a large electric field (in the order of megavolts per metre) can be applied to the material with little conduction current. With so little conduction current, the effect of displacement of bound charges becomes significant, still more so in the much higher electric field strengths that can then be applied to a good insulator.

Bound (non-free) charges can move only small distances, on account of a binding to other (opposite) charges nearby that is stronger than the force from the externally applied field. A wider definition of bound charges may include those that can move freely (conduction) for a distance of many atoms but are prevented by some barrier from travelling all the way between some conducting electrodes that apply the external field.

When the positive and negative parts of bound charges get displaced from each other by an applied field, the movement is in the direction that reduces the field in the material, i.e. that results in a positive surplus closer to the negative charges that

#### 3.1. DIELECTRIC SPECTROSCOPY

are producing the applied field, and vice versa. The difference in electric potential between the charges producing the applied field is therefore reduced.

In the practical applications of insulating materials, the material is between electrodes that are connected to a stiff voltage source. In this case, the reduction in potential difference between the electrodes that is caused by charge displacement in the material is rapidly countered by current from the voltage source. The charge required from the source is proportional to the product of the charge that has moved in the material and the difference in electrostatic potential through which it has moved; the related product of charge separation distance and charge quantity is an often used quantity called the dipole moment. The material is therefore exposed to a field determined by the external source, and the external source has to provide an extra current that is the time-derivative of the amount of displacement (polarisation) in the material. This extra current is called the polarisation current or displacement current, and is usually the quantity measured in DS methods. Some polarisation mechanisms are slow enough to have a significant delay compared to the changes in applied field. The polarisation can then be seen as time or frequency dependent, and this variation is called dispersion, hence the commonly used term 'dispersive media'.

#### Polarisation mechanisms

There are several distinct forms of charge displacement, of which more detail is given in [Jon83] and [Hel00].

Electronic polarisation is inherent to all materials and is a consequence of displacement between an atom's nucleus and electrons against the electrostatic force that binds them; an equilibrium position is reached very quickly, so there is negligible delay from movement of electrons even at optical frequencies in the order  $10^{14}$  Hz.

Molecular or atomic polarisation arises from relative motion of differently charged atoms within molecules that have no overall dipole moment; this has modes in the infra-red frequency range due to the movement of nuclei, as well as higher frequency modes due to movement of electrons.

Dipolar polarisation is the displacement of the mean position of permanent dipoles, e.g. water, such that they have a resultant electric dipole moment superimposed on the thermal motions; for small dipolar molecules the resonant frequency of this bound movement is still very high, e.g. gigahertz. An example of a much slower polarisation from permanent dipoles is the polarisation of segments of polymer chains. Some parts of the chain may have single bonds permitting rotation, but this requires overcoming the high-energy state when atoms joined to the segment pass by neighbouring atoms during this rotation [Ged95]. The polarisation of these groups is then a electric-field induced bias in the disordered thermal motion as rotating parts of the polymer chain get, randomly from the distribution of thermal energies, enough energy to overcome the elastic barrier. Significant increases in polarisation are possible even after thousands of seconds, in constrast to the fast mechanisms described above.

Space-charge polarisation is due to charge carriers that are able to move over greater distances than the atomic scale, and accumulate at barriers such as interfaces to other dielectrics with less freedom of movement. A considerable imbalance of charge therefore builds up in some parts of the material, as distinct from the previously listed polarisation mechanisms in which any volume of more than a few atomic distances is charge neutral.

Other less simply explained forms of polarisation are identified in dielectrics literature. Low-frequency dispersion (LFD) shows the two characteristics of polarisation — energy and charge storage and energy loss — continuing to increase even at very low frequencies down to the limit of measurement.

'True' or 'DC' conduction through a material is a steady-state process in which the charge density, and therefore also the electrostatic potential throughout the material, stay constant but charges are transferred all the way between the electrodes. Conduction therefore is sustainable for any period and stores no energy, as distinct from polarisation mechanisms that can return some of their stored energy and necessarily for a movement of bound charges have some limit, even if not a practical one, to how much time they can continue. Features of dielectric measurements described in the following section can be useful in separating conduction and polarisation phenomena from measured results.

#### **Dielectric response relationships**

There exists a lot of theory and terminology about DR from various disciplines. The main relations between applied electric field strength and displacement and conduction currents in dielectrics are presented, with some of the notation that is widely used. This description will start with time-domain methods and move to the frequency-domain complements that are used in the rest of this work.

Free space (vacuum) has the property that electric charges can interact across it. Any electrode arrangement such as a material measurement-cell or a stator winding and core, has even in the absence of any material between the electrodes a capacitance, i.e. an amount of charge that must be moved from one electrode to the other in order that the difference in electrostatic potential of the electrodes — the energy needed to move a (small) charge between them — should change by some finite amount. The geometry of course affects this capacitance, with greater separation of electrodes requiring less change in charge for a change in potential (lower capacitance) and extended electrodes at a constant separation giving a higher capacitance.

The factor that relates the geometry-dependent terms of the capacitor to the actual capacitance of the electrode arrangement is the the permittivity of free space,  $\varepsilon_0$ , a universal constant defined by the SI system of units as  $\varepsilon_0 = 1/(\mu_0 c^2) \approx$ 

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#### 3.1. DIELECTRIC SPECTROSCOPY

 $8.854 \times 10^{-12}$ F/m. The capacitance of a pair of electrodes with no material between them is the product of this permittivity and of the geometric term (equal to 1 for electrodes between opposite faces of a 1 m cube if ignoring fringing). This free-space capacitance is commonly denoted  $C_0$ , and is a useful quantity when one starts considering properties of specific electrode systems, such as stator windings, rather than just material properties.

Unless we are concerned with the time taken for changes in electromagnetic fields to travel through space, which here we are not, then the effect of  $C_0$  is instantaneous. The charge  $\Delta Q$  that must be moved between electrodes to effect a change in potential difference between the electrodes ('voltage') of  $\Delta V$  is therefore  $\Delta Q/\Delta V = C_0$ , without any dynamics — the charge, and therefore its time derivative the current, have a static relation to the voltage between the electrodes.

For reasons outlined in the above section, all material is to some extent influenced by an electric field, to become polarised in a way that shifts the positive and negative charges so that they reduce the potential difference between the electrodes that are applying the stimulating electric field. As long as this polarisation is linear (proportional to the applied electric field) and is too fast for its dynamics to be noticeable, then the polarisation can be seen as simply having increased the capacitance of the electrodes beyond the free-space value.

In many engineering applications where polarisation dynamics are negligible the permittivity of free space is simply augmented by a further multiplicative constant the relative permittivity  $\varepsilon_r$  or 'dielectric constant' of a material whose effective permittivity is then  $\varepsilon = \varepsilon_0 \varepsilon_r$  and likewise the capacitance of some electrode configuration with such a material is  $C = C_0 \varepsilon_r$ .

In situations where some fast polarisation dynamics can but other slower ones cannot be neglected, the capacitance due to the fast polarisation is often represented in the same way, lumped with  $\varepsilon_0$  as a single constant  $\varepsilon_{\infty}$ , representing the free space permittivity and the fast polarisation mechanisms, the  $\infty$  being a slight exaggeration signifying the very high-frequency of those mechanisms that are being treated as static. The combination of the free-space permittivity and very fast polarisation mechanisms is often called the 'prompt' response.

For the purposes of DS, particularly when measured in the frequency domain, the prompt response can all be bundled up in one term in this way, leaving the all-important dynamics of slower polarisation mechanisms to be treated.

From the descriptions of polarisation mechanisms, it follows that polarisation is a tendency to an equilbrium, hence another commonly used description as 'dielectric relaxation'; a changed electric field changes the equilibrium positions of charges in a material. This equilibrium is not static, but an average state among randomly moving thermally excited atoms. If the polarisation, i.e. the volume density of dipole moments, of the non-prompt mechanisms at time t = 0 is P(0), and at this time the applied electric field E becomes and remains such as to give an equilibrium.

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rium polarisation of P', then P(t) will tend asymptotically and monotonically to P'.

The dielectric response function f(t) describes the dynamic response of a dielectric's polarisation mechanisms: it describes how much polarisation will exist at time t after a certain amount of polarising effect, i.e. product of electric field strength and time for which that field is applied, has affected the dielectric; more rigourously,

$$P(t) = \varepsilon_0 \int_0^\infty f(\tau) E(t-\tau) d\tau$$
(3.1)

and several conditions exist on f(t) as axioms of much of the usual analysis of linear dielectrics should work: the function must be causal  $(f(t) \equiv 0 \text{ for } t < 0 -$ "the present doesn't depend on the future"); it must tend to zero at long times  $(\lim_{t\to\infty} f(t) = 0 - \text{ every polarisation relaxes in the end})$ ; it must have a finite integral  $(\int_0^{\infty} f(t)dt$  finite — there is a limit to the amount of polarisation possible in the material); it must also be linear and susceptible of superposition of the effects of different stimuli, as suggested by (3.1), although this is only an aid to analysis and is not physically obvious as at least the first and third point above are.

Step function excitation simplifies (3.1), removing the convolution: the polarisation at t from a step from 0 to  $E_0$  at t = 0 is just an integral of f(t)

$$P(t) = \varepsilon_0 E_0 \int_0^t f(\tau) d\tau$$
(3.2)

As long as very short measurement times are not needed, which would require excessive currents for the initial sharp change of a step function, step excitation is an analytically and technically simple way to stimulate and measure dielectric response.

In the presence of dielectric materials, the free space electrostatic variable of electric field strength E is sometimes conveniently replaced by the electric displacement D which is a measure of the charge density needed at a normal surface to balance the effect of the externally induced and polarisation induced electric field strengths so they do not continue at the other side of the surface ... more practically, it is the charge density,  $C/m^2$  on an electrode of a parallel plate capacitor consisting of a dielectric polarised to P and an electric field strength of E!

$$D(t) = E(t)\varepsilon_0 + P(t) \tag{3.3}$$

in which  $\varepsilon_{\infty}$  is, as described above, sometimes used instead of  $\varepsilon_0$ , to represent all the 'fast' or 'prompt' response, including for example electronic, atomic and some dipolar polarisations as well as the free-space value.

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It may be desirable to study in frequency the phenomena described above in time, for example due to the use of sinusoidal excitation in a particular practical application (power systems). "Convolution in the time-domain is multiplication in the frequency domain", and *vice versa* — so (3.1) may be transformed to

$$P(\omega) = \varepsilon_0 \chi(\omega) E(\omega) \tag{3.4}$$

where the frequency-dependent 'susceptibility'  $\chi(\omega)$  is the Fourier Transform of the dielectric response in time

$$\chi(\omega) = \chi'(\omega) - i\chi''(\omega) = \mathscr{F}\{f(t)\} = \int_0^\infty f(t)e^{-i\omega t}dt$$
(3.5)

whence  $\chi'(\omega)$  is seen as an even and  $\chi''(\omega)$  as an odd function of frequency, and

$$\chi'(0) = \int_0^\infty f(t) \mathrm{d}t \tag{3.6}$$

$$\chi''(0) = 0 (3.7)$$

In time, the total current density J(t) is given by differentiating (3.3) and adding a conductance term

$$J(t) = \sigma E(t) + \frac{\partial D(t)}{\partial t}$$
(3.8)

which, transformed into frequency, is

$$J(\omega) = \sigma E(\omega) + i\omega D(\omega)$$
  
=  $\sigma E(\omega) + i\omega \varepsilon_0 E(\omega) (1 + \chi'(\omega) - i\chi''(\omega))$   
=  $E(\omega)\omega \varepsilon_0 \left[ \left( \frac{\sigma}{\varepsilon_0 \omega} + \chi''(\omega) \right) + i(1 + \chi'(\omega)) \right]$   
=  $E(\omega)\omega \left[ \left( \frac{\sigma}{\omega} + \varepsilon''(\omega) \right) + i\varepsilon'(\omega) \right]$  (3.9)

Making the practical step of separating significantly dynamic polarisation mechanisms from those that are so fast as to be static,

$$J(\omega) = E(\omega)\omega \left[ \left( \frac{\sigma}{\omega} + \varepsilon''(\omega) \right) + i(\varepsilon_{\infty} + \Delta \varepsilon'(\omega) \right]$$
(3.10)

the non-prompt part of the permittivity,  $\Delta \varepsilon'$  is introduced. It is clear that several symbols introduced above stand for quite similar quantities, with sometimes a scaling by  $\varepsilon_0$  or sometimes the addition or subtraction of 1. These are all shown here as they are so widely used and may find their way into discussion, so an idea of their relation is good to have.

A commonly used value for objects rather than materials is the complex capacitance,

$$C(\omega) = C'(\omega) - iC''(\omega) = \frac{C_0}{\varepsilon_0} (\varepsilon'(\omega) - i\varepsilon''(\omega))$$
(3.11)

The multiplication by of some part of  $\varepsilon$  by  $C_0/\varepsilon_0$  gives a corresponding C, e.g.  $\Delta C'(\omega) = C_0 \Delta \varepsilon'(\omega)/\varepsilon_0$ .

Multiplication of these 'point' current density relations by the geometric factor  $C_0/\varepsilon_0$  gives the current  $I(\omega)$  for a particular geometry of electrodes in a medium whose dielectric properties are described by the material properties in (3.9). It is worth stressing that a real insulation system is likely to consist of several different materials, in geometries where the electric field need not be shared evenly. In this case the dielectric response measured at the terminals may have much more variation in time or frequency as a consequence of the connection of materials than as the natural response of any material. For example, two dielectrics in series in the field, with similar permittivity and different conductivity will initially share the electric field evenly due to their capacitances, but eventually the higher conduction current in the more conductive layer will cause surface charge at the interface to reach an equilbrium where the currents are equal, i.e. the more conductive material has proportionately less electric field across it. This simple case introduces a 'relaxation' of the surface charge, perhaps larger in its change than the relaxation within the materials.

#### Dielectric response measurement methods

These dynamic relations of current and applied voltage in time and frequency suggest two branches of methods for measuring dielectric response.

#### Time-domain DS (TD-DS)

TD-DS commonly employs a step in a DS voltage level, often up from then back to zero. This 'polarisation and depolarisation currents' (PDC) method has the advantage of allowing simple elimination of a true DC (conduction) component in the current, since this component is found as the difference between the polarisation (with conduction) and depolarisation (zero electric field, no conduction current), though the charging period must be considerably longer than the discharging in order that the pure polarisation responses of the charge and discharge really will be similar (negated) as is expected from the simple linear-system assumptions. Ideally, each step would be made only with all polarisation relaxed to perfect equilibrium with the initial state of electric field. Time constraints generally ensure that the polarisation part is not fully relaxed even by practical (let alone mathematical) definitions before depolarisation is started, so some reduction in long-time depolarisation current is likely. It should be ensured that the time spent polarising is several times the time for which depolarisation measurements are used.

