Material properties of SiC stress-grading material.

Measurements with DC and varied V and f sinusoids, directly across material samples, and a literature review of grading-material and grading-system models.

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1 Purpose

This report is a literature review followed by an analysis of data from material measurements made in the lab. The material properties of SiC (silicon carbide) based stressgrading materials are needed for use in numerical models of the end-winding part of stator windings. The main questions to be answered are the following:

Is there frequency-dependence¹ of conductivity, σ ? Is there frequency-dependence of permittivity, ε ? Is there voltage-dependence of σ ? Is there voltage-dependence of permittivity, ε ? How well do various equations fit the voltage-dependence of σ ? Does the SiC tape behave as a homogeneous material? What temperature dependence have σ and ε ? How does $\sigma/\omega\varepsilon$ vary with field |E| and frequency f? Do other works suggest our results to be a 'general case'?

The material properties should preferably be determined from direct measurements rather than from inferences of material properties based on fitting whole-system models to whole-system measurements. A direct measurement gives more confidence that each component in the whole model is correct, rather than that multiple errors in geometry, material and solver setting are partially cancelling each other out. It gives results more directly dependent on the investigated material, since there is not the large additional capacitive current typical of complete grading systems; the stress in the grading material is also more uniform when measured directly between electrodes rather than in the usual grading geometry with one floating end.

Nonlinearity may best be viewed in the frequency domain, where the often very dominant fundamental component can easily be ignored. Visual comparison of the full time-domain waveforms is not a sensitive way of judging the correctness of a model's harmonic components.

¹ Within the range of relevance to our work with dielectric measurements: quite low frequencies rather than the kilohertz range, and applied voltages in the order of the rated value.

2 Summary of literature

There are several points in this work which might be helped by doing a bit of reading around the field: better ways of doing the material measurements; suitable models for the material, in terms of $\sigma(|E|)$ function and any other needed input variables; confirmation of how much similarly there is between the properties we have measured for our one main material and the properties of other stator end-winding grading materials or other SiC composites in general.

The literature searched is just journal and conference articles from the timescale available electronically. On more fundamental issues such as discharge physics, it would probably be more valuable to find a single good, old book, and learn more from this than from any papers; a good review paper would be another useful source. The subject of a specific grading material and its empirical description is not, however, one that I have ever found in any book. The physical mechanism of the material's properties is interesting, but the actual, empirical behaviour of the real materials is the important goal, so deep study of literature on polymers, composites, Schottky barriers and so on would not be profitable.

Appendix A (page 9) gives details of a review of literature on modelling stress-grading systems and SiC-composites in particular. A brief summary is given in the following subsections here.

2.1 Material description

The material of main interest is a binder resin on thin support tape, containing a large amount of SiC powder as a filler; this is the construction of end-winding stress grading tapes. See the reply at the end of the summary of paper 'Min07', page 22, about the difference between machine SiC tapes and cable accessory composites. Other stress grading composites found in the literature include those using CB (carbon black) filler, those using a softer polymeric binder such as silicone rubber or EPDM, and those with very low filler concentration within a polymer intended as an insulator, to improve the stress distribution by relieving high concentrations of space-charge.

2.1.1 The form of $\sigma(E)/E$ relation

The familiar power-law 'varistor' model of the form $\sigma(E) = k|E|^n$ is used, without physical justification, in [Ref88, Rob95, Rhy97] There are variations on how the constant k is divided between parts outside and inside the $(\cdot)^n$ part, but the only fundamental variation of the power-law model is in [Lup96], where a simple change is made, $\sigma(E) = k(c + |E|)^n$, insignificant at high field but giving more friendly numerical properties as the field tends to zero, as well as having arguably more realistic physical properties.

The exponential model $\sigma(E) = k \exp(nE)$ is used in several stator-oriented works [Riv99b, EK03, EC05, Dav07, Min07], and in some cases for cable accessories, e.g. [Tuc99, Qi04].



Figure 1: A simple example of the appearance of the different families of functions suggested as models of conductivity or current with respect to applied field.

From our results, the power-law model has too little growth of conductivity towards high fields, as a log-log plot of experimental results is concave rather than straight as it would be if a power law were really followed; the exponential model instead rises rather *too* sharply, as a log-lin plot of experimental results is convex rather than straight. If only a small range of fields is used, then of course a plain power-law or exponential may make a good approximation; after all, given a very small range, a linear relation would fit But we would like to have a relation that works well over as wide a range of fields as will ever be experienced.

The best fit to our results for SiC grading tape is still the 'exponential of power' model (my phrase), $\sigma(E) = k \exp(nE^p)$, where p is about 2/3. This was first found in [Gul00], which claims it to be a good fit to real data; it is also used by [Bak02]. There is no direct theoretical derivation given of such a relation as the expected behaviour of these composites.

The measured currents, e.g. [Ref88, Var07] as well as our own, suggest insignificant dynamics of the conduction, which is not surprising given these materials are used as arrestors.

2.1.2 Permittivity

The permittivity ε of the SiC is usually treated as constant, or even as insignificant compared to the conductivity for some conditions. No source claims there to be a very strong nonlinearity of ε , but measurements on plain SiC powder in [Må01b] show a near doubling of ε from an already high low-field value of $\varepsilon_{\rm r} \approx 16$ up to $0.3 \,\text{kV/mm}$. The capacitive contribution to the grading current is significant at low fields and high frequencies (relative to our modelling interest). Figure 13 compares the conductive and capacitive components of current in the form of complex capacitance, for a piece of SiCbased end-winding stress grading tape. Figure 5 compares the components of current for a SiC powder.

