The dielectric response of stator end-winding stress-grading.

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Abstract This paper presents results from dielectric response (DR) measurements with varied amplitude and frequency of the applied voltage, made on test-bars consisting of non-linear resistive stress-grading materials applied to the surface of insulation with linear and low loss characteristics. The results indicate the DR characteristics of stress-graded regions in stator insulation systems, and the significance of these parts on the measured DR of a whole winding or coil. For routine diagnostic tests it is not practicable to avoid measuring the stress-grading's component of the DR, so recognition of the voltage and frequency dependent characteristics of the stress-grading is important if DR data is to be used to determine the condition of other parts of the stator insulation.

Keywords generator, stator, end-winding, corona protection, dielectric response, spectroscopy, stress-grading

DIELECTRIC RESPONSE OF STATOR INSULATION

The stator winding of a high-voltage electrical machine is a complex structure with many different contributions to measurements of dielectric response (DR) and partial discharge (PD). The insulation material itself is on modern machines one of several broad types of epoxy-based material, and on older machines often a bituminous compound with relatively high losses. In either case, mica flakes are included throughout the insulation on account of their great resistance to high temperature, high electric stresses and discharges. Some internal PD activity at cavities in this composite material is permissible even at normal working conditions: machine insulation must be economical with space and advantage is therefore taken of mica's durability against sustained small discharges. As well as the true material DR of the stator insulation and the effect of PDs in small internal cavities, PD currents may also arise from voids between insulation and conductors, for example between the stator iron and the bar, or along the surface of an end-winding when the stress-grading system is not functioning properly perhaps due to mechanical damage. Finally, the stress-grading itself may make a considerable contribution to the measured DR.

Traditionally, tests such as a 'tan δ tip-up' (voltage-dependence of loss at power-frequency), insulation resistance (variations on dc measurements) or 'hi-pot' (stressing the insulation to higher than the rated value to check for withstand) are performed on electrical machines at maintenance intervals to assess changes in insulation condition. Modern diagnostic techniques measuring with applied voltages down to very low frequencies can in some cases provide much clearer identification of the existence and nature of an insulation defect than is possible with basic power-frequency or dc tests. The measurement of DR over a wide frequency range down to the mHz range is known as dielectric spectroscopy and has improved assessment of insulation condition in many types of high-voltage apparatus.

In practical situations a large electrical machine is only available for routine diagnostic testing during a short maintenance down-time, and bar-to-frame measurements must be made from the terminals of the winding: the currents from the slot, grading and end-winding parts of the stator are therefore measured together. To make good use of sensitive DR measurements it is necessary to be able to understand and, at least partially, to compensate for the effect of the end-winding stress-grading that has nothing to do with the DR of the bulk of the insulation.

The main aim of this paper is to show measurements of what are, practically, the responses due to the presence of stress-grading alone, for systems using silicon-carbide (SiC) based non-linear resistive materials. Before this, the construction of the bars and its rationale are explained, the purpose and practice of stress-grading is briefly described, and results from measurements of the stress-dependent conductivity of the SiC-based materials are given.

LABORATORY MODELS

With the aim of seeing the pure response of the stress-grading system, some laboratory models were made (figure 1) consisting of a cylindrical inner conductor, a PTFE tube around this, and a short metal sheath on the outside of the tube, with stress-grading at both sides.

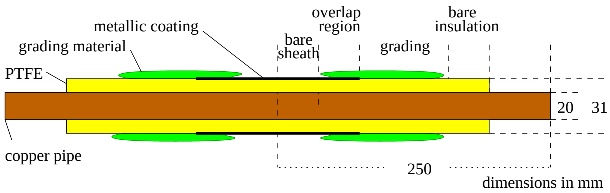

Figure 1: Diagram of the laboratory test-bars used for measuring DR of stress-grading systems

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

The low permittivity ($\varepsilon_{rPTFE} = 2.1$) and cylindrical $3/2$ geometry result in a capacitance that may differ from typical machine bars, in which case the component of DR measurements due to the grading resistance and insulation capacitance will be shifted in frequency between the model and the real bar. Further, the somewhat lower permittivity than that of machine insulation means that the surface stress around the edge of the earthed sheath — or at low frequencies the edge of the grading — will not become so large as in the machine case, as the smaller displacement current may be carried by the grading material with a lower level of electric stress. This may be of relevance if interested in precise values of DR at a certain voltage level or in the possibility of PD activity on the surface or end of the grading material, but to the general qualitative description of DR it is not expected to be significant.