The step function has the desirable properties of very simple analysis, as the current then is the same function as the response function. Rapid changes in the voltage across a test object are hard to make, as they require so much current. The maximum frequency of TD-DS is therefore less that that of sinusoidal (frequency
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domain) excitation.

Ramped voltage has the virtue of making the prompt contribution to current, which is the scaled derivative of the applied voltage, be a constant. Analysis of an underlying response function is not as direct as with a step.

Return voltage measurement (RVM) methods are also time-domain, but are distinct from all the others in that they do not apply fixed voltage at all times and measure the resulting current but instead apply a fixed charging voltage followed by a fixed zero voltage for a short period (tens of seconds) then open-circuit the test object and allow the combination of conduction currents, free-space capacitance and depolarisation to determine a voltage curve that is measured with a sensitive voltmeter; the curve can clearly be expected to start at zero, directly after shorting of the test object, and to tend to zero at the end when conduction allows the decay of all the polarisation. The relation between RVM and 'conventional' methods is covered in [IGT94].

Time-domain methods are relatively quick for low frequencies, as a single sweep in time covers many low frequencies that would each take a long time for a cycle of alternating voltage to be applied (although if the dielectric could really be assumed linear, several frequencies at one could be applied, and only the same frequency of current considered when detecting the responses).

#### Frequency-domain DS (FD-DS)

FD-DS methods generally apply a single sinusoidal electric field and have the advantage that the detected current can be very finely filtered to remove noise, since only a particular frequency, or small range of harmonic frequencies if some current harmonics must be measured on account of suspected non-linearity, is expected at each measurement point.

For higher frequencies, the limit being dependent on the size of the test object, frequency domain methods tend to be better than time-domain methods, as a sinusoidal signal is easy to apply at high frequencies (it contains only the one frequency).

For our purposes with combined PD and DS measurement, use of frequency domain DS is required in order that both systems can share a voltage source and measure the same phenomena: PD is highly non-linear and therefore its response to some applied voltage cannot just be transformed to a valid response for a different magnitude or time or frequency function of voltage. PD analysis with sinusoidal excitation is by far the most researched form at least for diagnostic use on high voltage insulation.

Measurement of many low frequency points requires many time-consuming measurements, rather than getting all in one go as with TD-DS. On the other hand, noise is greatly reduced with FD-DS, and TD-DS can require many averaged runs to get a clean signal.

Conduction current and prompt response are inescapable in the *measurement* by FD-DS, but if all the demands on f(t) — see (3.1) — are met, there is a way to separate, with possible analytical difficulty, these effects from the pure susceptibility.

Jonscher gives a long overview of time and frequency measurements of dielectric response in chapter 10 of [Jon96].

#### Useful relations between frequency-domain values

The frequency dependent susceptibility has both its components calculated as the real and imaginary parts of a complex number that comes from the Fourier transform of the time-domain response function f(t). As long as f(t) is linear, time-invariant, causal, finite and has a finite integral from 0 to  $\infty$ , there is a necessary relation between these two parts, such that either can be calculated from the other. The relations in both directions between these parts of the frequency-dependent susceptibility (or indeed any Fourier transforms of a function fulfilling the above criteria) are called the Kramers-Kronig relations (3.13).

$$\chi'(\omega) = \frac{2}{\pi} \int_0^\infty \frac{x\chi''(x)}{x^2 - \omega^2} \mathrm{d}x$$
(3.12)

$$\chi''(\omega) = -\frac{2\omega}{\pi} \int_0^\infty \frac{\chi'(x)}{x^2 - \omega^2} \mathrm{d}x$$
(3.13)

from which, for the static ( $\omega = 0$ ) polarisability gives

$$\chi'(0) = \frac{2}{\pi} \int_{-\infty}^{\infty} \chi''(x) d(\ln x)$$
(3.14)

The following are some consequences of the Kramers-Kronig relations.

From (3.14), any polarisation mechanism is associated with a loss in some frequency range; more specifically, moving down from the very high frequencies where insignificant polarisation and loss exist for a particular mechanism, the polarisation at frequency  $\omega$  is the integral of loss with respect to the logarithm of frequency from the high frequency down to  $\omega$ . Hence, the association of the sharpest increases of polarisation with the peaks in loss, as seen in the classical response models, is not just a feature of these models but is a fundamental characteristic of polarisation mechanisms. No dispersion-free material exists, since any material has some polarisability. Of course, at practical frequencies even for microwave work, some mechanisms are so fast that they can be treated as dispersion free. For our purposes with frequencies well below 1 kHz there are many materials with very low dispersion.

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If a measurement on a linear dielectric system gives results that are not Kramers-Kronig compatible,  $\chi'$  and  $\chi''$  are not properly measured or calculated: perhaps some conduction current has affected  $\chi''$  or a bad value for  $C_0$  has affected  $\chi'$ .

If one has a good measurement of  $\chi'$ , from a good knowledge of the geometry of the tested material, but has the a problem of unknown conductivity causing a current that affects  $\chi''$ ,  $\chi''$  may instead be calculated from  $\chi'$  and the conduction current found as the difference of the measured and the Kramers-Kronig calculated values of  $\chi''$ .

Additive quantities such as conductivity are lost in the transformation: the removal of unknown conductance from the loss and prompt capacitance from the capacitance by transformation both ways from  $\chi'$  to  $\chi''$  is a way to remove these *if* the actual polarisation response really did fulfill the requirements for the Kramers-Kronig relation.

The first of these points had a great interest just for what it says about basic features of polarisation and dielectric loss. The others, demanding that one actually use these integral transforms (3.13) on experimental data, carry the price that unless one has nice data that fits an easy function well, then this transformation is timeconsuming.

#### **Dielectric response functions**

Early researchers in dielectrics were able to make sufficiently accurate measurements on materials that the polarisation current of some solid dielectrics could be seen to fit well a 'fractional power-law' time response,

$$f(t) \propto t^{-n}, \quad 0 < n < 1$$
 (3.15)

A mathematical model that has long had favour in discussions of polarisation as a equilibrium state of independent dipoles is the Debye model, with the same response as a simple series R-C circuit:

$$f(t) \propto e^{-t/\tau}.$$
(3.16)

This is considered as a good model where independence of the dipoles can be assumed, but this cannot be said of solid materials or quite a lot of others.

Some uses of DS on polymers involove variations on the frequency-domain Debye model

$$\chi'(\omega) - i\chi''(\omega) \propto \frac{1}{\left(1 + (i\omega\tau)^{k_1}\right)^{k_2}}$$
(3.17)

with the 'empirical parameters'  $k_1$  and  $k_2$  being equal to 1 for the pure Debye response and used singly or together to tweak the response for a better fit to the

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experimental data; these models are hard to avoid in literature on materials.

Wide measurements on solid materials reveal generally a two-stage power-law response with respect to time, as in (3.18), i.e (3.15) but with two different exponents for different timescales, the time  $\tau$  determining the time of the middle of the transition between the two exponents.

$$f(t) \propto \frac{1}{\left(\frac{t}{\tau}\right)^{n_1} + \left(\frac{t}{\tau}\right)^{n_2}} \quad 0 < (n_1, n_2) < 1$$
(3.18)

This response is brought back to the mainstream in [Jon83] which offers pages of experimental data on solid materials demonstrating a great fidelity to (3.18). The relation is analysed further in [Jon96] as a feature of several other physical phenomena than dielectric response.

The descriptions of time-domain and frequency-domain representations of dielectric response referred to a Fourier transform of the dielectric response function. The fractional power-law time-domain model has a very nice Fourier transform that is also fractional power law, against frequency, in both real and imaginary parts but with an exponent which is n-1 and with a frequency-independent ratio of real and imaginary parts that depends on the exponent:

$$\chi'(\omega) - i\chi''(\omega) \propto (i\omega)^{n-1} \tag{3.19}$$

Thus, a time-response that hardly falls (small n) corresponds to capacitance and loss that increase rapidly towards low frequencies and where the loss part is much greater than the capacitance. A time response that falls rapidly at long times corresponds to capacitance and loss that increase only slowly towards low frequencies, with the capacitance much greater than the loss.

An interesting case is when the exponent  $n = \frac{1}{2}$ . This, in frequency, gives equal capacitance and loss at any frequency, with a quite rapid (gradient of -0.5) rise to lower frequency). This is the response of an infinite, distributed series R shunt C circuit [Jon83], which is of some interest later with regard to stress-grading on stator end-windings. A two part fractional power-law response has also been seen in new stator insulation, so this power-law relation is of interest throughout this work.

A power law relation is best plotted in log-log scale, in which a true power law becomes a straight line and the 'universal' response becomes two straight line sections with a curved join. An exponential relation becomes straightened by a log-lin scale, which means that the expected machine insulation case of a power law material and power law or exponential stress grading depending on the frequency, may well not fit either scaling well.

Highly relevant to the foregoing notes about plotting is that when capacitance is measured it is often measured as the sum of a polarisation and a prompt response, in which case C' has an added constant component, and when measuring objects



Figure 3.1: The power-law response, with exponent n at 0.1, 0.5 and 0.9, shown in time  $(f(t) = t^{-n})$  and in frequency  $(F(\omega) = (i\omega)^{n-1})$ . The interesting details to note are that the both the time-domain and frequency-domain functions are powerlaw so are straight in the log-log coordinates, a steep gradient in time corresponds to a small gradient in frequency, the real and imaginary parts in frequency have the same gradient, and the ratio between the real and imaginary parts in frequency is fixed by the exponent n.

with significant bulk or surface conductivity there is an added component to C'' which increases towards lower frequencies. With such extra components added to the pure C' and C'' from the polarisation, it will not be possible to see properly either the straight line slope of a power-law in log-log scale, or whether both C' and C'' have the same slope, or what the ratio of the C' and C'' values is!

#### Non-linearity of the measured system

The above 'classical' treatment of DS assumes linearity of the insulation system. Much of the analysis, such as superposition, Fourier transformations of the dielectric response function, and the Kramers-Kronig relations, breaks down if there is significant non-linearity. To explore the further dimension of the voltage dependence, more tests would be needed with varied voltage. Given good detail of the insulation system's geometry and of the shape of the non-linearity's function, a single voltage measurement with time-domain or frequency-domain DS may be able to determine the missing parameters, but one cannot realistically expect for HV equipment that even the exact geometry let alone the form of the expected response function to be known with confidence, hence the need for varied voltage.

The DS method of later interest is exclusively the frequency-domain one, with the applied voltage intended as a single sinusoidal signal. Just this case will therefore

be considered here.

When a sinusoidal excitation is applied to a non-linear system, the response consists of other frequencies that the excitation frequency — it is no longer a purely sinusoidal response. As the response is assumed to be an equilibrium response to a periodic signal, it is itself periodic, and the only components of the spectrum are therefore at integer multiples — 'harmonics' — of the excitation frequency which is known as the fundamental frequency or first harmonic.

It is useful for interpretation and easy with the available computing equipment to perform a discrete Fourier transform on time-domain measurement data to acquire the frequency spectrum of the measured current.

For an N-point time-series s of samples taken at a constant time interval T/N, the formal discrete Fourier transform (DFT) usually calculated by the fast Fourier transform (FFT), is given by 3.20.

$$S'_{n}(\omega) = \sum_{k=0}^{N-1} s_{k} \mathrm{e}^{-\mathrm{i}\frac{2\pi kn}{N}}, \qquad 0 \le n < N$$
(3.20)

 $S'_0$  is a measure of the mean of the time series. For  $0 < n \le N/2$ ,  $S'_n \equiv S'_{N-n}$  is a complex value giving a measure of the amplitude and phase of the sinusoid at frequency n/T with zero phase corresponding to a cosine with its zero at the start of the period over which the DFT was taken. These measures are not directly suitable for interpretation of their scale, and about half of the values are redundant. By taking just points  $0 \le n \le N/2$  and dividing point 0 by N and all the others by N/2, we come from S' to S which is of length 1+N/2 and in which component n actually gives the magnitude of the DC (mean), fundamental (f = 1/T) sinusoid and harmonics up to the order N/2 that are needed to generate the original time-series s.

Moderate, smooth non-linearities such as those considered here from stress-grading systems can be well represented by quite low harmonics, e.g. orders higher than the fifth are much smaller than the fifth. It is customary to represent these components either in polar form as a harmonic magnitude and angle or in a rectangular form as the magnitudes of a sine and cosine whose sum is the desired time-series of the harmonic. The approximate time-series  $\bar{s}(t)$  formed from just the spectrum up to and including the Kth harmonic can then be calculated according to (3.21) which also makes clear the relation of the cosine and sine components  $A_n$  and  $B_n$  to the complex  $S_n$ .

$$\bar{s}(t) = \operatorname{Re}\left[\sum_{n=0}^{K} |S_n| \mathrm{e}^{\mathrm{i}(n\omega t + \angle S_n)}\right] = \sum_{n=0}^{K} \left(A_n \cos(n\omega t) + B_n \sin(n\omega t)\right)$$
(3.21)

There are some useful properties of the frequency-domain representation that can assist in relating the harmonic components to the form of the time-domain signal.

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Converting from time to frequency only to try to imagine what the time representation would be like is not a purely futile exercise, since the frequency representation is an easy way to compare harmonics that are much smaller than the fundamental and to remove the noise from higher frequencies.

If the applied voltage is a sine, i.e. a transform of the voltage would yield a  $B_1 = |V|$  and  $A_1 = 0$ , then for the current the component  $B_1$  is the loss and  $A_1$  is a part of the capacitance.

It is a property of sinusoidal signals that the integral of the product of two such signals over a period that is a multiple of the period of both signals (in this case, a single cycle of the fundamental suffices as the harmonics are integer multiples) can only be non-zero if the signals are of the same frequency and have a component of their phasors in common, i.e. they are not purely in quadrature. The above statement that  $B_1$  represents the loss current in a system excited by a pure  $\sin(\omega t)$ is deduced from this property, as all the other current components,  $A_1$  and  $A_m$  or  $B_m$  with  $m \neq 1$ , will produce only an oscillating power.

Such a simple description cannot be given of  $A_1$  for the capacitance, which is a more difficult concept to define. Jonscher notes that the real and imaginary parts of susceptibility ( $\chi$ ) signify maximum energy stored and energy loss per radian, repsectively. Maximum energy stored does not depend directly on the fundamental capacitive current  $A_1$  for the non-linear case: the peak stored energy can be influenced by harmonic content. Later use here of the quantities C' and C'' ignores any such subtlety, using just fundamental frequency components, regardless of what the justification may be for using the term 'capacitance' for C' — these complex capacitance values can be seen as short-hand for fundamental currents normalised by voltage amplitude and frequency!