2.1.3 Working range of fields

The maximum surface field to avoid discharges is given as 0.6 V/mm by [Min07], and as 1.0 kV/mm by [Rob95] where 50 % RH (relative humidity) is stated. My FEM modelling based on SiC tape material and up to 15 kV peak, has found about 0.5 V/mm as the greatest stress within the grading, [Tay06]. In other peoples' measurements along material samples the applied fields have also been in this range of up to some hundreds of kV/mm.

2.1.4 Example parameter values

From [Tay06] the surface resistivity of SiC-based tapes (the same samples as are used in the later results in this report) is about $1.7 \times 10^{11} \Omega/\text{sq}$ at zero field, and the exponential-of-power model is a good fit: $\sigma(E) = 5.9 \times 10^{-12} \exp(0.00115 |E|^{2/3})$, with $\sigma(E)$ in siemens and E in V/m. The maximum field used is 0.3 kV/mm.

From [Eme96], the surface resistivity is between 2.5 G Ω /sq and 4.0 G Ω /sq at a surface current of 80 nA/mm, which corresponds to fields of 0.2 kV/mm to 0.32 kV/mm. The thickness is not given, and only this one I/V point is considered. At this highest field of 0.32 kV/mm, the material model of [Tay06] would have surface resistivity of about $5.9 \times 10^{-12} \exp(0.00115 \times 320000^{2/3}) \approx 0.8 \, \mathrm{G}\Omega/\mathrm{sq}$.

The (bulk) conductivity of a compressed SiC powder studied in [Må01b] is replotted in figure 4 of this report, and its (bulk) conductivity fits well to $\sigma(E) = 5 \times 10^{-9} \exp(3.4|E|^{0.6})$, with E in kV/mm and σ in S/m. The surface properties of a layer with the 0.5 mm thickness as the samples in [Tay06] would then have a surface resistivity at $0.32 \text{ kV/mm of } 1/[0.5 \times 10^{-3} \times 5 \times 10^{-9} \exp(3.4 \times 0.32^{0.6})] \approx 70 \text{ G}\Omega/\text{sq.}$

Figure 7 shows I/V characteristics of several commercially available end-winding stress-grading materials, showing a large difference in the 'knee-voltage'; the differences between the above values of surface resistivity are not great compared to differences between these I/V relations. The size of SiC grains is important, since the contacts are the most influential factor, and the number of series contacts per unit length is determined by grain size. Conclusion: in the order of $1 \text{ G}\Omega/\text{sq}$ at the quite high field of 0.3 kV/mm is a good approximate figure for these SiC tapes.

2.1.5 Isotropy

Isotropy of the grading material is of interest for simulations. The thinness of the radial dimension and the symmetry in the tangential direction in 1D and 2D models do suggest that only the axial direction of current is important, but it's still not obvious whether the field in the radial direction has an effect on conductivity in the axial direction. In [Tuc00], different i/v relations were found for each direction, but the tensor describing

these relations was diagonal, i.e. the field in one direction doesn't influence conductivity in another; the work is summarised on page 14, and is based on cable-accessories (with *extruded* polymer bases containing carbon-black particles, *not* highly percolated SiC). No mention of anisotropy was made in any of the found papers about machine insulation.

2.1.6 Slot stress-grading

The coating of stator windings within the slot is a very different material from endwinding stress-grading. It is usually carbon-black based, and has much higher, quite linear, conductivity. It can be mentioned briefly too, as it is usually the material by which currents from the end-windings are conducted into the stator core. From [Eme96] the maximum surface resistivity for suppression of PD is about $15 \text{ k}\Omega/\text{sq}$, and the minimum for an acceptable degree of heating by induced currents is about $0.15 \text{ k}\Omega/\text{sq}$. During the machine's lifetime the resistivity *falls*; a factor of 3 is suggested in [Eme96]. Measurements on new slot stress-grading materials gave surface resistivities of around $3.5 \text{ k}\Omega/\text{sq}$, falling to around $0.2 \text{ k}\Omega/\text{sq}$ after hard thermal and/or voltage aging. Approximate linearity seems assumed, since the level of voltage or current is not always specified; my measurements in [Tay06] suggested a linear material as long as several tens of volts were applied so as to get good conductance across the barriers of the electrodes.

2.1.7 Ideas on presentation of data

Plots of J/E or σ/E were widely used, with the problem that most data fit somewhere between power-law and exponential relations, which means the plots are not straight in log-log or in log-lin scales.

The use of Lissajous figures for the measured I/V, in [Ref88], was an interesting alternative way of studying the results, rather like the old form of oscilloscope-based PD pattern. This idea is clearly not new in the field of surface contamination: for example, it is shown on fig. 10.5.1 within [LaF82] for overhead line insulators.

2.1.8 Notes on the material models

Unit-dependence determines whether a statement such as 'the material had a nonlinearity n = 4' can be compared to another material's n regardless of the units used for the applied field.

For a power-law model $\sigma(E) = k_{\rm p} |E|^{n_{\rm p}}$, there is a fundamental significance to the value of *n* regardless of units used for *E* and σ ; if *E* is scaled such that the same physical quantity is now expressed as aE, then the $a^{n_{\rm p}}$ term can be combined into a new value of $k_{\rm p}$.