Two bars have been used for the measurements in this paper: they are named 'tape' and 'paint', derived from the form of the grading material. For reason of different requirements at the times when the bars were made, the 'paint' one has 40mm greater length of earthed sheath without grading (see figure 5 for dimensions). As most measurements later presented have had removed the contribution of the capacitance outside the grading area, this difference should not have a significant effect; the grading material extends 80mm from the electrode in either case.

MEASURED MATERIAL PROPERTIES

Two types of commercial stress-grading material have been studied; both use silicon carbide (SiC) as the active component. The first 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. The second material ('paint') is in the form of a paint that is applied to the bar in a single coating and sets at room temperature over 24 hours. Application by hand of such a paint to a bar is a process that results in considerable variation of the thickness and therefore of the electrical properties of the final grading. The thickness commonly applied is less than 0.5mm, and on the bar used for grading tests it is considerably thinner than this.

To assess the electrical properties of these two materials, samples were applied along the surface of a PTFE tube of respectively 20mm and 30mm internal and external diameters, between copper-tape electrodes. Measurement along a thin tube, 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, since the frequencies are around or much below power frequency, so dc measurements are sufficient and extra capacitances due to the presence of the PTFE insulation affect only the time to reach a steady dc value. The thickness of the tube may indeed be helpful in providing some thermal inertia: SiC-based materials' conductivities are strongly temperature dependent.

The tape was measured in four sections, with lengths of 10, 20, 40 and 80mm of taped surface between the electrodes. For each section the current was plotted against the mean electric field strength, i.e. the ratio of applied voltage to electrode spacing. The variation between the samples' measured conductivity is considerable at high stress, but there is not a uniform trend of conductivity with length that would suggest strong significance of the electrode contact region. If the 20mm sample is omitted then there is a trend in the remaining three lengths, with shorter lengths having lower currents. This is explicable by considering that the electrode contact happens over a short but considerable length of the electrode overlap, resulting in an extra length of current flow that was not included in the calculation of mean stress. Since the tape was applied by hand the tension and the precise degree of overlap are both variable. At high stresses a small relative change in stress can cause a considerable difference in conductivity, so this may well be the source of some of the variation and of the 20mm section's refusal to allow a simple trend.

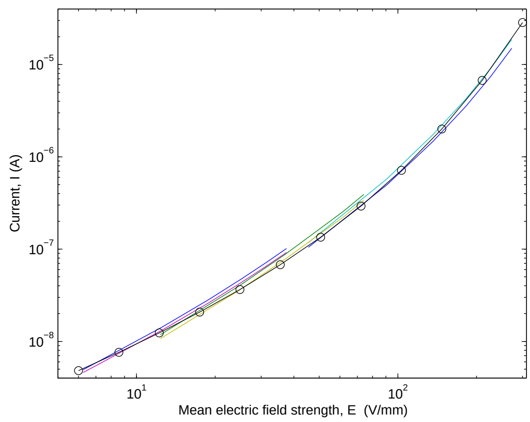

Figure 2: Fitting (marked with circles) of eq. (1) to data from two measurements on each of four lengths (10,20,40,80mm) of half-lapped tape along a 30mm diameter tube.

Figure 2 shows results from two measurements on each of the four lengths of tape, along with a fitted curve. Equation (2) 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.

$$I = EG_0 e^{nE^{2/3}} \quad (1)$$
$$I = AE^{n'} \quad (2)$$

At high stresses the fit is badly impaired: equation (1), in a resistance form, has been cited in [1] as giving a good fit to all of several SiC-based stress-grading materials, and fitted well for the materials here also. It was found to deviate slightly to the other way from (2) for high electric field strengths, which could be improved by a slight reduction in the $2/3$ exponent to about 0.6. Equation (1) 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.

The paint was measured in three sections, each of 10mm length between the electrodes, these sections having different thicknesses of paint. Even for the thickest case the surface conductivity is lower than that of the tape, but the relatively small thickness of the paint may mean the material conductivity not greatly different between the two materials.