 $A_0$  is the DC component, which may be seen as the mean of the time-series.  $B_0$  will always be zero unless the time-series contained imaginary parts!

A signal that has positive and negative parts that are simply negated and phase shifted by  $\pi$  has no even numbered harmonics (including of course zeroth order).

As an example of the consideration of these properties, the non-linear stress-grading systems dealt with in this work are not expected to be polarity dependent. It is therefore expected that only neglible even harmonic content will be observed from DS measurements. When PD currents are included, some even harmonics, including DC, may be present, if the PD for example near an electrode so that it is polarity dependent.

#### **Dielectric measurement practicalities**

Some dielectric measurements are made as material measurements, in which case the usual method is to apply an even electric field strength to a well defined geometry of the material. Leakage of currents between the measurement electrodes around the surface of the material may be significant, particularly with high-voltage measurements where non-linear behaviour of surface leakage gives it a stronger ef-

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fect, or with low-loss materials where only a small addition of loss could be a large proportion of the total loss in the system. [GO94] cites an ANSI standard (for DC measurements on materials) as claiming that a 25% to 90% change in relative humidity could cause a change by a factor more than  $10^6$  in the surface conductivity of materials. [Edi01] has a section on surface conductivity measurements performed on mica and some polymers as part of work on surface discharges. When an object's material conductivity is low and its size is not so great as to make the surface have a tiny influence on the bulk, it is therefore important to prevent measurement of surface leakage currents. Fringing of the electric field through a material held between simple electrodes results in the geometry of material whose current is measured being poorly defined, making material properties inaccurate. To prevent surface leakage currents and to ensure a well defined measured geometry for material measurements, a guarded measurement system is usually used: the material is held between high and low voltage electrodes, and the low-voltage electrode has a central part whose current is measured, surrounded closely by a 'guard' electrode at the same potential but whose current is just sunk to the other side of the current measurement device — see the bottom electrode of the measurement object of figure 3.2.

When dielectric measurements are made on whole systems, e.g. two or more materials, perhaps with a geometry more complex than the classic two-layer parallel plate capacitor, many components of the measured response can arise just from the interaction of these materials. [Gä04] gives some practical examples of such systems, and [Jon83] goes through the expected frequency-domain dielectric responses for some canonical cases. The use of guard electrodes may be required for some measurements on insulation systems, for example cables with very low loss insulation, and may allow the removal from the measurement of certain parts of more complex systems — the end-winding region of stator bars may be guarded out when measurements on individual bars are made in the lab, allowing a more pure material property to be obtained for the solid insulation. The final part of section 3.1 covers a little more on the practicalities of measuring and guarding electrodes with installed equipment when measurements on solidly earthed electrodes must be made.

#### Historical development of DS

DS measurements in some form have been performed for over a hundred years in investigation of materials. DS methods are a powerful way of gaining an insight into materials' molecular dynamic properties. Jonscher's work started with semiconductor physics, and polymer physics makes extensive use of DS [Ged95], apparently favouring Debye models with the adjustment exponents of (3.17). DS is used even in biological systems, for example for assessment of body tissues and the condition of fruit. There are therefore well-established methods, the physical science ones

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being particularly relevant, for interpretation of DS.

The widespread use of capacitance and loss measurements at a single frequency for condition assessment of power equipment is hardly DS, even though it might be claimed as a special case! The frequency dependence is not considered, and in the case of stator insulation any changes in response with aging are likely to come from conduction and partial discharge rather than as a significant change in the polarisation function of the solid material. The term DS with nevertheless be used for the general method of DS-type measurements, whether or not a material property or system property is the aim.

A little over a decade ago, the interest in identifying water-treed cross-linked polyethene (XLPE) power cables, together with availability of good electrometers, high-voltage amplifiers and data-processing equipment at reasonable prices, led to the development of high-voltage DS being used on power cables [WTE<sup>+</sup>01] [HWC01] with sweeps of frequency down to the millihertz range.

### Application of DS to stator insulation

The presence of end-winding grading on stator insulation has effects described in section (4.1), leading to significant frequency and voltage dependent change in measured dielectric parameters of a stator insulation system unless each end-winding is guarded; guarding is utterly impracticable for routine measurements on typical machines that have hundreds of bar ends. The real response of the insulation material (which is itself a compound system of epoxy and mica) cannot then be directly seen.

Machine windings are unusual among HV insulation in their tolerance of moderate PD and the likely presence of PD in operation. PD during a HV DS measurement will also add to the measured response.

This might make DS a good way to measure PD current, particularly if PD is the main non-linearity in which case the harmonics of the current can give a good idea of the PD even when the fundamental frequency component of the PD is lost in the current from the insulation's capacitance. On the other hand, it is widely considered that maximum PD amplitude is more significant than, or at least important in addition to, the total PD current; in this case a direct PD measurement may be useful in addition to a DS measurement including PD.

When the effect of end-winding grading is included, the PD is no longer the only non-linear, harmonic generating component of the current at high voltage. The harmonic spectra of PD and stress-grading are not greatly different, but the response of grading is visible at all voltages while that of PD starts beyond some inception voltage. Knowledge of the relation between quite low voltage and high voltage stress-grading response may allow the high voltage stress-grading response to be estimated for removal from the PD current.

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Note here how important the harmonics may be: the fundamental frequency components are combined with larger currents from the insulation material. Current practice in electrical diagnostic measurements on stator insulation of whole machines at maintenance times generally uses some simple dielectric measurement such as megging (IR), likely often to show other phenomena than bulk material properties (e.g. surface conduction), and PD measurement whether by powerfrequency capacitance and loss measurement with varied voltage (tip-up test) or by direct PD pulse measurement. The time-domain response giving by IR ('megging') is largely aimed at identifying excessive proportions of conduction current.

Some organisations, notably the Canadian hydro utilities, have presented details of their work with time-domain DS methods as a part of their maintenance-period condition monitoring. [McD00] considers stator insulation absorption characteristics of the materials based on this experience over several decades. [CHTH02] and [DLN02] are recent investigations of DS methods applied to machine insulation.

Use of DS has been far more popular in laboratory contexts, whether production or research, than in the field. This is not surprising when the end-winding stress grading is considered: in a laboratory this is almost always guarded out of the measurement, making a material (plus possible PD at higher voltages) measurement possible. In any field or even production situation with a whole machine, this guarding cannot reasonable be done, and any attempt to get sensitive measurements of materials properties fails. [FBG06] is a recent university work on frequency domain dielectric response measurements.

An industrial laboratory context where DS has been of interest applied to stator insulation is that of assessment of condition of bars or coils before complete assembly of a machine, generally testing samples from a batch. The central purpose of [Hel00] is the study of how the DS parameters change during curing of the impregnating resin, i.e. DS as an assessment of cure. Use of DS as a more general quality check is considered by [GCCF00], and with more whole machine orientation in [GKC<sup>+</sup>98].

#### The DS measurement system used for this work

The DS results presented in chapters 4 and 5 have been made with a commercially available system called IDA200, from Programma AB, which performs frequency-domain DS at varied voltage.

The system has internal 10 V and 200 V peak supplies, capable of driving around 50 mA at up to 1 kHz, and can be used with an external amplifier which in our case is a  $\pm 30$  kV unit that can be driven at up to 100 Hz. In either case, the system can measure down to frequencies of 0.1 mHz, i.e. periods of about 3 hours!

Inside the system a sensitive electrometer is used to measure the current into a well screened measurement electrode. The voltage at the output of the external amplifier can also be measured by an electrometer connected to a gas capacitor

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#### 3.1. DIELECTRIC SPECTROSCOPY

voltage-divider. This sensitive voltage measurement is needed to get good resolution of low-loss components where the exact voltage-current phase-angle is important. It is also useful in order to know the harmonic content of the applied voltage in order that harmonics in the measured current may be approximately compensated the by the values that the applied harmonics in the voltage could be expected to cause.



Figure 3.2: Measurement circuit and block diagram of the Dielectric Spectroscopy system used for the later described measurements. This shows typical laboratry connection, where the measurement electrode is not forced to be earthed so all other electrodes and earth may be guarded out of the measurement. When measuring on a stator winding, the stator earth would be connected into the current electrometer to measure all the current apart from anything guarded out by connection to the measurement signal earth. Many components to do with protection of the sensitive components, voltage isolation and compensation are not shown (and indeed are not known by us). The feedback components 'FBv' and 'FBi' are parallel combinations of resistive and capacitive elements.

The electrometer earth floats from the systems's supply-plug earth. This allows connection of the measurement electrode to an earthed object such as a generator stator or cable sheath, without shunting current around the electrometer. Electrodes on the test object other than those connected to the high-voltage or the measurement electrodes can be connected to the other side of the electrometer in order to make them be guards having almost the same potential as the measurement electrode but with their current not being measured. Ideally one can guard earth and possibly other electrodes, to avoid measuring stray capacitances. If the measurement electrode is unavoidably earthed, as usually is so for a stator core, then stray capacitance is increased.

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An analog-digital converter (ADC) and digital signal processor (DSP) are used to sample the measured quantities at 16 kHz, which allows up to the 8th harmonic to be recorded at the maximum frequency of 1 kHz. (A DSP is a microprocessor specifically designed for such operations as FFTs.) Limitations in the processing speed of the DSP cause these eight harmonic values to be the maximum recordable number even at the lower frequencies. A computer within the system receives the measurement data from the DSP as a set of eight complex numbers for the harmonic orders 1 to 8 of both voltage and current. The zeroth-order (DC) component is unfortunately not recorded, perhaps owing to an analogue-side restriction on DC input. Control files are used to set sweeps of frequency and amplitude of the applied sinusoidal voltage, and the measured data is appended as text to the control file. The computer can plot the data on the system's screen. Separate, more detailed data processing programs have been written within this project for analysis of the system's measurements on a full-size computer.

## 3.2 Partial Discharge measurement and analysis

## Partial discharges

Gases that are not ionised are highly insulating, but when a high enough electric field is applied to a gas there can be so large a force on charges that that electrons generated by any small ionisation occurring due to external effects (ionising radiation) be accelerated enough to ionise more atoms. Depending on many factors such as the electric field strength and divergence, the gas and any electrodes, the region of newly ionised gas may come to spread, multiplying the ionisation, and possibly extending to the point of forming a channel of ionised gas between the electrodes. In suitable conditions of field and temperature this channel may then conduct a current that warms and ionises the channel sufficiently to lead to a spark that forms a very hot and highly conductive connection between the electrodes. Only stopping the supply can then stop the continued discharge, which is therefore called a disruptive discharge.

A *Partial* Discharge (PD) is a discharge that, by similar mechanisms of ionisation and possible avalanche or streamer, moves charges in an electric field, but in which the discharge path does not come to link the electrodes, so preventing the formation of a disruptive discharge. Since a PD fades away without causing a high-current spark between the electrodes, it does not cause an interruption of service of its host component.

The failure to bridge the electrodes may be due for example to a solid or liquid insulating layer that is not as easily broken down as the gas, as in the case of a gas-filled 'void' or 'cavity' in solid insulation. Another common situation for PD is in the high field region of a highly divergent electric field, such as that around a 'sharp' surface. Discharges formed in the high field move out and reach a point where the electric field no longer sustains the discharge's propagation. This form of PD is well known as the crackling noise around high-voltage overhead conductors, and is called corona discharge. Surface PD has in common with corona a divergent field, but has also interaction with some dielectric surface.

Cavity PD within the mica insulation, and surface PD around the end-windings are commonly met forms in PD in stator windings.

#### Electrical measurement of PD

A PD is typically a very quick and short motion of charge in the direction of an applied electric field. Just as described for polarisation in dielectrics, the shifting of unbalanced charge along the direction of an electric field results in a change in potential of the charges that are applying that field, which in turn in the practical case of a stiff voltage source results in a current flowing from the supply to maintain the potential difference between the electrodes. The difference from dielectric polarisation is that a PD pulse moves potentially many charges a much longer distance than an atomic size, and does so in a very short time, in the order of nanoseconds. The result is that the current into the electrodes is a sharp pulse, and that considerable radio frequency (RF) emission can be expected from the PD. The high rate of change of current also means than in the time-scale of the PD the supply that is driving the voltage on the insulation will, owing to the inevitable inductance in the supply and connections as well as the time for propagation of electromagnetic waves along a length of lead, be unable to maintain the voltage between the test object during the time of the PD pulse.

Detection methods for individual PD pulses (single pulse methods) rather than mean currents measure radio frequency emission, current in conductors by inductive couplers, changes in voltage on conductors by capacitive couplers, or the voltage across a measurement impedance in series with some conductor that carries current from PDs in the test object. The last of these methods is the one commonly used for off-line testing of insulation system, and is the method of the system used in this work.

In a laboratory situation it may be possible to insert the measurement impedance directly in a conductor to the test object, typically the earth conductor with its desirable low potential. In other situations, e.g. a stator winding, where the test object has one electrode solidly earthed, and where connections of a measuring system to the high-voltage electrode are not reasonable, a capacitor may be connected in parallel with the test object, and the current in the capacitor's earth connection may be measured. In the short time of PD pulses the nearby capacitor will supply nearly all of the extra current into the test object, since the remote and likely inductive supply has so much impedance to the high-frequencies. The current in the capacitor's earth connection is therefore in proportion to the PD current into the test object, and is equal as long as other shunt capacitances to earth are neg-

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ligible and the supply has a much higher impedance. If instead the contribution from the supply is not negligible for the time during which PD is detected, then the proportion of the current to the test object that flows in the capacitor earth will be dependent on the frequencies in the PD current, i.e. in the pulse waveform; this variability is just one of the problems involved in calibrating PD measurement systems to give a measured apparent charge that can be compared between different test objects and measurement systems.

Microscopically, a PD might be said to have moved a certain quantity of electrons a certain mean distance within the time of the PD, or of more direct relevance, to have moved a certain charge through a certain change in the electrostatic potential induced by the electrode system. The only measure of this quantity at the electrodes is the product of this charge and potential-change, in that it is the same as the product of the voltage between the electrodes and the charge that has to be supplied to the electrodes to maintain this voltage in spite of the movement of the charges in the PD. This charge at the electrodes, is called the 'apparent charge' and it the quantity usually mentioned in practical PD measurements rather than theoretical discussions of more microscopic PD phenomena. Clearly, for a *partial* discharge, the apparent charge is less than the actual PD charge since the actual charge does not move through the full potential difference.