For the exponential model $\sigma = k_{\rm e} \exp(n_{\rm e}|E|)$, including the case with the possible extra of a constant power of |E|, e.g. $|E|^{2/3}$, a scaling of E cannot be done by changing just $k_{\rm e}$ rather than by changing $n_{\rm p}$. Thus, comparisons of $n_{\rm e}$ are valid only if the same dimensions are used: I have used $\sigma(E) = 1.17 \times 10^{-8} \exp(0.00115|E|^{2/3})$ in my simulations, i.e. $n_{\rm e} = 0.00115$, with E in V/m and σ in siemens; [Gul00] has used $n_{\rm e} \approx 4$ with E in kV/cm, in which units my $n_{\rm e}$ would become $0.00115/(10^{-5})^{2/3} \approx 2.5$.

The relation of $\sigma(E)$ and I(E) is just $I(E) = E\sigma(E)$. Some sources work in terms of I(E), others of $\sigma(E)$ which is more suitable for describing materials for simulations. This report prefers $\sigma(E)$, for simulation reasons.

For the power-law case $\sigma(E) = k|E|^n$ means that $|I(E)| = k|E|^{n+1}$, so the slope is changed but the relation to the independent variable E has the same basic form.

For the exponential case $\sigma(E) = k \exp(n|E|)$ means that $I(E) = k E \exp(n|E|)$, which compared to the pure exponential relation is exaggeratedly large or small above and below E = 1.

2.2 Grading-system models

In the literature that has been found here, cable accessories have been of more interest than stator end-windings. The cables have true axisymmetry, so only 1D or 2D models are needed. The rounded-square shape of stator bars changes the field a little, and there are 3D FEM simulations of a stator bar-end in [Bak02], with favourable comparison of modelled potentials with measurements on real bars. There is 2D simulation of cable accessories by FEM in [Lup96], which also goes on to derive the 1D simplification from the 2D model and to state supposed conditions of acceptability of this simplification. A 1D model capable of having conductive and capacitive nonlinear series elements is given in [Rhy97], and a 1D model with nonlinear conductive series elements is approximated in [EK03] by a describing function.

3 Summary of measurement data

We have:

4 test objects, with imperfect geometry and material consistency,

120 AC-measurement points for each object; constant V or E, 6 voltage levels, 10 frequencies,

additional shunt capacitance, dependent on length

non-linearity that yields at least 3 significant complex numbers from each point — the fundamental, 3rd and 5th harmonics

interaction between the extraneous capacitive field in the air/PTFE and the grading material

ill-defined grading material model, i.e. it's not known in advance whether constant ε' and variable $\sigma(E)$ or $\sigma(E, \omega)$ is adequate, or whether the use of variable ε' and non-zero ε'' would fit better.

There is therefore quite a lot of data, containing quite a lot of 'noise', and some assumptions and approximations are therefore needed in order to get anywhere useful. It should be remembered that the intended use of a material model is in calculating currents into the grading of a set of stator coils, where the material properties *will* vary; *extreme* accuracy in the form and parameters of the model is pointless, so each reduction should be judged on how much it is likely to affect such models' results.

Model 1: fixed capacitance (air, PTFE, grading), and non-linear conductance fixed capacitance (air, PTFE), non-linear all:

A More detailed notes on the reviewed literature

A.1 Sources and search terms

Using IEEExplore, the following 'advanced search' terms gave, 12 matches, rising to 100 if omitting the last two conditions:

```
( sic <or> silicon carbide ) <and>
( non-linear <or> nonlinear ) <and>
( composite <or> grading <or> resin <or> filler ) <and>
( conductivity <or> conductance <or> resistivity <or> resistance <or> capacitance <or> permittivity )
```

Searches were also made in Inspec (matches with manually input search terms, for a small 'cream' number of results in spite of a large number of indexed works) and Google Scholar (matches pretty much anything, over a wide range of works, to provide an awful lot of matches). Nothing new was discovered this way.

Search terms on Google Scholar: >3000 matches for

```
( sic OR "silicon carbide" )
( composite OR filler )
( resin OR polymer OR epoxy resistance OR resistivity OR
  conductance OR conductivity OR "electrical properties" OR
  permittivity OR capacitance )
( nonlinear OR non-linear )
( exponential OR power OR "iv relation" )
```

A.2 Summaries of the selected works

In the following paragraphs, summaries are made of the main papers of interest. Paragraph headings (bold) are the citation keys used in the bibliography. Text within square brackets is my comments on the reasonableness of a claim. My beloved format of FirstAuthor(3letter)Year(2digit) is used, being still the most clear and recognisable method I've found. The order is chronological.

[Ref88] The behaviour of SiC in surge diverters 'is usually given in the form' $I = I_0 (V/V_0)^k$, with $k \approx 4$, not very strongly nonlinear compared to Zener diodes ($k \approx 12$) and MOVs (even higher). This work is about SiC-loaded insulator surfaces.