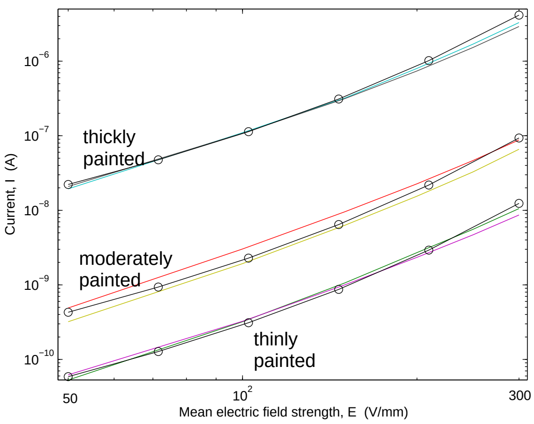

Figure 3: Fitting (marked with circles) of eq. (1) to data from two measurement sequences on each of three sections of paint of different thickness along a 30mm diameter tube.

Figure 3 gives similar fitting of (1) to 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 measurement of something so thin and varied as the thickness of hand-applied paint on the PTFE surface was not possible to the extent of making accurate comparisons. 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.

Material	**G_0**	**n**
Paint (thin)	2.5e-13	0.114
Paint (medium)	1.8e-12	0.115
Paint (thick)	1.0e-10	0.110
Tape,	5.5e-10	0.115

Table 1: Material model parameters from axial DC measurements of stress-grading material around a 30mm diameter tube, to fit eq. 1: E is the mean stress (V/mm) between the electrodes, I is the resultant current (A)

STRESS GRADING

The purpose of the stress-grading is to reduce the surface stress around the end of the earthed stator core and the semiconductive coating that ends as the bar emerges from the slot. It is accepted as being more reliable to let end-windings' outer surfaces float at the high potentials capacitively coupled from the internal conductors than to try to maintain earth potential around these parts that have particularly sensitive insulation due to winding-joints, bends and possibly coolant pipe connections. The surface potential then must increase from zero at the end of the slot to a high potential in the end-winding region, but at a moderate rate that does not cause surface breakdowns. Figure 4 shows the purely electrostatic field around such a transition in the absence of stress-grading: the clustering of the equipotentials around the edge of the earthed sheath makes clear the high field strength at this point at which electric displacement through the capacitance of the insulation is concentrating at the edge of the electrode.

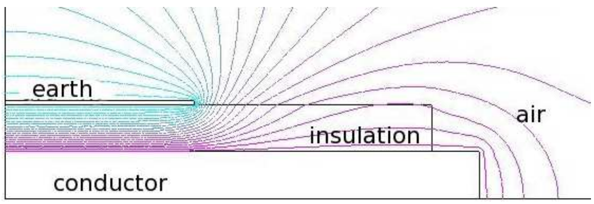

Figure 4: Equipotential lines for the electrostatic case of a high-voltage central conductor, solid insulation, and earthed outer electrode that stops part way along the insulation surface

The high stress around the edge of the earthed electrode (e.g. the stator iron or the slot semiconductor tape) is a problem if it reaches the inception level for the surrounding medium, which is often air. There are various means used to make the change in potential smoother: geometric grading relies on the shapes of electrodes or additional dielectric material to reduce stress in the critical area; plain resistive grading forms an RC filter along the graded length, giving a frequency-dependent potential-distribution; non-linear resistive grading uses voltage-dependent materials to conduct most where the stress is at its highest. Reference [2] gives a machine-oriented summary of common methods. Extreme non-linearity (from ZnO) has been used in some experimental cable terminations, holding stress down to almost exactly a chosen maximum value. For machines SiC is the common method, and gives enough non-linearity to allow the grading to function at power frequency and with a moderate harmonic content.

The materials commonly used for stress-grading of stator end-windings of high-voltage machines have a sufficiently high resistivity to allow, at power frequency, the potential across the grading to vary from earth-potential at one end to nearly the potential of the high-voltage conductor at the other. If the frequency is very low then there is time for the capacitance between the high-voltage conductor and the stress-grading region to be charged considerably through the grading's resistance; i.e., the remote end of the grading becomes close to the earth potential of the stator end and the 'grading' function is not effective. The spreading of earth potential out along the grading can be expected to cause a considerable change in capacitance, that could obscure dielectric response from the stator insulation itself. The passage of displacement current from the graded section of insulation through the resistive grading material will clearly cause losses, which with a low-loss insulation material could be significant or dominating in the loss component of the response.