Calibration of PD measurements is essential for quantitative comparison of results. PD calibrators inject a pulse of a known charge into the measurement circuit, near to the test object, to simulate a discharge occuring in the object. The measured size of the known charge is used to calibrate the system. Since PD detection systems generally are frequency dependent due to input filtering and even just the transmission path of PD signals, similar amounts of calibration or apparent PD charge may register different values on the system depending on the shape of the pulse generated and the electrical properties of the test object and connections.

Stator windings contain long lengths of conductor inside earthed magnetic material, then unshielded end-windings. High frequency components travel between coils in the end-winding, low frequency components travel along the windings. Attentuation happens in either case. A PD measurement on a whole stator winding cannot therefore be expected to return at all similar results for similar PDs that simply happen in different parts of the machine.

## Effect of PD activity on insulation

The effects of PD on insulation have already been touched upon in relation to aging processes in machine insulation. Although on a small scale, a PD produces, ultraviolet light, heat, and possible reactive chemicals depending on the chemicals originally present, e.g. oxygen in the gas allows the generation of ozone. The ions in the gas and on surfaces, electrons (particularly on surfaces), wear on surfaces, chemical changes and byproducts and heat, change the environment in a cavity

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or along an external surface in the case of surface PD, and this has an effect on later PD, the effect depending on the time between these PDs. [Mor93] is a good reference on the effects of PDs on insulation, reporting work by its author as well as a set of references on the subject. The decade-later paper [Mor05] is a short description of the subject with references, more quickly accessible from internet reference sources.

## Development of the use of PD measurement

PD phenomena have been familiar since the beginnings of HV equipment, often noticed only by sound, possibly by sight in the dark, and by the chemical effects in particular the generation of ozone when occurring in the presence of oxygen. Large amounts of PD activity are susceptible of measurement as an increased loss during dielectric tests, so Schering bridge methods for detecting voltage-dependent dielctric loss have also been used as an 'average' PD measurement, as still is done today with common stator insulation test methods.

Electrical measurement of PD currents in insulation, performed with oscilloscopes to analyse to some extent the individual PDs rather than just a mean PD current, was reported as early as 1941 (a reference in [Mor93]), and an application to machines was reported in 1951 (a reference in [HB05]). These early measurements of stator insulation PD required a very experienced operator to separate PD signals from ambient electrical noise in the environment of a power station or industrial complex. Popularity of the PD method grew with improved measurement and signal processing abilities in the 1980s and later, when phase-resolved methods could sort arriving pulses by phase of the applied voltage and amplitude of the pulse, to produce a pattern that can tell a lot about the nature of the PD source. See figure 3.3 for an example phase-resolved PD pattern (PR-PDP) measured on the bar A1 of chapter 5 after rapid thermal aging. This pattern is a quite classic internal PD with largely symmetrical positive and negative parts and a lot of activity around voltage zeros.

## PD methods on stator insulation

PD measurements are very common on machine insulation: they are widely used both off-line and on-line. [HB05] is a good introduction to interpretation of patterns, showing how some classic types of insulation defect appear. [Std00a] gives some condensed advice about PD measurements on stator insulation, including a discussion of the limitations of calibration in so large and highly inductive an object where the position of a PD can affect so strongly the measured apparent charge.

#### Variable frequency PRPDA

The behaviour of PD can be expected for many reasons to be frequency dependent. Due to the main PD source of interest in machines and to other work in the de-





(a) A phase-resolved partial discharge pattern, PR-PDP. The coloured scale shows the mean number of pulses per cycle in each phaseamplitude channel. The sinusoid shows the phase of the applied voltage.

(b) Time-domain mean current, calculated from the same measurement

Figure 3.3: An example of PR-PDA pattern and the mean PD current due to this pattern. This data is from a stator coil with high PD activity after rapid thermal aging.

partment, the case of gas-filled voids in solid dielectrics will be considered as the main case here.

Several factors may give a time (or frequency) dependence to different PD 'indices' such as number per cycle, number per second, maximum charge, difference between positive and negative charge, and even statistical moments of the phase-resolved pattern. Considering the classic cavity in solid insulation, there are time constants associated with how the voltage across the cavity varies as a consequence of the solid material's permittivity, conductivity and dispersion and of possible significant surface conductivity of the cavity. There is also a 'statistical' time-lag, for the presence of an electron, usually generated from external background radiation, to initiate a discharge. When no initiating electron is present although the electric field is large enough to cause PD if the electron were present, a large PD can be expected when finally an electron becomes available in an enhanced field. Much effect of frequency and of course voltage on the measured PD can therefore be expected.

There have been some investigations of frequency-dependence of PD for some 50 years. Specific to the case of machines, [FLU<sup>+</sup>89] mentions the increased PD at rather lower frequencies than power frequency, and [Nie95] continues this interest in some models of PD behaviour in cavities. More recently, variable frequencies have been taken up as a matter of assessment of how different measurements with

damped resonant test-supplies can be on account of difference in frequency, [CM06].

[Edi01] was performed with the primary aim of studying PRPD measurements with frequency as an independent variable as well as voltage magnitude of an applied AC voltage. As well as some of the development and testing of the measuring system described later, some measurements on naturally aged stator bars were made, besides other more laboratory style test objects.

[For05] continues the work, focused more on the mechanisms of PD in cavities, using comparison of numerical modelling of frequency dependence with measurements on laboratory test objects. Figure 3.4 gives an example of a statistic (pulse count) of the PD pattern of a cavity in solid insulation, showing how it varies in frequency for different cavity sizes and placements.

It is of particular interest here that by far the largest distinction between the different cavities is seen in the low frequency range. Two turning points are seen in the frequency dependent curve at the top of each figure, suggesting at least three different phenomena affecting the frequency dependence. A suggestion is that the very low frequency reduction in the count is due to charge leaking away around the cavity's surface before PD builds up, the middle frequency range has decreased count with increased frequency due to the statistical time lag, and the high frequency increase may be due to remnant charges after the quick voltage reversal.



Figure 3.4: Example from [For05] of number of PDs per cycle as a function of frequency for a well defined cylindrical cavity in polypropylene dielectric.

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## The PD measurement system used in this work

As part of PhD and masters project work during the latter 1990s, a commerically available PR-PDA system, ICM from PowerDiagnostix, was joined with a DAP (data acquisition processor) connected to a desktop 'wintel' computer, to control the reference voltage to a high-voltage amplifier and provide a gating signal to let the ICM system know when the start of each cycle occurred. The ICM system after a specified number of cycles then sends the measured PR-PD pattern back to the computer as a matrix of 256 phase channels by 256 charge-amplitude channels, each element containing a 16-bit integer of the number of PDs detected at that phase and amplitude.

The ICM system gets the PD measurement from a measurement impedance inserted in the earth connection of either the test object or the decoupling capacitors that provide the local low-impedance voltage source that supplies the high-frequency PD currents.



Figure 3.5: Measurement circuit and block diagram of the Variable Frequency Phase Resolved Partial Discharge measurement system used for the later described measurements. PRP is the phase resolved pattern, a matrix of counts of PDs at each combination of 256 phases within the cycle and 256 charge magnitudes, that is sent from the PD detection system to the computer. The computer generates a reference voltage at the required amplitude and frequency, and sends a synchronising signal to the detection system to define the start of each cycle.

Many settings of the ICM system are determined from within the computer program: these control for example filtering, dead-time (delay before being able to detect a new PD), and gain of a pre- and main-amplifier.

Programs for analysis of the data have been written at that time and since then as parts of other projects including this one, to cater for the particular needs of each person's work.

## 3.3 Combined DS and PD measurement

From the foregoing descriptions of high voltage frequency domain DS and variable frequency phase-resolved PD measurements, it is clear that the high voltage power supply and leads and the controlling computer can be common to both systems. Particular to the DS system is an electrometer to measure current and, in the present implementation, another to measure voltage *via* a gas capacitor in the supply in order to get good angle resolution for low-loss objects. Particular to the PD system are the HV filter and the detection circuit. The filter together with its containment is quite bulky. The detection circuit is expensive but takes up less space than an oscilloscope.

### Potentials for combined measurement: DS and PD

There are several main forks to the reason for studying the use of combined measurements.

The combined measurements may allow some compensation of one measurement by the other, with a useful result: for example, subtraction of PD current in cavities, from a DS measurement, may provide a good estimate of dielectric response of a material with cavities, by removing much of the extra loss.

The combination of results may be useful in itself, just as separate (fixed frequency) PD measurements and (primitive) DS measurements are used as complements in current practice. In this case combining the systems, may save some expense, space and, especially importantly when dealing with low frequencies, time.

It may turn out from the combined measurements in the continuation of this project, that for some types of insulation system the DS method can show much of the parameters of PD that normally require a separate and quite expensive PD measurement system. If the DS system really can be a good substitute for a PD system as well as showing the DS results, this may offer a more efficient way to make low frequency diagnostic measurements.

If total charge from PDs is of relevance, and there are not other non-linear effects in the measured system, it may be more easily possible to make a DS measurement to determine this charge than to try to calibrate a PD system such that it does not saturate on the highest charges and does not miss small charges under its detection threshold.

#### Relations between DS and PD results

The DS system tries to hold its output voltage to whatever the present value is of the reference sinusoid for the frequency-amplitude point. The effect of PD is, as suggested above, just like a rather rapid group polarisation: a current does ultimately

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have to flow to compensate the changed internal polarisation. The PD current is, though, rapid, and if the DS system has low-pass filtering or transient protection some of the current may avoid the current measurement stage (electrometer).

The DS system used here has been designed with the intention of measuring as part of the DS current, rather than sinking to earth, these high frequency signals. It is assumed unless later experiments show otherwise, that whatever PD current gets into the lead of the DS system does get measured as a component of the 8 harmonics of current that the system gives as output. The discrete Fourier transform methods (3.20) can then be applied to a known PRPD pattern to determine what currents those PDs would have caused to be measured on the DS system, as described in [EG98].

In laboratory work to date, which has only recently been focusing on the PD measurement aspects, there have been found to be much higher (as much as 50 times) currents measured in the DS system, when measuring large numbers of PDs in a single stator coil that was guarded so the the end-windings would not introduce a confusing non-linear response rather like the PD. This is interesting in that the DS method might be able to measure hidden PD current, but it also might be that this current is not very meaningful from a condition assessment viewpoint. If the two systems provide very different current measurements even after adjustment of the PD system for counting as much charge as possible, it will be clear that there is no hope in using the PD measurement to compensate for the PD component in the DS measurement.

## Chapter 4

## Non-linear stress grading with varied amplitude and frequency of the voltage

The end-winding region of a stator winding has the potential for electric fields high enough to cause surface discharges if steps are not taken to reduce the field around the point where the earth potential of the conductive stator core and quite low resistance slot semiconductor layer finish.

The usual method used to prevent such discharges is the application of a thin, highly non-linear semiconducting material of much higher resistivity than the slot semiconductor, to the part of the end-windings just beyond the stator core. This has quite a strong effect on dielectric measurements on the stator winding, with dependence on both frequency and amplitude of the applied voltage. This effect upon the parameters of complex capacitance and current harmonics has been modelled on simple physical models of end-windings and by simulation; some results are presented in this chapter.

The modelling is also relevant to modern polymeric cable terminations that use non-linear resistive grading around the end of the cable's earthed sheath.

## 4.1 Purpose and practice of end-winding stress-grading

Consider two concentric cylindrical conductors with a space between them. The internal cylinder is at high voltage, and the external one is earthed. There is then a radial electric field in space between the cylinders, and no field elsewhere.

If a length of the outer conductor is removed, there will be an axial component in the field around the edge where the outer conductor finishes, and a higher stress there than before on account of the effect from the inner conductor that continues without any outer conductor to keep the axial potential zero.

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Any solid dielectric material has a power-frequency relative permittivity,  $\varepsilon_{r(50Hz)}$ , at least about twice that of air, so if the space between the conductors is filled with solid insulation and the space outside is air or some other gas, the situation is made even worse just outside the surface of the solid insulation at the end of the outer conductor. If the electric field in the solid insulation is designed to be making good use of the insulation, it is probably already too high for air. The abrupt ending of the outer conductor therefore results in an excessive electric field, and this field concentration must be prevented.



Figure 4.1: Axisymmetric cross-section of equipotential lines for the electrostatic case of a high-voltage central conductor (horizontal, bottom), solid insulation, and earthed outer electrode (coming from the left) that stops part way along the insulation surface: note the high electric field strength around the end of the outer electrode.

## Methods of grading

The situation described above is met in cable terminations and with a more rectangular cross-section in the end-windings of machines as described in section 2.1. The methods of preventing the concentration of field are known as stress grading, potential grading or voltage grading, and there are several main types.

Geometric grading makes use of a modification of the geometry of insulation and/or conductors, typically with a swelling of the insulation and outer conductor to the point where the surface stress is acceptably low. Extending the solid insulation a way around the outer conductor is a way to increase the acceptable maximum stress at this critical point. Refractive grading uses some dielectric material of higher permittivity than the main dielectric, to modify the distribution of the electric field. These methods, relying on grading materials that are mainly capacitive at power frequency and higher, has the advantage of small frequency dependence in this high frequency range, although the field in the millihertz range, not normally encountered, may become dependent on material conductivities. Resistive (linear) grading makes the transition from outer conductor to no outer conductor more gradual: a semi-conducting layer on the surface of the insulation extends the outer conductor, having just enough conductivity that it can carry the displacement current from the inner conductor through the insulation material without the electric field along the outside becoming enough for surface discharges. A major advantage over the previously described forms of grading is that the space occupied can be very small. There is no need to change the geometry of the conductor system, and a thin layer of moderately resistive material can have sufficiently low impedance to give good grading. This is because materials with a wide range of resistance can be made while permittivity can be varied only over a far narrower range. The resistive layer has a low enough resistance that with an acceptably low electric field along it, it can carry the current that results from the capacitance between the inner conductor and the resistive layer with that field distribution and at the design frequency.

This capacitive current is frequency dependent, so the grading effect of purely resistive grading changes with frequency: it is a distributed R-C filter. Well-designed grading giving a smooth change in surface potential at 50 Hz will have a potential distribution like a good conductor at 1 mHz and might almost as well not be there at 10 kHz.

High frequency performance is important for gradings in cable terminations, due to the need to grade voltage impulses with high-frequency components. Some machines, mainly motors fed from pulse width modulated (PWM) inverters, also have a need of good high-frequency grading as well as good grading at the normal power frequency.

Non-linear resistive grading shares the benefit of small size, and uses a voltage dependent resistivity to compensate for variations in frequency. A material is selected that is normally highly resistive but becomes much less so as the electric field strength in the material approaches the maximum permitted value for the surface that is being graded. In this way, if the non-linearity is sharp enough, the objective of limiting surface electric field is achieved for a wide range of frequencies.