The 'ideal' [theoretical] semi-conducting diode has an exponential nonlinear conductance $i = i_0(\exp(v/v_0) - 1)$ as well as shunt capacitance $C = C_0/\sqrt{1 - v/v_0}$. From this, the junction capacitance falls with voltage in a forward conducting junction; modelling SiC-based material as being simply a network of diodes gives the wrong result for the material's variation of capacitance [but, isn't it more relevant to include the reverse biased diodes? – I wouldn't take much notice of these equations]. There are some rather interesting points about the presentation of current/voltage measurements. A difference between measured and low-harmonic filtered signals is shown as an indicator of the quality of voltage measurement. An i(t)/v(t) loop [i.e. Lissajous figure] is used as well as a simple curve of $I_{\rm rms}/V_{\rm rms}$. The i(t)/t curve has the same basic shape [static nonlinearity plus capacitive current] as our SiC material measurements.

[Rob95] This is a stator-oriented paper. The sometimes proposed Schottky-at-contacts or Poole-Frenckle-in-bulk models of the non-linearity would both give 'log $I/E^{1/2}$ current dependence'. [It's not clear what this means! log $I \propto E^{1/2}$, in which case I(E) has the same form as $\sigma(E)$ in the exponential models?]

An empirical description of a 'wide variety of SiC-based products' is, however, $I = kV^n$ (*n* about 4 or 5), 'more usefully expressed' as $A = A_0 E^n/E_t$ with E_t being a threshold field. Some examples shown have quite low stresses, 0.05 kV/mm to 0.5 kV/mm, and are plotted very steeply making it hard to check how well points fit a log-log plot.

The troubles of painted grading are: particle settlement, solvent evapouration, abrasive damage. The B-stage tapes are older and less VPI-suited than fully-cured flexible polyester resin ones.

The maximum permissible surface stress beyond which breakdown is likely, is about $1 \,\mathrm{kV/mm}$, at 50% RH.

[Eme96] Even for the slot-part, it seems Westinghouse at this time used a varnish rather than a tape; there were worries about the effect of VPI on the tape's properties, so the time-consuming and less consistent varnishes were preferred. An internal report from 1984 is cited, which investigated conductivities of *slot* corona-protection paints, and looked for optimal values based on temperature rise. An increase in conductivity of about a factor of 3 was expected for 40-year operation. The temperature rise between coils was about 2 °C [a permissible value for the rise; a design maximum]. Maximum surface resistivity required for suppression of PD is about $15 \text{ k}\Omega/\text{sq}$. Minimum initial surface resistivity, allowing for a reduction to 1/3 over the lifetime, while still not heating too much, is $375 \Omega/\text{sq}$ (air-cooled) to $1.8 \text{ k}\Omega/\text{sq}$ (hydrogen-cooled). [No, I don't see sense in why the values should be this way around.] Measurements on three manufacturers' slot tapes when applied to a full coil, before and after impregnation, showed a several times increase (4 in one case, initially $20 \text{ k}\Omega$, 15 in another, initially $4 \text{ k}\Omega$) in resistance along the slot-section, but the surface resistivities were within a allowed range. Accelerated thermal aging showed a large drop in resistivity, down from $3.5 \text{ k}\Omega/\text{sq}$ to $200 \Omega/\text{sq}$.

Requirements for end-winding voltage grading, for $13.8 \,\mathrm{kV}$ to $15.5 \,\mathrm{kV}$ machines, is withstand of 50 kV rms without visible or audible surface arcing, with no smoking after 60 s at 60 kV. Surface resistivity is from $2.5 \,\mathrm{G}\Omega/\mathrm{sq}$ to $4.0 \,\mathrm{G}\Omega/\mathrm{sq}$, at a surface current density of 2 μ A/inch dc. This translates as about $0.2 \,\mathrm{kV}/\mathrm{mm}$ to $0.32 \,\mathrm{kV}/\mathrm{mm}$ for a current density of about 80 nA/mm i.e. a for current of about 8 μ A in our 30 mm diameter objects.

Two suppliers' end-winding tapes were used; both manufacturers recommended Bstage ones for resin-rich groundwall insulation, and fully-cured ones for VPI insulation systems. The reported measurement of surface resistivity on the VPI fully cured lab samples gave about $4 \,\mathrm{G}\Omega/\mathrm{sq}$ at the same $2 \,\mu\mathrm{A/inch} \approx 80 \,\mathrm{nA/mm}$ of current in the surface as was used for the earlier requirements; these samples failed the arcing test at just half the required voltage.

Fully cured tape was found not to work well: applied before VPI it allows surface arcing at too low voltage, but applied after VPI it has adhesion problems. Very resin rich tape can be applied before VPI and curing and still work well; normal resin-rich tape must be applied after VPI and before final curing in order to work well.

VPI and curing, on the resin-rich tape, increased the resistivity of two ends by about 30% and made another two ends stay similar or decrease a little: values ranged from $2.6 \text{ G}\Omega/\text{sq}$ to $4.4 \text{ G}\Omega/\text{sq}$.

During voltage endurance testing at 35 kV rms the surface resistivities of two ends varied only a little up conclusion of the tests groundwall breakdown; in both cases the variation was non-monotonic, and the greatest variation was 25% (reduction) between start and half-time; the two ends even changed in the opposite ways most of the time!

A conclusion is that the surface resistivity measurements may be quite similar (here, within 20% or so) while the noticeable arcing occurs at twice the voltage in one as in the other; the ac arcing test is considered more meaningful.

[Lup96] Cable-oriented, mentioning SCT as the 'practical object' of interest. Thermosetting polyolefins, or silicone rubber, is the substrate of these objects, with a filler of carbon black (CB), SiC or barium titanate. High permittivity is desired, and these composites can have $\varepsilon_{\rm r} > 20$. [The paper makes it sound as though the permittivity is the main aim, the filler is the means, and the increased and nonlinear conductivity which ensues is just an annoyance that also deserves some modelling.]