RESULTS

On the taped bar, DR measurements at peak sinusoidal voltages of 0.5 to 20 kV and at frequencies from 100Hz down to 10mHz were performed, as well as a frequency sweep down to 0.1mHz (the equipment's limit) at 10kV to check for any further effects. The painted bar had, on account of the previously described much lower grading surface conductivity, a response shifted to lower frequencies; it was therefore measured down to 0.1mHz for each voltage level. All voltage values refer to the peak value of a sinusoidal signal. Measurements were made with an 'IDA200' frequency-domain dielectric spectroscopy unit, applying a sequence of intended sinusoidal voltages over a sweep of amplitudes and frequencies, and recording the complex Fourier coefficients of current and voltage from the fundamental to the eighth harmonic.

For the following plots, apart from figure 8, the measured current values used have been 'compensated'. That is, the capacitance (C') measured at 200V and 10Hz between the bar's sheath and core before application of the stress grading is used as an approximation of the capacitance, over the whole voltage and frequency range, that is not due to the grading. The fundamental and harmonic components of current in this capacitance due to corresponding components measured in the applied voltage are then substracted from the corresponding components of the measured currents. This has advantages of making clear the relative sizes of C' and C'' from the grading section alone and of removing some of the harmonic current that is due to harmonic voltages in the supply.

Figures 6 and 7 show the (compensated) capacitance of the two bars, over a wide range of applied voltage. The

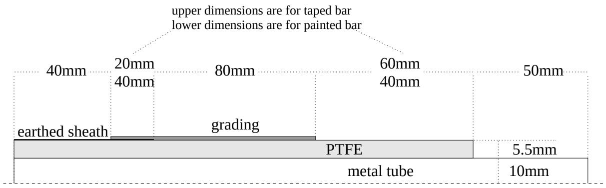

Figure 5: Geometry details of the bars: a symmetric quarter geometry.

particularly strongly sinking part at the right of the 1.5kV curves indicates that the capacitance at high frequency is tending to the value with no grading, which was the value used for compensation: as the compensated current 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 of the grading material with very low stress is sufficient to charge the whole grading region to a potential close to that of the earthed sheath, so the capacitances at low frequency tend to a maximum value with weaker voltage dependence.

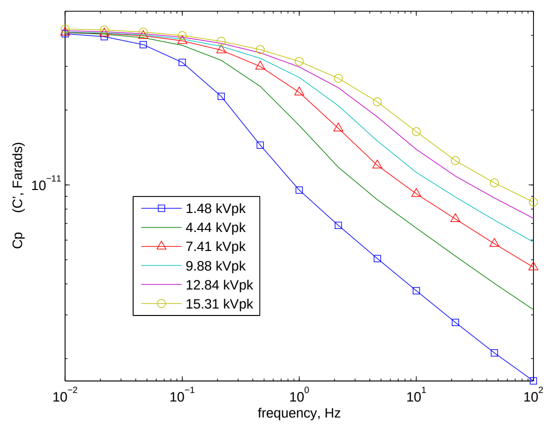

Figure 6: C' for the taped bar, 1.5 - 15 kV

Consideration of C' shows the extent of frequency dependence of the potential across the grading. Taking the taped bar as an example, the earthed sheath is 120mm long, which together with the diameters and the permittivity of PTFE gives a capacitance of 32.0pF, ignoring fringing. The capacitance measured at low voltage (200V) with the DR equipment before application of the field-grading was 34.6pF, from which it is assumed that 2.6pF is due to fringing. Small variations in diameter or variation of ε_r from 2.1 could also be responsible for some of the difference here, so believing these figures to precisions of better than the order of 1pF is not reasonable. If all the stress-grading region of the bar is treated as being conductive, the capacitance would be 74.6pF. The fringing is approximated by adding to this

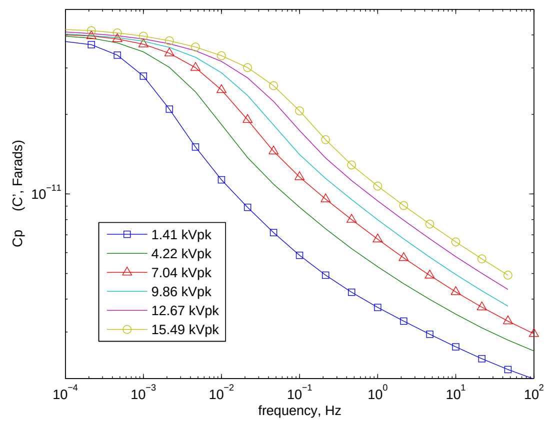

Figure 7: C' for the painted bar, 1.5 - 15 kV

value the 2.6pF for the ungraded case. This gives 77.2pF as the capacitance if the whole grading region were at the same potential as the sheath. Looking at figure 6 and the close-up and *uncompensated* view in figure 8, it is clear that at the lowest frequencies used the measured capacitance is almost exactly this value.