The material has some finite conductivity — much more than a good insulator — even with no applied field. At very low frequencies at which there is very low current through the dielectric's capacitance, this minimum conductivity may still be too high for good grading, and the grading will become a continuation of earth potential from the outer conductor. This point has been of no interest previously, as power frequency, PWM frequencies and impulses from the net were the matters of importance and there was no reason to consider frequencies in the millihertz range!

### Non-linear, SiC-based grading

The dominant form of stress grading in use for machine end-windings and cable terminations is non-linear resistive grading based on silicon-carbide — SiC. Only

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this form is considered hereon. Small particles of SiC are held in a base material, for example some resin that can be cured in the same way as the main insulation over which the stress grading is applied. The particles' concentration affects strongly the non-linearity and conductivity. The 'percolation threshold' is the region in which the concetration gets large enough that paths of contacting SiC particles form through the material; well below this region the electrical behaviour is dominated by the filler, well above this region the electrical behaviour is dominated by the SiC, and within this region the contacts between SiC become important. Somewhere around the percolation threshold is desired for SiC stress-grading materials. [Må00] considers the physics and modelling of SiC-based stress-grading materials. The contacts have by several workers been modelled as Schottky barriers, and a further non-linearity can be expected from the electrostatic attraction of adjacent particles in the situation of high field, enhancing the contact pressure.

## Industrial interest

The industrial interest is in the opposite side of the spectrum, on power frequency and higher frequencies met due to disturbances from outside, and due to PWM converters that are used for driving some medium power machines. The wear of grading materials with the high currents caused by sustained high-frequency components in the supply has been of particular importance [BGW02].

Quite a lot of work is published about models, ranging from a few discrete components up to distributed finite element models, and characterisation of materials even at high frequency and electric field strength. Such works usually use the same basic methods as are used in this work, of tubular model bars for grading models and thin insulating tubes as the bases for material characterisation. In this work with low frequencies, the situation is rather easier as the maximum electric fields are lower and the SiC material has very dominant conduction rather than displacement current, making characterisation a matter of measuring a steady response that is not limited in the time for which it can be applied.

# Relevance of stress-grading to low frequency DS and PD measurements

#### **Dielectric Spectroscopy**

In the above description of non-linear grading, it is mentioned that at low frequencies even the low conductivity of the grading material at low electric field is sufficient for the spreading of earth potential along the grading material from the stator core to the end of the grading material.

When the current into the insulation system is measured by DS, this spreading of earth potential produces an increase in capacitance, C', up to the capacitance of the whole length of slot and end-winding semiconductor layers rather than just

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## 4.1. PURPOSE AND PRACTICE OF END-WINDING STRESS-GRADING 55

the length of the slot semiconductor layer as at high frequencies. With several centimetres of grading on each end-winding of a stator that is only of the order of metres in length, the increase in capacitance due to the grading may be as much as that due to the insulation material's own frequency-dependence of capacitance. The loss, C'', is expected to increase too with decreasing frequency, then to fall as the capacitance approaches its maximum value. With a low-loss insulation material this loss due to passage of a current through a high resistance into the capacitance of several extra centimetres of the winding could be significant or dominating in the loss component of the response.

The increase of C'' (usually seen as  $\tan \delta$ ) and C' with increased voltage due to nonlinear end-winding grading is well known from standard 'tip-up' tests performed at power frequency, and the measurement of small amounts of PD can be obscured by this end-winding response. The use of varied and low frequency adds another independent variable to the measurement, but the end-winding response has a strong variation in response to this variable too, again potentially obscuring other effects such as the currents from PD and the frequency-dependence of the bulk insulation material. Measurement of harmonics in the current provides more information about the non-linear components of the current, mainly expected to be from PD and from end-winding stress grading.

In the absence of other frequency and voltage dependent effects the variation of C', C'' and the harmonic currents might be useful as an indicator of changes in the stress-grading. In the realistic situation, these effects are combined with those of PD and conduction. The compound response is then more difficult to analyse for the detail of each contributing physical mechanism, and it may indeed not be at all reliably possible to separate the non-linear responses from the end-windings and from PD.

## PD

The stress-grading is intended to prevent is PD on the outer surface of the endwinding insulation, but for very low frequencies, particularly when together with high voltages, it has already been shown that the earth potential may spread to the end of the grading material. What happens then is dependent on the way that charges behave in the surrounding air; there may be PD at intervals as long as the voltage stays high, with the interval determined by the time for space-charge to diffuse, or the high field may cause space-charge to be held to the grading and the insulation surface, preventing further PD but causing PD when the voltage is reduced and reversed.

It is of interest to study whether this effect is likely to occur during measurements at expected amplitude and frequency of the applied voltage, and what effect such PD would have on the measured response.

## 4.2 Response of end-winding stress-grading

The aim of this section is to show the dependence, on amplitude and frequency of the applied sinusoidal voltage, of the fundamental and low harmonic components of the current into a pure stress-grading system using silicon-carbide (SiC) based nonlinear resistive material. The fundamental components of the current are studied in the tradition complex capacitance C', C'' form of dielectric response. 'Pure' in this case means that additive currents from other sources, for example the insulation directly between the metallic electrodes, is not included, and that the dielectric material over which the stress grading is applied has negligible loss, dispersion or non-linearity.

This study starts with results from measurements on some physical models using commercial stress grading materials on a stable, low loss insulator, and then describes numerical modelling of the non-linear distributed network formed by the grading, making use of material measurements of the grading material.

As described later in more detail, the insulation material and dimensions used here do give a rather lower capacitance per unit length than is typical for a stator winding. The result is to shift the response seen here up in frequency, which has the quite positive effect that more is seen here of the interesting loss-peak region than would have been possible if this had been off-scale at the low-frequency end of the scale.

## The physical models

With the aim of seeing the pure response of the stress-grading system, some laboratory models were made (figure 4.2) consisting of a tubular inner conductor, a PTFE tube around this, and a short metal sheath on the outside of the tube, with stress-grading at both sides.



Figure 4.2: Diagram of the laboratory test-bars used for measuring DS of stressgrading systems

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#### 4.2. RESPONSE OF END-WINDING STRESS-GRADING

PTFE has a permittivity and loss that are low and practically linear in the measurement range of interest, and it endures the temperatures of the curing process for the tape. In this respect this model fulfills its aim well, in providing a response without internal PDs or the DS of the slot part of a winding and in keeping low the effect of the insulation on the DS measurement.

Two types of commercial stress-grading material have been studied; both use silicon carbide (SiC) as the active component.

The first material (from now on referred to as 'paint') is in the form of a paint that is applied to the bar in a single coating and that sets at room temperature in 24 hours. Application by hand of such a paint to a bar is a process that results in much variation of the thickness and therefore of the electrical properties of the final grading. The thickness commonly applied is less than 0.5 mm, and on the bar used for grading tests it is considerably thinner than this and was not susceptible of reliable measurement of its properties.

The second material ('tape') is an epoxy based material in the 'B-stage' (still soft) containing the SiC powder, fastened to a thin woven polyester tape. The tape is wound tightly half-lapped onto the bar and then is cured for 2 hours at 160°C after which it is hard and the individual windings are well melded together. The thickness of the cured tape is about 0.5mm.



Figure 4.3: Picture of the test-bars with cured SiC B-stage tape (top) and SiC paint (bottom)

Two bars have been used for the measurements in this paper, named 'paint' and 'tape' after the grading material used; these are shown in figure 4.3. There were in fact two bars of each type fabricated, in order to allow estimation of the variation of parameters of objects that had been intended to be similar. Just one of each type was selected for obtaining the following results.

For reason of available materials when the bars were made, the 'paint' one has 40 mm greater length of earthed sheath without grading. As the measurements later presented include removal of the contribution of the capacitance from the central earthed sheath region, this difference between the bars should have no effect; the grading material extends 80mm from the electrode in either case.

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Dimensions of the bars are given in figure 4.4. Note the subtlety that the external diameter of the insulation here is about 31 mm, but in the later section on measuring SiC material properties around an insulating tube without internal electrode, the diameter is only 30 mm. This is due to the tight fit of the electrode in the tube in the bars.



Figure 4.4: Geometry details of the bars: a symmetric quarter geometry.

## Material properties

The numerical simulation model requires a good description of the non-linearity of the stress-grading material. This material property is also interesting to know for less detailed analysis of the measured behaviour of the grading.

For the industrial interests of power frequency and higher, and particularly for accurate calculations involving large, high frequency impulse voltages, the characterisation of the material can require much attention, on account of the significance of the material's capacitance and the impossibility of applying high stresses for at all long without excessive heating. [BZ00] describes the common method of a small sinusoidal superposition on a ramped voltage for measuring linear and non-linear components of capacitance and resistance. When the capacitance is so significant that its possible non-linearity is important, attention is needed to the point that the capacitive current is dependent on the time rate of change of voltage and of capacitance with voltage. [RLL+98] discusses the use of direct measurement of surface potential on gradings, and contrasts the results with methods more directly measuring material properties than grading properties..

In this low-frequency case, it is easier. The stress will never be so great as in cases such as impulse voltage, so very large values that could cause significant heating do not need to be used. Only the DC value of resistance need be determined, as this is so dominant in the material's I-V relation at low frequencies.

To assess the electrical properties of these two materials, samples were applied along the surface of a PTFE tube of respectively 20 mm and 30 mm internal and external diameters, between copper-tape electrodes. Measurement along a thin tube,

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e.g. glass-fibre, has been reported in various papers about resitive coatings. If permittivity is of importance then the tube is reasonably desired to be as thin as mechanically possible, but in this case the conduction is believed to be of dominating importance. The thickness of the tube may indeed be helpful in providing some thermal inertia: SiC-based materials are strongly temperature dependent.

Four different lengths -10, 20, 40 and 80mm - of taped surface between the electrodes were used, and for each length the current was plotted against the mean electric field strength. Measurement on the tape was very easy as it had a quite high conductivity and therefore the potential distribution in the grading material, tube and air reached a steady state more quickly than could be noticed. High stresses, 300 V/mm, resulted in a current that after several seconds started to increase: in these cases the value taken was the minimum noted. The greatest power-loss is that in the 10mm section with 3kV applied: in this case, the current of  $20\mu A$  dissipates just 60 mW over the  $19 \text{cm}^2$  area of the tape. This may be sufficient explanation of the rising current, due to the temperature sensitivity of the material. This effect is of importance for stress-grading systems at high frequency, in which case the displacement current from the high-voltage inner conductor to the grading is large and stresses within the grading material are consequently high, but for the low frequencies of interest here this effect should be able to be ignored. It is just in this material measurement case that the material is directly between the electrodes without a series capacitance to limit the current, so the heating effect is noticed.

Measurement on the paint was less repeatable: considerable variation in measured current was observed over time for the thin layer with its high resistivity, and there were orders of magnitude of difference in the behaviour of samples differing only by the intentional modification of thickness of the paint. The surface conductivity is lower than that of the tape, but the relatively small thickness of the paint may mean the material conductivity is similar or even greater. The non-linearity is sharper in the tape.

Figure 4.5 shows results from two measurements on each of the four lengths of tape, along with a fitted curve. Equation (4.1) was initially chosen as an approximation to the measured data, as the relation of I to E was seen to come closer to a straight line in log-log coordinates than in log-lin or linear.

$$I = \operatorname{sign}(E) A |E|^{n'}$$

$$(4.1)$$

$$I = EG_0 \exp\left(n |E|^{2/3}\right) \tag{4.2}$$

At high stresses the fit is badly impaired: equation (4.2) is commonly used for industrial estimates of the SiC conductivity, giving a good fit to all of several SiCbased stress-grading materials, and it fitted well for the materials here also. It was found to deviate slightly to the other way from (4.1) for high electric field strengths, which could be improved by a slight reduction in the 2/3 exponent to about 0.6. In the later simulation models the standard 2/3 is however used.



Figure 4.5: Fitting (black circles) of (4.2) to data from two measurements on each of four lengths (10, 20, 40, 80mm) of half-lapped tape along a 30mm diameter tube.

Equation (4.2) has an important advantage for simulation purposes in that it has good behaviour even with small E, its conductivity tending to the coefficient  $G_0$  as E tends to zero. This makes it suitable for use in solvers where the current has to be expressed as some function multiplying the electric field strength, rather than just as a function of the electric field strength.

Figure 4.6 gives similar fitting to (4.2) of the dc measurements on the three different thicknesses of paint. The actual grading bar using paint as the grading material has a thickness around that of the 'medium' section here, but this is just judged by visual comparison of a thin layer so accurate use of the 'medium' parameters cannot be expected to give good modelling of the painted bar. Painting a real stator bar thickly is rather easier than painting PTFE thickly; it is to be expected that painted end-windings have a surface conductivity considerably higher than the painted bar.

#### Results from DS on the physical models

On the taped bar, DS measurements at peak sinusoidal voltages of 0.5 to 20 kV and at frequencies from 100 Hz down to 10 mHz were performed, as well as a frequency



Figure 4.6: Fitting (black circles) of (4.2) to data from measurements on each of three sections of paint of different thickness along a 30mm diameter tube. The orders of magnitude difference for a moderate difference in brush-use, and the considerable variation between measurements on the same sample, indicate the impracticality of making accurate modelling of painted stress-grading.

sweep down to 0.1 mHz (the equipment's limit) at 10 kV to check for any further effects. The painted bar had lower frequencies for each part of its response, due to the higher surface resistivity of the paint; it was therefore measured down to 0.1 mHz for each voltage level. All voltage values refer to the peak value. Values of current, and therefore C' and C'', for each bar are 'compensated' by removal of the current expected from the measured applied voltage being applied to the complex capacitance that was measured for the bar at each frequency at low voltage (200 V) before application of the SiC material. This includes therefore removal of approximations of the currents due to C' and C'' from the grading section alone, and the small harmonic values of the voltage source (typically less than 0.1% for the third harmonic relative to the fundamental). The removal of the capacitance from the middle section of the bar lets special features of the C', C'' relation be seen, for example similar gradients (in log-log scale) and even similar magnitudes in the special case seen here for low voltage where the grading material's non-linear effect is weaker and therefore the grading behaves more like a linear distributed R-C circuit.

Material	$G_0$	n	$ \rho(0)_{\text{surface}} = 2\pi r/G_0 $
Paint(thin)	$2.5 \times 10^{-16}$	0.00114	$3.9 \times 10^{14}$
Paint(medium)	$1.8 \times 10^{-15}$	0.00115	$5.4 \times 10^{13}$
Paint(thick)	$1.0 \times 10^{-13}$	0.00110	$9.7 \times 10^{11}$
Tape	$5.5 \times 10^{-13}$	0.00115	$1.7 \times 10^{11}$

Table 4.1: Material model parameters according to (4.2), from axial DC measurements of current through the stress-grading material around a 30 mm diameter tube, so  $r = 15 \times 10^{-3}$ .