Long-winded derivation of the 2D-axisymmetric model, then of the simplifying assumptions to reach 1D (transline) approximation, claiming that this is only valid when the axial potential distribution is near-uniform. [I'd suggest the relation of axial/radial field being low is the more important point, helped if axially long and radially thin.]

The (thin) active part of the SCT is said to have high, linear, permittivity, typically $\varepsilon_{\rm r} = 20$, and a non-linear conductivity given by $\sigma(|E|) = \sigma_0 (1 + |E|/E^*)^{\gamma}$, where example values are $\sigma_0 = 2 \times 10^{-11}$ Sm, $E^* = 0.1$ kV/mm and $\gamma = 2.5$ [actually, this seems to have been expressed in the inverse way, as resistivity, but to be incorrectly used in another equation as a conductivity: I've converted to conductivity by reciprocating σ and making γ be used as a positive exponent].

The 2D model is solved by Galerkin approximation, and comparison of differences between this and the 1D solution, as errors in potential and field distributions.

[Auc97] This is about insulation materials (very high resistivity) with *some* nonlinear filler in order to help dispersal of space charge when it is causing high local fields.

A review of theories used to describe the i/v or i/T relations: Fowler-Nordheim emission of carriers at electrodes, due to high field rather than temperature; Schottky field-dependent lowering of the barrier for thermionic emission at electrodes (so, temperature-dependent), with i/v relation reducible to the form $|J| = k \exp(n|E|^{1/2})$, where k and n are constants, verifying my guessed interpretation of the equation in [Rob95], and approximating a plain exponential; Poole-Frenkel field-reduction of barriers to movement of charges in the bulk (Poole-Frenkel and Schottky have similar equations); space-charge-limited current (SCLC) in a trap-free insulator, proportional to V^2/d^3 i.e. to E^2 when the thickness of insulator is fixed.

Samples with SiC at 10% or 20% by volume, within polyester, were not radically different from the unfilled material (less than one order of magnitude change in current, similar i/v slope). The sample with 30% volume SiC had a large change, apparently some 6 orders of magnitude greater current, but no direct comparison possible due to the current exceeding the instrument's range long before reaching the same field strengths as were used for the lower concentrations; this sample had about $1 \times 10^{-11} \text{ A/mm}^2$ at a field of 0.3 kV/mm, and the Arrhenius plot gave a lower activation energy than for the other samples, suggesting less temperature-dependence.

[Rhy97] This paper considers a 1D model of a cable termination, aiming at an adequate analytical description of the non-linear voltage profile, for preliminary design work. The insulation is treated as purely capacitive, but the grading is modelled generally as a field-dependent capacitance and conductance.

'Where capacitive effects can be neglected', $\sigma_{\rm FG}(E) = \sigma \left(|E| / E_{\sigma} \right)^{\alpha}$.

Looks moderately useful to someone who wants a non-numerical solution to certain grading design problems.

[Tuc99] discussion of [Rhy97]: The above paper is challenged on several counts in this 1999 discussion, and is defended by the authors.

The first point is due to different definitions of non-linear capacitance — use of C(v) = Q(v)/v or $C(v) = \partial q(v)/\partial v$, which without explicit statement led to misunderstanding of the validity of some derived equations.

Tucci notes that a Poole-type exponential relation, $\rho(E) = \rho_0 \exp(-eaE/2kT)$ is appropriate for carbon-black loaded silicone rubber and EPDM (with a high threshold field around 1 kV/mm below which the relation is weaker), while the power-law is better for polyolefins (polyalkenes).

The authors note that the conductive component of current in typical grading materials is higher than the capacitive component during impulses, in spite of the high rate of change of field, and that for DC grading a complete resistive layer between earth and HV is useful, hence the conductive component of gradings is not useless.

[Må98] EPDM samples loaded with mixtures of 17% vol SiC and either 11.7% or 13.1% vol CB, showed field-dependent (2 hour) conductivity from $\approx 0.1 \text{ kV/mm}$ to 2 kV/mm, without permanent change in the material. Low-frequency behaviour is LFD, suggesting localised hopping transition of charge-carriers. High-field conductivity declines after a while of maintained field (charge depletion?).

[**Riv98**] SiC and ZnO grading materials: 'the inclusion's fraction is usually below the percolation threshold' [presumably this is thinking more of cable terminations than of stator insulation?].

Some test-objects were made with SiC or ZnO based composites ranging from 35% – 70% inclusion by mass: AC showed higher current than DC, but higher inclusion or higher stress reduced this difference; higher inclusion gave greater non-linearity, but only ever when above $0.35 \,\mathrm{kV/mm}$.

Not very good. Strange reasoning about results. Unfair to refer to capacitive as opposed to resistive grading, when all that's been done is to reduce the resistive current by some orders of magnitude without any increase in capacitive current, keeping the graded section similar!

Claims that the non-linearity is pointless as the stress for it to show up is so high ... or something.

[Riv99b] SiC or ZnO relation $\rho = \rho_0 \exp(-kE)$, is said to be commonly used, citing a 1964 CIGRE paper.

Measurements were made at 50 Hz at up to 0.9 kV/mm on SiC and 0.5 kV/mm on ZnO, with mass fractions 35-75%.