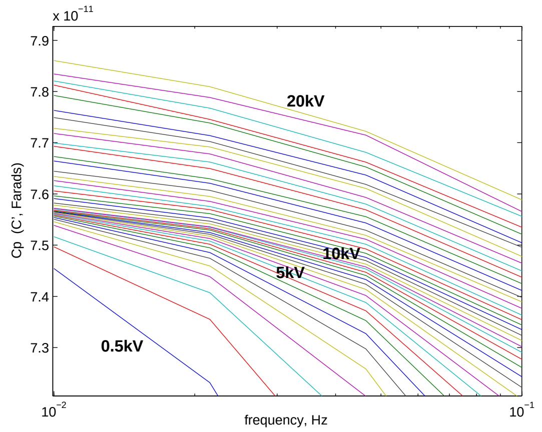

Figure 8: C' for the taped bar, showing the clustering of low-frequency capacitance at intermediate (5-10kV) voltage levels

Figure 8 deserves further attention. In the range 5 to 10 kV applied voltage the measured capacitances appear to tend to a maximum value of a little under 76pF, and at less than 5kV there is still a trend of the curves that suggests that a further decade lower in frequency could allow these curves to reach this value too. The curves from voltages greater than about 10kV, on the other hand, discard the flattening tendency of the 5–10kV range and exhibit a final capacitance that increases quite steadily with increased voltage. This behaviour is visible for both bars. Since the spreading of earth potential throughout the grading material means that there will be a strong field at its edge, which is just what the "corona protection" stress-grading is supposed to avoid at normal frequencies, it is credible that PDs may occur at the edge of the grading. These would add to the measured response [3], although at very low frequency one would expect the PD currents to coincide with the peak voltage and therefore for this current to be shown up mainly in the loss rather than the capacitance component. Measurements with PD apparatus and inspection in a dark room with dc applied voltages up to 30kV gave no evidence of PDs, but a point-plane test object has previously been used to demonstrate that some discharge current can be measured by the DR equipment while not visible as PD impulses of size detectable by the equipment used. Surface leakage across the PTFE from the end of the grading is another possibility which is not practicable to screen away without modifying the stress distribution. Thorough modelling is being worked on, in order to see whether this effect can be attributed purely to the grading behaviour.

Figures 9 and 10 show the loss components corresponding to figures 6 and 7. Unsurprisingly for such an RC circuit, the response is Debye-like with the loss initially falling off steadily around the peak. At lower voltages, i.e. below about 8kV, 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. At about the 10kV level, where the low-frequency value of C' resumed its increase (figure 8), 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'.

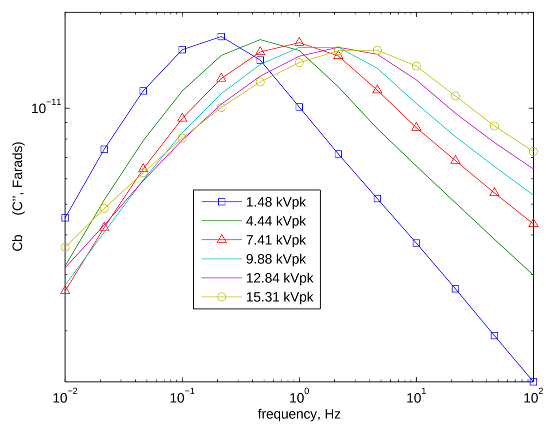

Figure 9: C'' for the taped bar, 1.5 - 15 kV

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 non-sinusoidal: it contains 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