Figures 4.7 and 4.8 show the capacitance of the the bars' gradings, over a wide range of applied voltage. The particularly strongly sinking part at the right of the 1.5 kV curves indicates that the capacitance at high frequency is tending to the value with no grading, which was the value used to compensate: as the compensated value approaches zero the curve falls rapidly in its logarithmic scale. The large positive correlation of capacitance with voltage at high frequency shows how an increased stress around the earthed sheath causes an increased conductivity in the grading material and therefore the earth potential spreads out further along the grading. At very low frequencies even the conductivity with very low stress is able to conduct enough current to make the slow changes in charge to maintain the earth potential over the whole grading region, so the capacitances tend to a maximum value with weaker voltage dependence.

The capacitance (C') values give an idea of the extent of the spread of earth potential through the grading at different frequencies: the taped bar will be used as the example. The earthed sheath is 120 mm long, it had a capacitance of 32.0 pF guarded and 34.6 pF unguarded, measured at low voltage (200 V) with the DS equipment before application of the field-grading, from which it is assumed that 2.6 pF is due to fringing.

If all the stress-grading region of the bar were treated as being conductive, the capacitance would be 74.6 pF, calulated by scaling the capacitance of the electrode over the extra length. The fringing is approximated by adding to this value the 2.6 pF for the ungraded case. This gives 77.2 pF as the capacitance if the whole grading region were at the same potential as the sheath.

Looking at figure 4.8 and the close-up and *uncompensated* (total current of electrode and gradings) view in figure 4.9, it is clear that at the lowest frequencies used the measured capacitance is almost exactly this value, while at the highest frequency, 100 Hz, the capacitance with moderately low voltage that doesn't increase the grading's conductivity very strongly is almost as if the stress-grading material were not present.

Figure 4.9 shows an interesting effect. In the range 5 to 10 kV applied voltage



Figure 4.7: C' and C'' for just the graded parts of the painted bar, 1.5 - 15 kV. The highest amplitude and frequency combinations were too much for the amplifier, so are missing.

the measured capacitances appear to tend to a maximum value of a little under 76 pF, and at less than 5 kV there is still a trend of the curves that suggests that a further decade of lower frequency could allow these curves to reach this value too. The curves from voltages greater than about 10 kV, on the other hand, move from the flattening tendency of the 5–10 kV range and exhibit a final capacitance that increases quite steadily with increased voltage. Looking at C'' from figure 4.8, it can be seen that the same high voltage levels have a change in the downwards trend of C'' with low frequency, breaking away from the low voltage points and moving upward with further decreasing frequency. Both this change and the change in capacitance are of similar order of magnitude, a few picofarads.

At about the 10 kV level, where the low-frequency value of C' resumed its increase (figure 4.9), the value of C'' begins to deviate from its straight line and to tend upwards. The amount by which it increases is of a similar size to the corresponding increase of C'.

The spreading of earth potential throughout the grading material means that it



Figure 4.8: C' and C'' for just the graded parts of the taped bar, 1.5 - 15 kV. A higher power supply was used than for figure 4.8, allowing all points to be measured.

will have a strong field at its edge, which is just what the "corona protection" stressgrading is supposed to avoid at normal frequencies. One suggested explanation for this increase in C' and C'' is that PDs may be occurring at the edge. These would add to the measured response, typically with quite similar real and imaginary components of current. Measurements with PD apparatus, and inspection in a dark room with dc applied voltages up to 30 kV revealed no evidence of PDs. A pointplane test object has previously been used to demonstrate that some discharging current can be measured by the DS equipment when not visible as PD impulses of detectable size, so there may be a small surface discharge leakage of charge around the grading end that cannot be detected as definite pulses large enough for the PD system or the eye to see.

Surface leakage across the PTFE from the end of the grading is another possibility which is not possible to screen away without changing the field distribution or using a buffered guard with very high input resistance and high voltage capability. Plain conductive leakage would not explain the increase in C', but with regard to the capacitively coupled current through the insulation to a slightly conducting layer on the surface, the phenomenon may be able to be explained.



Figure 4.9: C' for the taped bar, showing the clustering of low-frequency capacitance at intermediate (5 - 10 kV) voltage levels

The main interest in this slight current increase is the possibility of PD current that is visible with the DS system and not the PD system.

At lower voltages, i.e. below about 8 kV, a change in voltage works almost exactly to shift the curve in frequency: a simple part-explanation is that the change in stress changes the conductivity which chages the RC time-constant of the grading system.

The C' and C'' values deal only with the fundamental component of the current, i.e. the component with the same frequency as the applied voltage. As the grading material is non-linear it is expected that the current in the grading is significantly non-sinusoidal, containing higher harmonics as well as the fundamental component. Since the material can reasonably be taken to have properties independent of the polarity of the voltage, the current waveform must have positive and negative parts that are simply negations of each other. The odd harmonics are therefore the only expected components of the harmonic spectrum, and this was confirmed by the measurements. Only the 3rd, 5th and 7th harmonics are therefore shown in figures 4.10 and 4.11, which show the amplitude of each of these harmonics as a proportion of the fundamental component of current into the grading, for several frequencies at each of three voltage levels.



Figure 4.10: Painted bar, 3rd 5th and 7th harmonics, as proportions of the fundamental component of current. For each harmonic, values are ordered by ascending voltage magnitude then within this by ascending frequency.

## Simulation models

In this subsection a simulation of the non-linear distributed-parameter system of stress-grading is compared to the earlier measurements on physical models of stator end-winding grading. The simulation uses all the parameters of one end of the physical model bars, so the currents shown here are doubled to match the physical model. For easier use of the simulation model, the part that is really the high voltage conductor is made the earth (0 V), and the end of the outer electrode (slot semiconductor) is made the high voltage electrode. This also makes later presentation of the potential at the end of the grading more relevant, as it is then with respect to the nearby inner electrode.

The obvious basic model is a resistive series component and a capacitive parallel component, in a 'transmission-line' arrangement. In qualitative discussion a linear, lumped-element model has often been used for rough descriptions of the observed results from the laboratory models. The unavoidable fact that the resistivity can


Figure 4.11: Taped bar, 3rd 5th and 7th harmonics, as proportions of the fundamental component of current. For each harmonic, values are ordered by ascending voltage magnitude then within this by ascending frequency.

change by an order of magnitude in the real case of non-linear materials, may then be approximated by decreasing the resistivity for increased applied voltage.

On the way to a better model it is instructive to look at some of the steps from the simple linear lumped-element model to non-linear distributed models and possible further components. If the model were to be used in practice for calculating an expected response from knowledge of material and dimensions, it is of particular advantage to have as simple a model as is sufficiently accurate in the frequency and electric field ranges of relevance, to prevent the calculation time being a trouble.

Figure 4.12 shows a generalised circuit for a grading model, defining components for discrete or distributed cases and including some components (dashed lines) that may be included in order to model finer details than the simplest form.

A simple R-C lumped circuit is a pure Debye response, better known in electronics



Figure 4.12: The general case of a 1-dimensional model of a grading. The unit in parentheses is a segment of a discrete model or an elemental length dx of a distributed model. The component values  $C_{\rm p}$ ,  $R_{\rm s}$  etc. but not  $G_{\rm end}$ ,  $C_{\rm end}$  are per unit length. A simple yet quite accurate model can use just  $C_{\rm p}$  and  $R_{\rm s}$ . Conductive elements, R or G, may be non-linear functions of electric field strength rather than constants.

as a first-order low-pass filter!

$$C' - iC'' = \frac{C_{\rm s} - i\omega R_{\rm s} C_{\rm s}^2}{1 + \omega^2 R_{\rm s}^2 C_{\rm s}^2} = \frac{C_{\rm s}}{1 + \omega^2 R_{\rm s}^2 C_{\rm s}^2} - i\frac{\omega R_{\rm s} C_{\rm s}^2}{1 + \omega^2 R_{\rm s}^2 C_{\rm s}^2}$$
(4.3)

Cascading of such filters may easily be done, analytically, but if the distributed case is really desired this is very simple to solve directly in the linear case. A simple R-C distributed-parameter model can be solved by the general LCRG transmission-line equations as presented in for example [Che89]. When these equations are taken from time to the frequency domain, on an assumption of linearity, they becomes a general case of distributed series impedance  $Z_{\rm series}$  and shunt (parallel) admittance  $Y_{\rm shunt}$ , whose solution is valid for any complex value of either, i.e. one may choose both elements to be only capacitive and resistive or some even more exotic combination.

In our case, as suggested by the solid-line components of figure 4.12, the special case of a diffusion where  $Y_{\text{shunt}} = i\omega C_{\text{shunt}}$  and  $Z_{\text{series}} = R$  is of primary interest, and an extension of  $Z_{\text{series}}$  to have a capacitive component may be desirable as a later finesse.

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#### 4.2. RESPONSE OF END-WINDING STRESS-GRADING

The main interest here is the current into such a distributed network, and the input impedance  $Z_{in}$  is the closest standard transmission line value fitting this:

$$Z_{\rm in} = \frac{Z_0}{\tanh(\gamma l)} \quad (\text{when } Z_{\rm end} = \infty)$$

$$(4.4)$$

$$Z_{\rm in} = Z_0 \frac{Z_{\rm end} + Z_0 \tanh(\gamma l)}{Z_0 + Z_{\rm end} \tanh(\gamma l)} \quad (\text{else})$$

$$(4.5)$$

where l is the length of the line (grading), and the characteristic ('surge') impedance  $Z_0$  and propagation constant  $\gamma$  are given by

$$Z_0 = \sqrt{\frac{Z_{\text{series}}}{Y_{\text{shunt}}}} = \sqrt{\frac{R}{\mathrm{i}\omega C}}$$
$$\gamma = \sqrt{Z_{\text{series}}Y_{\text{shunt}}} = \sqrt{\mathrm{i}\omega CR}$$

in which Z, Y, R and C (and therefore  $\gamma$ ) are values per unit length. The complex capacitance is then found as

$$C' - iC'' = \frac{1}{i\omega Z_{\rm in}} \tag{4.6}$$

Figure 4.13 shows the results for C' and C'' obtained by these two simple models, using three values of resistance as a crude approximation of the effect of an increased amplitude of applied voltage causing a lower resistivity in a non-linear grading. In the discrete case the resistance of the entire length of grading is in one lump, in series with the capacitance of the entire length of the grading. Most notable is the difference at high frequency: the discrete case has the classic Debye reduction of C'with increased  $\omega$  at twice the gradient of the the reduction of C''; the distributed case has both C' and C'' tending to the same value, with a gradient of 0.5. This situation was mentioned in chapter 3: any linear distributed infinite R-C line has this property, and at high frequencies the end of the grading is hardly influenced by the applied voltage, so the grading is effectively endless seen from the input.

Such simple models are of interest only for loose and qualitative discussion; the non-linearity must be included in detail if one is to come close to calculating the real response of the grading, but it is instructive to see how much difference the distributed and non-linear parts of the model make. Extending the above pair of models to non-linear resistances, first discrete then distributed, the non-linear discrete case is a solution of

$$V_{\rm NL} = V_{\rm supply} - V_{\rm capacitor}$$
 (4.7)

$$C\frac{\mathrm{d}V_{\mathrm{capacitor}}}{\mathrm{d}t} = V_{\mathrm{NL}}G_0 \exp\left(n |V_{\mathrm{NL}}|^{2/3}\right) \tag{4.8}$$

and for just one R and one C component, using the non-linear resistivity of (4.2) and the total R and C of the length of the grading, the result can be seen in figure



(a) Linear discrete model: a single R-C low-pass first-order filter)



(b) Linear continuous mode: a finite length, open-ended R-C transmission line (diffusion)

Figure 4.13: Example responses from easily understood *linear* models, discrete and continuous; the continuous case becomes the special case of  $\omega^{n-1}$ ,  $n = \frac{1}{2}$ , from (3.19), at high frequencies where the end of the grading is so electrically far that the inifinite length assumption is valid.

4.14. This differs most obviously from the linear discrete case in that the low frequency C'' becomes similar for all curves because the difference in potential across the grading is so small and therefore the resistivity is near its lowest value whatever the applied voltage. Otherwise it seems the effect on the fundamental frequency quantities is such that the non-linearity has the effect of changing a linear resistor's value for each applied voltage amplitude.

The complete 1-dimensional non-linear R-C model solves a PDE with one dependent variable, the electric potential V, in the independent variables of single space and time dimensions, x and t,

$$C\frac{\partial V}{\partial t} = \frac{\partial}{\partial x} \left( \frac{\partial V}{\partial x} G_0 \exp\left( n \left| \frac{\partial V}{\partial x} \right|^{2/3} \right) \right)$$
(4.9)

subject to boundary conditions (BC) that apply the sinusoidal supply voltage to point x = 0 (essential BC) and require no current at point x = l (natural BC).

The results of this are shown in figure 4.15, and are in figure 4.16 compared to the meaurements on one of the taped physical models.

#### Comparison of physical and simulation models

Figures 4.16 and 4.17 show a comparison of measured C' and C'' from the physical models against the values obtained by simulation. The fit is quite good when one



Figure 4.14: Simulation of measured C' and C'' of a single discrete series R-C circuit where R has a non-linear *i*-v relation of the form of (4.2) with the parameters for SiC tape from table 4.1; the values of R and C are those of the total length of the grading. [NOTE: figure corrected since printed thesis]

considers that the SiC on the physical model is not the same piece of SiC as was on the sample bar used for obtaining the material parameters. Over to the extremes of frequency there is considerable difference between the measured and calculated values, but these extremes are fortunately away from the frequency range expected to be of greatest interest.

Several extensions of this simulation model (4.9) are easily made and have been tried with estimated parameters, but without improvement of more than small parts of the matching between the results of the physical and simulation models and without further measurements to verify the parameters for the extra terms, for example a reasonable value for surface conductivity.

Some conductivity in the insulation material can be included by a source term, i.e. a  $-V/G_p$  term on the right of (4.9).

Leakage from the open end of the grading can be included as a mixed BC where a possibly non-linear function relates flow (current) to the potential V.