At 50 Hz: non-linear behaviour started around $\approx 0.45 \,\mathrm{kV/mm}$.

Simulations used resistive varnishes with bulk conductivity from 1×10^{-7} S/m to 5×10^{-4} S/m.

There is some strange reasoning about resistive/capacive efficacy and benefits, ignoring e.g. the extreme needs during impulses.

[Riv99a] $\rho = \rho_0 \exp(-kE)$, again, and points out that the varnish thickness simulated was 0.5 mm [assume the same in [Riv99b].]

Again, very funny reasoning about the usefulness of SiC (resistive, or non-linear) grading.

[Gul00] The relation $\rho_{\text{surface}} = K \exp(-n|E|^{2/3})$ has been found to fit measurements of a large range of machine stress-grading materials. Widely varying values of K, and moderately varied values of n, were found for different objects to which SiC tapes were applied.² This paper claims that [Eme96] shows measurements on a wide range of end-winding stress grading materials to have a good fit to the above $\sigma(E)$ model, and that there was much variation in the parameters. In fact, the cited work does neither, although an internal report cited within it may do so; quite likely is that references 2 and 3 have been muddled (or 3 is just wrong) — but reference 2 is hard to get hold of for checking.

A feature of the measurements here is the comparison of a single type of resin-rich (B-stage) SiC tape on simple tubular objects with those on real stator coils. Two stator coils were used, rated 13.8 kV and 20 kV, the latter having vacuum-processed high-solvent

 $^{^{2}}$ See section 2.1.8, page 6, for a reminder of the unit-dependence of n for this model.

insulation. Conductivity measurements were made along a 40 mm length of the grading, using a DC supply.

A good fit of voltage distribution was obtained by FEM calculations based on the measurements on the tube, compared to direct potential measurements on the 13.8 kV bar. [The not so good fit with the 20 kV bar is perhaps just through using a bad material model; it seems that the different insulation material and treatment made the grading parameters different on the 20 kV bar.]

Aging was done by high voltage (up to $2.0 U_n$) and by high voltage and high temperature (up to $1.5 U_n$ and $140 \,^{\circ}$ C), for 4000 hours. The parameters varied when measured between 1000 hour bouts of aging, with measurements of K (G Ω) varying up to about 500 and down at the end to about 30, having started off around 80; variation of n looks less, being 'only' a few tens of percent, but as a coefficient in an exponential term it could make a large difference too. The variation was attributed to initial shrinkage of the matrix, making greater contact, then degradation of the matrix and possible development of high-resistance surfaces; this seems rather guessy and dodgy — isn't K the wrong way for this? Anyway: if their (not much described) methods were sensible, e.g. making measurements at the same temperature and checking for low variation in results of several repeated measurements, then it's interesting to note that we perhaps should be more careful about assuming constant properties of our gradings after curing.

Arcing at tape overlaps is reported (a photo is given) on a group of three bars of the 13.8 kV type (described above). From this it is inferred that the contact is bad, significant current travels in the helical direction, and therefore measurements of grading properties must be over a greater length even than the 40 mm used here and certainly than the commonly chosen 10 mm, in order to have no direct path through a single piece of tape.³

[Tuc00] Based on work from this author's group, behaviour of carbon-black loaded composites is claimed to be different in the axial (Poole type, $\sigma_{zz} = \sigma_0 \exp(d|E_z|)$) $\sigma_0 \approx 2 \times 10^{-11} \text{ S/m}, d \approx 4.6 \times 10^{-6} \text{ m/V}$), radial (space-charge limited, $\sigma_{rr} = \sigma_1[(|E_r| + E_0)/E_0]^g, \sigma_1 \approx 1 \times 10^{-10} \text{ S/m}, g \approx 2.5, E_0 \approx 1 \times 10^5 \text{ V/m}$), and tangential (near-constant, about $8 \times 10^{-12} \text{ S/m}$) directions, up to $\approx 5 \text{ kV/mm}$, beyond which there is a rapid increase in conductivity 'regardless of conduction mechanism' (presumably meaning regardless of direction of stress).

A relative permittivity $\varepsilon_{\rm r} = 10$ was considered reasonable for this substance.

The tensors used to describe the anisotropy were diagonal, i.e. different directions' conductivities are independent.

The extrusion process is mentioned as a source of the anisotropy.

The conclusion is that only the z-direction (axial) properties of the material are important for grading purposes.

³ My results, done on samples of 10, 20, 40 and 80 mm, suggest that this isn't important: all had very similar I/E relations.

[Må01a] DC conduction in SiC powders in air, dry or damp, is studied, including the effect of pressure. A justification for the relevance of the plain powder is that many grading applications use percolated SiC with some largely linear dielectric as the filler.

The variation $I = I_0 (U/U_0)^{\alpha}$ is mentioned simply as a relation that is sometimes used but that becomes 'artificial' when α has to be made voltage dependent in order to maintain the fit over wide voltage ranges.