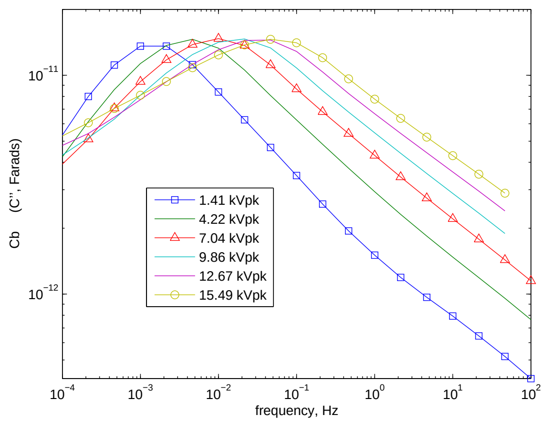

Figure 10: C'' for the painted bar, 1.5 - 15 kV

was confirmed by the measurements. Therefore, for clarity, only the 3rd, 5th and 7th harmonics are therefore shown in figures 11 and 12, which show the amplitude of each of these harmonics as a proportion of the (compensated) fundamental component, for several frequencies at each of three voltage levels. Since common dielectrics at working stresses are largely linear, harmonic components of DR measurements on stator insulation can be expected to arise mainly from the end-winding stress-grading and from periodic PD patterns. Use of C' and C'' values must be treated with caution when strong harmonics are present. For example, consider that a fixed amount of charge per cycle is being transferred. If this is transferred as a short, high amplitude current rather than as a sinusoidal current, there is a strong third harmonic *and* the fundamental component is larger too, so analysis of C' could lead to the conclusion that there existed a greater capacitance than really existed.

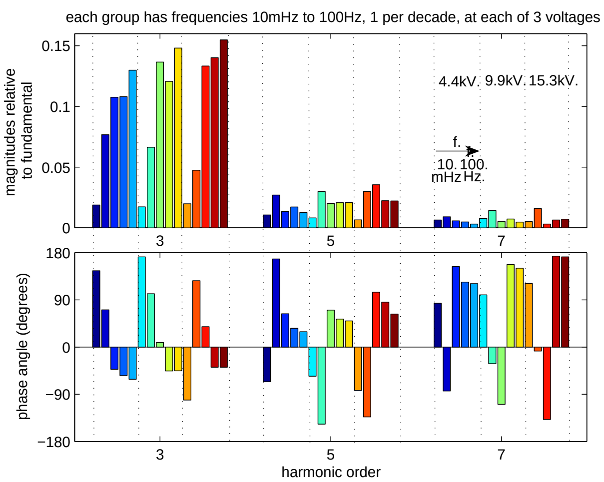

Figure 11: Taped bar, 3rd 5th and 7th harmonics, as proportions of the fundamental component of current. For each harmonic, values are ordered by ascending voltage magnitude then within this by ascending frequency.

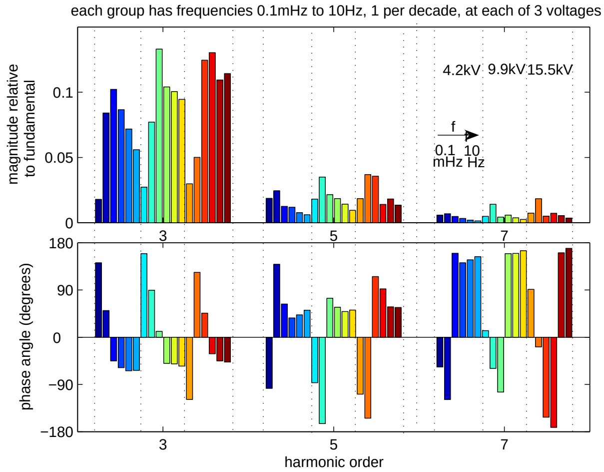

Figure 12: Painted bar, 3rd 5th and 7th harmonics, as proportions of the fundamental component of current. For each harmonic, values are ordered by ascending voltage magnitude then within this by ascending frequency.

SUMMARY

This paper has presented some measurements from pure stress-grading systems that indicate the form of response expected from the stress-grading during low-frequency diagnostic tests. Compared to the change in capacitance with voltage or frequency of a modern epoxy based insulation system, the end-winding stress-grading has a significant effect when measuring from frequencies high enough to make the grading capacitance very small to those low enough to make the entire length of grading act as a conductor. The loss and its variation with voltage and frequency are similarly strong compared to losses of modern insulation materials. The harmonic spectrum of the non-linear material's reponse has large values of the 3rd harmonic and may be useful in estimating the magnitude of the end-winding component in an otherwise largely linear stator response.

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