Series capacitance, the  $C_{\rm s}$  of figure 4.12, may be significant in the high frequency range and can be included by introducing a further dependent variable set



Figure 4.15: Simulation of measured C' and C'' of a distributed series R-C circuit where R has a non-linear *i*-*v* relation of the form of (4.2) with the parameters for SiC tape from table 4.1. C' has a continuous line, C'' has a dashed line. Note that this models the response of *one end* of the physical test bar.

to the time derivative of V, in order that the necessary  $\frac{\partial}{\partial x}C_{s}\frac{\partial}{\partial t}\frac{\partial V}{\partial x}$  term can be implemented within the rules of the 1st order PDE solver.

#### The simulation model harmonics

The harmonic content of the current is of great significance as a means of studying the amplitude and frequency dependence of the non-linear phenomena alone, expected to be primarily PD and end-winding stress grading. It is therefore important that the simulation and physical models should be in good agreement about the harmonic content as well as about the fundamental frequency values C' and C'', if the simulation model is to be used to study the harmonics.

Figure 4.18 shows a comparison of three voltage levels at 1 Hz, comparing the simulation of the taped bar with the measurements on the taped bar. As in the fundamental frequency case, the fundamental frequency current due to the 34.6 pF capacitance measured for the central electrode of the physical model has been subtracted from the measured current.



Figure 4.16: Comparison of measurements of C' on physical models using SiC tape with the results from numerical solution of the non-linear distributed-parameter model

If the fundamental component of current due to the linear insulation can be removed, the waveform of grading and PD currents can be seen, but this removal requires a very accurate value for the capacitance since the fundamental component of such non-linear phenomena as end-winding grading or PD can be a small proportion of the total capacitance.

It may be that working in the frequency domain, studying just the third harmonic or perhaps a few low harmonics, is a good way to characterise the non-linear component of the insulation system, e.g. change in amplitude and phase of third harmonic with amplitude and frequency of the applied voltage. As an example of the effect of amplitude and frequency on the low order odd harmonics, figure 4.19 shows numbers 3, 5 and 7 from the simulation. Only the odd harmonics are expected to be of significant size, since the grading behaves in the same way for positive or negative applied voltages. At higher frequencies these harmonics have quite similar change with frequency, but smaller absolute values for the higher harmonics. In this case there is therefore a lot of common information, which could be obtained from just the third harmonic.



Figure 4.17: Comparison of measurements of C'' on physical models using SiC tape with the results from numerical solution of the non-linear distributed-parameter model



Figure 4.18: Comparison at 1 Hz of measurements of i(t) on physical models using SiC tape (solid lines) with the results from numerical solution of the non-linear distributed-parameter model (dashed lines).



Figure 4.19: Magnitudes of the three strongest components of the current, parameterised by voltage, plotted against frequency. For each harmonic, the three curves correspond to the three voltage levels 1.5, 7.5, 15.3 kV, with increased harmonic amplitude for increased voltage.

#### Surface potential in time and space

Measurement of surface potential of a physical stress-grading is reported by others working with higher frequencies in gradings, but equipment and necessity for us to measure potential on the physical models were not close at hand. The numerical models, on the other hand, provide an easy way to get a picture of the way that potential is distributed along the grading. This is not as simple as a linear case where a sinusoidal input signal ensures that any point's potential may be represented as a phasor. Here, the waveform is expected to change across the grading.

This subject is of lesser interest here than the current measured at the start of the grading, but it is relevant to the possibility of PD at the end of a grading. An estimate of this potential can be made from how much the capacitance has changed, but in view of its good correspondence to the physical model's fundamental and harmonic currents it is expected that the simulation will give a better estimate of the end potential, including phase and the distortion due to non-linearity.

From figure 4.20 it is seen that the degree of harmonic content in the potential at the open end of the grading is strongly increased by increased amplitude or frequency of the applied voltage, i.e. the cases where the stresses in the material are highest. In the higher amplitude cases the end potential reaches even a higher proportion of the applied amplitude, due to the increased conductivity under higher electric field. This makes the end potential depend 'super-linearly' on the applied potential. At high voltage, the 15.3 kV point in this case, the end potential is almost equal to the applied amplitude even at 100 mHz, as expected from the capacitance values presented earlier.

The potential at the end is delayed in phase more with lower amplitude or frequency, again an effect of the electric field altering the conductivity of the grading material. The shift in peak value between low and high frequency at the highest voltage is more than  $90^{\circ}$ , which has some relevance for phase-resolved measurement of any PD that may occur at the end of the grading, although at large phase retardation the potential will be lower anyway, so there could not be PD in the extremely delayed cases.

The spatial variation in waveform is interesting: a quick change of the sinusoidal input to a sharply non-sinusoidal waveform at x = l/4 through the most highly stressed part of the grading, but then the later parts, under less stress and therefore closer to linear components, have on account of the R-C nature of the grading a filtering effect that yields an apparently more sinusoidal waveform later on.

#### Limitations

The ideal use of the above modelling would be to put parameters for a particular machine into the model, get out calculations of fundamental and harmonic currents



Figure 4.20: Simulation of V(x,t) in a grading. Note the model's use of the reference (earth) on the inner conductor, i.e. that the connected end of the grading is connected to the voltage source. At the top are the potential against applied voltage phase angle, at the open end of the grading, first with varied frequency then with varied amplitude of the voltage. Note the use of normalised potential in the second case. Bottom left is the spatial distribution (left is driving end) of the peak potential for several amplitudes and frequencies. Bottom right is the time-waveform at different proportions of the length away from the driving end.

due to the end-winding stress grading at all the amplitudes and frequencies of applied voltage that are to be measured, and then to remove these values from measured currents to get the response without the change due to the end-windings.

PD would then be the main contributor to non-linear components of the current, and this may in turn allow the fundamental components due to PD to be estimated from the non-linear currents, perhaps by use of the voltage-dependence; this would in turn allow the bulk material's properties C' and C'' to be seen without the additional currents from PD and grading.

Useful application of the modelling results would need accurate calculation of the

end-winding currents. For example, the end-winding may increase the capacitance by some percent of the total winding capacitance, and the absolute change in loss is of a similar order, which in view of the normal loss of the bulk material — of the order 0.5% to 1.5% of the capacitance for epoxy resin or bitumen in good condition — is very large. A small error in compensating this loss will give a significant error in the compensated value for the bulk insulation or for PD.

This ideal situation in which modelling is done based on parameters of the winding is not realistic for practical application to machines. On stator insulation the application of SiC compounds is done to prevent a problem of excessive surface stress, not explicitly to acheive highly consistent dielectric response.

There can be variations between different SiC products and between how these have been applied to the insulation. Some SiC gradings may be applied as Bstage tape over a resin-rich insulation system and then the whole coil or winding may be cured, or in other cases the tape is applied to non-impregnated insulation that is then given VPI treatment with a resin, that may affect the proximity of SiC particles in the tape. Older machines commonly had a SiC-containing paint applied to the end-windings, which can be expected to give far less consistent results than the tape — this is confirmed by measurements reported later.

The length of the grading might well differ between end-windings on the same machine, and indeed some machines may have had some coils or bars replaced with others of slightly different grading design. Typically, the grading material is covered with some protecting and compressive tape, which makes measurements of its electrical properties or even just its length not practicable. Aging from thermal and mechanical stresses is likely to change the properties of the grading material from the original condition: the significance of contact between SiC particles in the base material means that changes in the base may change the electrical properties considerably.

#### Differences between the physical models and real stator insulation

The simple description given of end-windings and stress grading assumed isolated cylindrical bars, and this geometry was continued into the physical and therefore the simulation models. The real case is different in several important ways.

The cross-section of that bars is rectangular, with rounded corners, so some variation in potential around the circumference at a given axial position can exist. This makes the one space dimension model less appropriate.

Many bar-ends are clustered close together, so fields between them have some significance. During normal operation there are higher voltages between phases than from phase to earth, and different turns have different potentials. During off-line diagnostic testing each winding has a single potential, and either one winding is energised while the others are earthed, or all are energised together. There

#### CHAPTER 4. NON-LINEAR STRESS GRADING WITH VARIED AMPLITUDE AND FREQUENCY OF THE VOLTAGE

are therefore rather different stresses on the end-windings than in the simple case considered, although the presence of gas (low permittivity) in the gap between windings does mean the effect of adjacent conductors will be quite weak compared to the effect of a conductor just a few millimetres away through insulation of several times this permittivity.

More significantly, for the matter of comparing this chapter's results with measurements on real machines, the permittivity and insulation thickness of the models are unrealistic on account of the desire to use a low loss, low dispersion, heat resistant material in a conveniently available tubular form.

Rather than the model's insulation thickness of 5.5 mm, outer-inner radius around 3/2 and relative permittivity  $\varepsilon_r \approx 2.1$ , an example 7.2 kV stator coil has an insulation thickness of a little under 2 mm, rectangular cross-section, and  $\varepsilon_r \approx 4$ . This leads to higher capacitance but with little difference in the circumference that determines the resistance per unit length of the grading material.

The effect is to reduce the loss peak frequency, and indeed from measurements on the example stator coil of chapter 5 this peak was apparently only just being reached with 10 kV at the very impractically low frequency of 0.1 mHz — see figure 5.3 for the bending of C'' below 1 mHz. With frequencies likely to be acceptable for the time constraints of industrial use, and with voltages not exceeding the standard test value of line-voltage applied from phase to earth, the amplitude and frequency points used will tend to be all or mainly on the high frequency side of the grading's loss peak. This makes previous consideration of the frequencies far below the loss peak, for example in the context of the increasing C'' at low frequency (figure 4.17) far less relevant. It also has the useful consequence of simplifying the response, at least of the fundamental frequency components, if largely fractional power-law responses are obtained along the high frequency tail of the dielectric response.

### Chapter 5

# Examples with real stator insulation

The diagnostic methods considered in this work have little or no previous application to stator insulation systems. To the author's knowledge, VF-PRPDA has not been used in this application by any other group, and frequency-domain DS has been very scantly investigated but not industrially adopted. It is therefore of interest to get some idea of whether and how these methods show changes in stator insulation systems.

Although this work on (HV,FD)DS and VF-PRPDA is concerned partly with general investigation of the utility of coupling the two measurement methods, there is also a focus on the industrial application of such measurements to motors and generators. It is therefore necessary to be familiar with some such machines, industrial diagnostic practices, the practicality of connecting a measurement system to a machine *in situ*, permissible measurement times, insulation voltage stresses, and some typical values of the results. Due to the wide variations of machine construction and of modes of insulation degradation it cannot be expected that anything approaching a wide view of the subject will be gained during this project, but at least some dead-ends might be avoided and a better idea acquired of the necessary properties of an acceptable industrial diagnostic method.

Two small investigations have so far been made on real stator insulation: one used some new coils made for use in 7.2 kV motors, and studied the DS and PD measurements before and after accelerated thermal aging; the other was plain DS measurements on an complete stator winding of a 10 MVA hydro-generator before and after some maintenance.

#### 5.1 New stator coils and accelerated thermal aging

Four new epoxy-mica insulated stator bars were obtained, for laboratory measurements of DS and PD and for seeing the effects of thermal aging. There were two small such coils and two large. Just the two small ones have as yet been used. These are called A1 and A2, and dimensions are given in figure 5.1.



Figure 5.1: Dimensions of the 7.2 kV stator coils A1 and A2.  $l_s = 1550 \text{ mm}, l_e \approx 290 \text{ mm}, l_c = 2300 \text{ mm}, l_w = 310 \text{ mm}, w_1 = 33 \text{ mm}, w_2 = 11.5 \text{ mm}$ . The length of slot semiconductor between the guard-break and the start of the end-winding stress-grading layer is about 14 mm, and slot semiconductor then continues for about a 20mm overlap.

#### Slot semiconductor

The resistivity of the slot semiconductor layer is of interest for these measurements as it determines what minimum placement of electrodes is needed for a desired accuracy of results. If this surface resistivity is considered negligible then a single electrode may be applied to each of the two slot parts of the coil, to collect the current from the entire length. At a high enough frequency the effect of the series resistance of this arrangement will become significant. A wide frequency range of measurements is desired here, and as electrodes may have to be removed and re-applied several times during cycles of high-temperature aging followed by measurements, it is useful to know when single electrodes will suffice.

Measurements of current at several applied DC voltages were made, along 1000 mm and 500 mm lengths of the slot semiconductor surface, between electrodes of 25 mm wide copper tape with conductive gum. The measured resistance, divided by the length in metres of the measured section, is shown in figure 5.2, for the cases of before and after thermal aging. An effect of the thermal aging was to reduce the slot semiconductor resistivity by a factor of around 3. If the electrode contacts

could be assumed to have similar resistances in all cases and the resistivity of the slot semiconductor could be assumed to be uniform, then the contact resistances could be calculated from the two different lengths measured; the contact resistance was, however, seen to be dependent on pressure, by watching the current as the electrodes were squeezed. From the closeness of all the results in figure 5.2 it is clear that the contact resistance is unlikely to be more than a few percent of the 1 m length resistance, and that there is not significant variation in the several different sections of similar lengths that were studied.



Figure 5.2: Slot semiconductor surface resistance, for the new (cured) coil before and after aging at 180°C for 6 days.

For DS measurements before aging there was no noticeable difference at below about 1 Hz in C' or even C'' as a result of using just one electrode or putting metal foil over the whole surface of the measured part of the coil between the guardgaps. This can also be calculated from the measured surface resistivity and the object's capacitance. At higher frequencies approaching 50 Hz, only the presence of a metallic electrode across the entire length of the bar prevented an obvious increase in C'' with frequency. A full-length electrode of firmly taped aluminium foil with ends of copper tape was used for all following measurements of DS and PD. This was verified to show very little increase in high-frequency loss, so the contact of aluminium to the semiconducing material is adequate even if not as good as the copper tape with conducting gum. The aluminium foil electrodes are quick to apply and very cheap, which is important if the coils are to be repeatedly measured and then aged in a way that precludes, due for example to high temperatures, the presence of electrode material and tape.

#### Dielectric response of the new coils

DS measurements were made with varied voltage and frequency, randomised in time. The guarded mesaurements, of the bulk material properties, showed very high linearity, as C' and C'' were not noticeably correlated with voltage amplitude. The frequency dependence was an example of a double fractional power-law (universal response) function, with each part being two straight lines in the log-log scale.

The unguarded measurement on the new coil, figure 5.3, shows a quite different situation from the SiC-grading coating PTFE bars of the laboratory tests of the previous chapter, without the pronounced peak in loss being visible in the measured freuqency range. The behaviour of C'' at low frequency suggests that the peak is coming, but at much lower frequency than on the laboratory models, as expected from the higher insulation capacitance of the real coil and from the possibly increased resistivity of the stress-grading material which has been VPI treated along with the rest of the coil's insulation system. The voltage dependence of the end-winding response is seen on both C' and C''.