Some modelling assumptions, claimed to be justifiable by results, are that the oxide layer between particles is very thin (3 nm), and that the lack of metal doesn't invalidate the Schottky model (as the metal properties often are not significant compared to the interface and semiconductor) although it does make image-force barrier-lowering be irrelevant. Current density by thermionic emission over the barrier (presumably forward bias?) is proportional to the square of temperature and to the difference between proportions of energies above the (field dependent) barrier height at the applied voltage and at zero voltage (so, exponential terms in the voltage). In reverse bias, thermionic emission, tunnelling, or a mixture, may be the controlling influence on current: heavy doping, high voltage or low temperature, tend the tunnelling to dominate, and a simplified reverse field-emission expression contains $V_{\rm rb}^{1/2} \exp(-a/V_{\rm rb})$ terms (but actually much more than that, including division by a sine, and some $\Phi_{\rm b}$ parts). The reversebased barrier starts to break down by avalanche above a critical voltage. Models based on compressive electrostatic forces between SiC particles, and their effect on the contact area, suggest that ratio of apparent/volume conductivity is proportional to the 2/5power of average electric field due to this compression.

Experimental results are from green and black (electrical grade, higher and more consistent doping) SiC powders of varied fineness and of 0.5 mm to 1 mm thickness. The dry samples had been heated to 250 °C in vacuum for 24 hours, implying that 'moist' ones were simply 'normal' (room-exposed). Conductivity and nonlinearity were higher for the black SiC. Smaller particles gave much reduced apparent material conductivity, e.g. about a factor of 1000 using '1200 mesh' rather than '360 mesh',⁴ which makes sense for the smaller number of contacts in series. The dryness gave a higher current by a few decades at the lowest values (fine mesh, low field), but hardly any difference (or even slightly lower current) at higher values. Higher doping gave higher nonlinearity and conductivity, indicating that any oxide layer must be very thin, the interfacial barriers at grain contacts being the controlling influence on conductivity.

Fields from 2 V/mm to 3 kV/mm are plotted, giving current densities from about $1 \times 10^{-5} \text{ A/m}^2$ to 10 A/m^2 for the coarsest green SiC. Per-contact voltages ranged from about 20 mV to 20 V for green, and up to 6 V for black SiC. The black SiC had much higher conductivity and nonlinearity. Equations for tunnelling alone failed to model the black SiC beyond about 3 V per contact, but the addition of pre-avalanche multiplication was able to give a very good fit.

⁴ This is presumably the 'Tyler sieve mesh', a number expressing the number of holes per inch (linearly) of a sieve, where the size of sieve-wires must also be taken into account when calculating hole-size. http://en.wikipedia.org/wiki/Mesh_(scale). So, 360-mesh is approximately 40 μ m, and 1200-mesh is about a third of this linear size.



Figure 2: DC conductivity for three grain-sizes of SiC powder, at room temperature and 410 kPa compression, dried (open marker) or not (filled marker). From fig. 9 of [Må01a].

Plots, log/log, of total current j with respect to mean applied field E or to intergraincontact voltage V_c , had increasing gradients, i.e. the function is not a direct power but has some exponential heritage The one log/lin plot had a decreasing gradient, i.e. the function is not a straight exponential. This does nothing to contradict the $k \exp(n|E|^{2/3})$ (not mentioned at all here).

Final conclusions are: contact area may be the imporant effect of externally applied pressure; the macroscopic conduction properties of the powders can be well described in terms of grain contacts modelled as Schottky-like barriers with effective height around 0.4-0.5 eV, with tunnelling by field emission being the main mechanism in these heavily doped materials over most of the nonlinear voltage range, and with pre-avalanche multiplication at the highest voltages.

[Må01b] AC conduction in SiC powders in air is studied, a continuation of [Må01a].

The basic model of a SiC grain junction is a fixed capacitance through the space between grains, a non-linear capacitance due to variation of the depletion-layer charges with field, and a non-linear conductance from a Schottky-like back-to-back junction at grain contacts. Frequency-dependence is assumed to be due to the connection of many such circuits.

Pure sinusoidal excitation is assumed, but with a non-linear capacitance one cannot assume that its quadrature fundamental current is the sole component due to the capacitive effect.

The in-phase component of fundamental current, together with all current harmonics, is assumed to be due to the conduction, and the peak of this combined current is related to the peak (spatial)mean applied field to give an apparent AC conductivity.

Pressure, varied over two orders of magnitude, gave an approximately power-law effect upon permittivity (increased about $\times 5$ in this range) and conductivity (increased about $\times 20$).

The measurement methods used were: DR (dielectric response), measuring the current due to a sinusoidal applied voltage of 10 V to 2.5 kV and 0.01 Hz to 100 Hz; C/V (capacitance-voltage) measuring DR with a 10 V 10 Hz sinusoid superimposed on a 100 V to 1.05 kV DC bias; AC-pulse measurements, applying just two cycles of a 10 Hz, 300 V to 900 V sinusoid, and measuring current on the second cycle (strange: this suggests that the AC-pulse measurement used much lower maximum stress than the DR or C/V, although its purpose is to allow higher stress); I/V (current/voltage) measuring the current after 120 s of application of between 50 V and 1.1 kV DC to the sample.

Variation of permittivity with frequency is similar for the green and black SiC powders, decreasing by a decade over four decades of frequency. Variation of total AC conductivity with frequency is quite flat from 0.01 Hz up to around 1 Hz, but then rises for the green SiC sample by about one decade from 1 Hz to 100 Hz. The frequency dependencies are reconciled with the frequency-independent models of the particles, junctions and surrounding, by noting that the material is a network of different junctions, in which the dominant path varies depending on the (frequency-dependent) displacement currents and the different junction properties: frequency variation changes where the stresses lie.