Figure 5.3: Dielectric response of entire new coils, including voltage and frequency dependence of the end-windings. Even at very low frequency the loss peak is not reached.

A PD measurement was tried on the new coil and no PD could be detected even at 11 kV peak. The new coil was then warmed within about an hour up to  $180^{\circ}$ C and left for 6 days. It was cooled over several hours, and taken out and tested with a DS measurement up to 7 kV, but even at 5 kV a noise from internal PD was heard. The PD was confirmed by listening by ear and by an ultrasound detector as coming from pretty well all of the coil's length. A similar set of measurements and similar accelerated thermal aging were then used on the second, similar coil, with quite similar results.

Figure 5.4 shows the voltage dependence of capacitance and loss when new and when aged, for the guarded (without end-windings) and unguarded cases. This, done at 50 Hz, is effectively a C' and tan  $\delta$  'tip-up' test, showing linear tip-up with voltage when the end-windings are the only non-linearity, and a much sharper tip-up starting at about 4 kV in the aged case when PD starts. The capacitance and loss have been reduced over 10% by the aging, credibly due to expansion with release of gases, and the presence of the consequent voids.



Figure 5.4: Changes in C' and  $\tan \delta$  of A1 as a function of voltage at 50 Hz, before and after aging at 180°C for 6 days. Shown with (guarded) and without (unguarded) the contribution of the end-windings.

Figure 5.5 shows the PD current as measured by the PD system, displayed in complex capacitance form of its fundamental components. This is a useful form for comparison with DS measurements and for dividing away the strong differences caused by varying voltage and frequency. That the trends are opposite in frequency for the two bars is rather an interesting difference not at noticed from the PD patterns.

#### Comparison between DS and PD currents

Although no clear claim can be made that the accelerated aging as used here has produced something typical of a naturally aged stator coil, this coil is a useful example of stator insulation with many cavities, which can be used for initial comparisons of the PD and DS systems' measurement of PD currents.



Figure 5.5: The fundamental components of measured PD current, expressed in complex capacitance form. The main purpose of this figure is to show the approximate values of C' and C'' and that they are very similar to each other: the phase of the fundamental PD current remains close to  $45^{\circ}$ . That the frequency dependence is opposite between the coils is of particular interest. A2 was measured with amplitude and frequency points randomised in time, while A1 was measured in classic amplitude up, frequency down, amplitude first, order.

From the DS, measured guarded after aging, there are low voltage measurements that give the complex capacitance of the insulation including voids, and there are high voltage measurements that give this along with the currents from PDs. The capacitance of the insulation is so much bigger than the PD current that it must be removed in order to see anything of the fundamental component of the PD current. An initial comparison of PD and DS currents can be by assuming the solid insulation material to be still linear after aging, but that the presence of gas-filled voids presents an added non-linearity of low permittivity gaps that may lose their insulating properties when sufficiently high electric field strengths build up across them. Then, an approximation of the component of the current due to PD may be made at a given frequency simply by removing from the high-voltage measurement the current due to the high-voltage applied to the low-voltage value for complex capacitance (5.1).

$$\mathbf{I}_{\rm PD} \approx \Delta \mathbf{I} = \mathbf{I}_{\rm HV} - \frac{\mathbf{V}_{\rm HV}}{\mathbf{V}_{\rm LV}} \mathbf{I}_{\rm LV}$$
(5.1)

Since the applied voltage in the DS measurement was measured as containing some small harmonic content, the currents were approximately compensated by subtracting the current that each harmonic component of voltage would cause in the fundamental frequency capacitance of the coil.

Figure 5.6 shows a particular voltage-frequency point where the PD current was calulated from the PR-PDP given by the PD system, then filtered to the same num-

ber of harmonics as the DS current. Since the PD current was still much smaller than the DS current, it was also scaled to compare the waveforms, which can be seen to be remarkably similar.



Figure 5.6: Coil A1, after aging, comparison of current measurements by DS and PD at 8 kV 50 Hz. The DS current is calculated according to (5.1) using a 0.7 kV 50 Hz measurement for the low voltage complex capacitance and compensating for harmonic voltages by removing the current these would cause into the 50 Hz capacitance. The PD current is also shown scaled to the same maximum value as the DS current for comparison of waveforms. The ripple on the PD current is a consequence of the low number of harmonics used, partly to match the DS result and partly to remove the noisy variations.

Figure 5.7 does the same thing with coil A2 and several frequencies at a high voltage. For each case the scaling factor needed to make the PD system's current match the DS system's is given.

The differences in magnitude yet the similarities in waveform are quite surprising, between the PD and DS system's measurements.

The measurements are not yet being made simultaneously with the two systems, as a new PD system is awaited for this. This cannot explain more than a



Figure 5.7: Coil A2, after aging, comparison of current measurements by DS and PD at 9 kV and 50, 5, 0.5 and 0.05 Hz. The DS current (solid) is calculated according to (5.1) using a 1 kV measurement at each frequency and with compensation for harmonic voltages. The PD (dashed) current is also shown, in its first 8 harmonics, scaled to the same maximum value as the DS current for comparison of waveforms, with the scaling factor shown. As usual, a sinusoid to represent phase of the applied voltage is included.

small proportional change in the actual PD values: several tests have been done to check the quite good consistency of consecutive PD measurements as seen by either system.

It is expected that the PD system would lose some of the charge through filtering and through dead-time, through sub-threshold PDs and through PDs too big to fit on the scale of the PD pattern. It is also relevant that the measurements on coil A2 did have some 'ringing' — pulses of opposite polarity recorded when the system recovers from dead-time just on the inverse oscillation of a recent pulse, which would remove charge from the current that should be added, though this doesn't even explain a factor of two in the error. It seems rather surprising in this case that the waveform should be so consistent between both systems. It may turn out that there is some error, or at least that there is a lot more PD that can be measured with the right settings of the PD system. If, however, the much larger DS current believed to be PD, does turn out to be PD and the PD system really cannot measure it, that is very interesting for the combined use of the systems as a PD total current and PD biggest pulses measurement.

#### 5.2 Field tests

As an introduction to normal practice, the practicality of the methods investigated in this work, and the insulation properties of an example of a whole naturally aged stator winding, measurements on a 10 MVA 6.3 kV hydro-generator were made in conjunction with the testing that was to be done before and after some maintenance work on the generator.

The tests usually performed by the consultant are a standard set working up from shorter lower voltage ones to high-voltage 50 Hz capacitance, loss and PD measurements, then to a hi-pot test.

It was intended that the full set of tests should be performed before and after the maintenance work, but on the day intended for the first set of tests (1a) the IR measurement revealed extremely high current in the insulation of one phase and abnormally high currents in the other two. The relative humidity (RH) of the air was measured as 84% on that occasion, and the air temperature as 22°C. From the points in chapter 3 about effects of humidity on surface leakage currents, the very high RH is of interest as a possible contributing factor to these results.

Figure 5.8 shows these IR results together with those of the two later occasions. Bear in mind, from the description of IR in condition assessment, given in chapter 2, that a common expectation is several thousands of megohms at 10 minutes, and that the ratio of 10 minute to 1 minute values is expected to be at least 2 and likely closer to 5. In view of the very poor IR, the higher voltage tests were postponed while the insulation had a chance to get dry. The repeat tests (occasion 1b) also showed several times worse IR than is usual, but no phase was as bad as before and indeed the one, w, that had been so very bad was then better than the others!

On occasion 1b, with RH of 32% and temperature of 28°C, it was decided to continue with the rest of the tests in spite of the IR results. The capacitance and loss measurements were performed at 50 Hz with a voltage of 0.2, 0.4, 0.6, 0.8 and 1.0 times the rated line voltage (i.e.  $\sqrt{3}$  times the usual working value), applied to each phase in turn with the others earthed and then to all the phases together. The PD measurements were performed with the same voltage, with a phase-resolved system like the one described at the end of section 3.2 but with a resonant transformer of fixed power-frequency applying the voltage. The PD measurement system was connected to the windings' phase ends, again with the phases energised separately then together. The hi-pot test was performed without problem, and a quick IR measurement afterwards showed no strong change.

After all the tests were completed, there was a chance to make DS measurements for about an hour. Only the basic DS system with its built-in 10 V and 200 V sources had been taken along on this occasion, so only low voltage measurements way below real stimulation of stress-grading or PD could be made. Due to the desire to measure the response of three separate phases and all phases together, the lower limit in frequency was quite high, and the number of points used was small.



Figure 5.8: Insulation 'resistance' measured by a 'megger' meter applying 5 kV DC at t = 0 to phases u, v and w in turn, with the others both earthed, then to all phases u,v,w together. This was done on three occasions, denoted 1a, 1b and 2.

Most measurements were made at 50V peak, with just a quick 50 Hz and 5 Hz measurement at 200, 100 and 10 V on each phase to check no significant amplitude dependent variation of the response in this low voltage range. Figure 5.9 shows the real and imaginary parts of the complex capacitance from this measurement, for each phase and for all phases together. Within the precision allowed by plotting C' and C'' together, all phases' values at higher frequencies lie on the same points, but towards lower frequencies

After the maintenance work, the tests (occasion 2) showed still a lot worse than expected IR and PI in all phases and that one phase, u, had about half the IR of the others — on occasion 1b it had also been worse than the others but not this bad. It was again decided to continue with the HV AC measurements. There was afterwards an opportunity to spend an hour making DS measurements, this time with the HV amplifier having been brought along. It was decided that individual phase measurements should be used, in order to see how much the differences observed with IR measurement were seen with DS. To make good use of the small time available for each phase measurement, and to explore the dimension of voltage



Figure 5.9: C' and C'' for the short 50 V measurements on the stator windings on occasion 1b.

amplitude that had been ignored on occasion 1b, only a few frequencies were used. 5 kV peak, as used also for the DC supply for 10-minute IR measurements, was established as a cautious maximum acceptable level for these quite high frequency (not much less than 1Hz) measurements. The available current limited the maximum frequency at 5 kV to a little below 1 Hz for all windings together, or about 1.5 Hz for each winding alone. Time constraints prevented frequencies lower than 0.3 Hz being used for most of the measurements: 0.1 Hz was used for the measurement on all windings together. Figure 5.11 shows the voltage dependence at 0.316 Hz: this was the only frequency for which each phase and all phases together were measured at every intended voltage level. The voltage dependent change is of the same order of magnitude between C' and C'' and is very similar between all phases for C' and between phases u and v for C''. The 'problem phase', u, has some 20% higher C'' and almost twice the increase with voltage, compared to the other two phases.

This first opportunity for field measurements cannot really be thought to have given an example of a typical machine, as the IR measurements at least were far from the normal range. The very limited time available also meant that the interesting lower frequencies of tens of millihertz could not be investigated together with varied voltage if all phases were to be measured. A compromise, taking all phases together to get wider sweeps may be worth trying at some later time. A better idea of the practicalities of attaching measurement equipment and of reasonable values for IR,



Figure 5.10:  $\tan \delta$  for the short 50 V measurements on the stator windings on occasion 1b:



Figure 5.11: Per-phase C' and C'' plotted linearly against applied voltage amplitude

 $C\text{-}\mathrm{tan}\,\delta$  and PD measurements was however obtained.

Perhaps the most striking point about the unusual IR was that there was a profound difference seen between the windings and between these windings and 'normal' ones, in *one* measurement method's result, varying strongly in time, while the other methods showed very little or no difference. There need not be a significant increase in probability of insulation failure during operation as a consequence of the mechanism that is causing the unusual IR. If there is not, then the IR is oversensitive but is nonetheless a simple method of getting some index of the highvoltage behaviour of the system, that might in some cases be helpful for giving 'probably sound' or 'probably unsound' verdicts.

The virtue of having several different measurement methods is seen here, but the trouble of interpretation is also seen. The poor IR may be due to leakage over a damp surface around the terminals, or to some small break in the insulation. In the former case the very normal values of 50 Hz C' and  $\tan \delta$  may be rightly reassuring, if there is just a long and wide surface path with quite small conductivity on account of temporary dampness. In the latter case, the IR results tell of a current which, although lost in the power frequency currents, may be a warning of a small channel that after a little more wear could break down and thereby fail the whole winding.

It is worth considering how much time is acceptable for measurements in a system for practical use. As soon as several phases at several voltage levels are to be measured down to matters of tens or ones of millihertz, long times are needed. On the other hand, coming much above 1Hz reduces the possible advantage of a small voltage-source. Perhaps the practical frequency range is limited really to this two-decade region of about 20 mHz to 2 Hz. Significant changes in PD behaviour and material and end-winding response are expected in this range, and later PD measurements will be of great interest for seeing what changes in VF-PRPDA statistics and DS measurements of the PD can be noticed, and how they relate to the state of the insulation.

## Chapter 6

# Conclusions

A model that solves in time the distributed R-C line having non-linear conduction function measured for stress-grading materials used for end-winding stress grading has provided results of fundamental frequency and harmonic currents that are well matched to those observed on physical models.

The dielectric response from the stress-grading of real stator insulation has a losspeak at much lower frequency than the models used here, meaning that at practical measurement frequencies the change in C' and C'' with frequency is largely a single power-law relation, particularly at low voltage where the grading behaves more linearly.

The changes with frequency of C' and C'' from the stress-grading are strong and mask the dielectric response of the insulation material.

The harmonic components of current due to stress-grading can be of the same order of magnitude as those due to considerable PD activity, at high voltage.

The harmonic components of current in the total measured dielectric response of the stator are a good way to get information on the small, non-linear effects of PD and stress-grading that in the fundamental frequency components are swamped by the current from the linear dielectric response of the bulk insulation.

The PD currents are not present below some inception voltage, while some degree of stress-grading non-linearity can be seen even below this. If sufficient stress-grading parameters can be determined from the voltages below PD inception, then the effect of stress-grading at higher voltages may be able to be compensated in the measured harmonic currents to leave the component due to PD. The non-linearity of the two SiC based materials investigated here was very similar, so a scaling of the base conductivity  $G_0$  may be the only parameter needed to be found from the

lower voltage measurements.

It seems so far that a lot of PD current is measured by the DS system and not by the PD system. This has been observed on other objects previously, but not to such an extent. Different calibration or different detection settings of the PD system may be found to narrow the gap between the currents, or the extra current in the DS measurement may turn out to have been from another source not considered. If indeed there does turn out to be lots of 'missing' PD in the PD measurement, this suggests another advantage of measuring with both systems, to measure total PD charge as well as to identify the largest pulses.

The possibility of PD at the end of the stress grading at low frequencies and high voltages is apparently not of practical concern; no such PD was detected even on the model bars at 1 mHz, and the real coils showed a continued functioning of the grading material even at such low frequencies. This may not be true for very aged paint-based stress-grading.

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