Variation of permittivity and AC conductivity with average applied electric field is shown in figure 3. The lin/lin scale of figure 3a shows the permittivity to be almost linear, while the log/lin scale of figure 3b shows the conductivity to be sub-exponential (although it looks well above power-law, at a guess). Over the range from very low fields up to 1.5 kV/mm, there is a doubling of the already high ($\varepsilon_{\rm r} \approx 20$) permittivity, and more than two orders of magnitude increase in AC conductivity. Figure 4 shows these points replotted, with fitting of a line or the sub-exponential model. Figure 5 has the same data, with permittivity scaled into an 'admittivity', plotted on the same axis, to show where the conductive and capacitive currents are of similar magnitude. High field or low



Figure 3: Permittivity and AC conductivity of green SiC powders at room temperature and 410 kPa compression, measured by several methods at 10 Hz. From [Må01b].

frequency leads to dominant conduction current, as expected. The C/V measurement of conductivity gives large values than other methods, as the measured values are with small changes around the stated field rather than as sinusoids that include the low-

conductivity low field regions. The I/V measurement included 'for comparison' is of course not 10 Hz, so different behaviour is unsurprising.

From the two sets of curves, equal magnitude of $\omega \varepsilon$ and σ_{ac} at 10 Hz would be with a field of about 0.1 kV/mm to 0.2 kV/mm.

[Bak02] Using the $\sigma = K \exp(n|E|^{2/3})$ relation as in [Gul00], 3D FEM models are made of end-winding stress-grading systems, treating the SiC layer as a zero-thickness. surface. The grading material changes with aging, its coefficient *n* decreasing.

[EK03] Stress-grading resistance is modelled as $\rho = \rho_0 \exp(-n|E|)$, without any reference. The capacitive current in the grading is said to be very small compared to the conductive current (power frequency seems to be the main interest). A describing-function method is used, with RMS values from one cycle being used to determine the parameters for the next cycle.

[Oka04] Investigation of composite grading materials with Fe₃O₄ as well as or instead of SiC. Polybutadiene resin was used as the binder for a tape and bar model of machine end-winding grading. Polyethene was used as the binder for some composite sheets.

The SiC non-linearity is from a barrier effect through the grain boundary. The percolation threshold is about 30%. Pure SiC filler needs to be above 15% vol before significant effects occur. The relation of (general) physical properties to a power of the filler deviation from the percolation threshold value is 'well known', i.e. $f \propto |p-p_{\text{thresh}}|^{\alpha}$, with typically $\alpha = -2$ for conductivity, and $\alpha = -1$ for permittivity.

The non-linearity coefficient [not defined — is it an exponent in a power-law relation, or a coefficient in an exponential relation?] is seen to be constant, n = 3.5, at concentrations above the percolation threshold, but to rise towards lower concentrations; this is given as a reason why machine non-linear grading composites are heavily loaded with filler — for a stable relation [but presumably the base conductivity, the coefficient outside the nonlinear term, *does* keep increasing as concentration increases].

[Qi04] The objects of study are polymeric tubes for cables.

 $\sigma(E) = 6 \times 10^{-9} \exp(2.22 \times 10^{-6} |E|)$; approximately exponential rise in σ with E during lightning impulse, 0.2 kV/mm - 5 kV/mm, $1 \times 10^{-8} \text{ S/m} - 3 \times 10^{-4} \text{ S/m}$.

 $\sigma_i(E,T) = 3.28 \exp(-0.56q/k_{\rm B}T) \sinh(2.78 \times 10^{-7}|E|)/|E|$

Grading tube (cable), $\varepsilon_r = 22$, $\sigma(E) = 6 \times 10^{-9} \exp(2.22 \times 10^{-6} |E|)$. All dielectrics reach some nonlinear point at high field.

[Con05] Very little on SiC itself. It's mentioned that 'SiC' describes a wide range of practical materials, from 90% purity 'metallurgical' for e.g. abrasives, up to 99.9995% 'high purity' for semiconductors; its volume conductivity is dopant-dependent, ranging from 100 S/m to $1 \times 10^{-4} \text{ S/m}$ [not very relevant to us, since its just a filler, and surface effects are probably much more important]. A figure (copied here as figure 7) is mildly interesting, showing *i*-*v* relations for various grades of SiC-loaded tape.



(a) Relative permittivity $\varepsilon_{\rm r}$, fitted with a straight line.

(b) AC conductivity $\sigma_{\rm ac}$, fitted with the classic $k \exp(n|E|^p)$ relation.

Figure 4: Permittivity and AC conductivity as in figure 3 replotted with fitting. Data from [Må01b].



Figure 5: Comparison of permittivity in 'admittance form', $\omega \varepsilon_0 \varepsilon_r$ in the lower set of curves, and AC conductivity σ in the upper set of curves. Data from fig. 8 of [Må01b].



Figure 6: Conductivity versus applied electric field for varied concentration of plain SiC filler in polybutadiene resin. From fig. 3 of [Oka04].

[EC05] Slot semiconductor is carbon-black based, conductivity $\approx 1 \times 10^{-2}$ S/m. End-winding grading is $\sigma = \sigma_0 \exp(kE)$, from their measurements, valid for two materials with different sharpness of non-linearity (assume SiC-based?).

[EC06] This is now on to cable terminations rather than the stator windings of their paper the previous year. FEM models are used, including thermal modelling. The power-law relation $J = kE^{\gamma}$ is used for simulation, with mainly the SiC-based powders having $\gamma < 5$ and mainly the ZnO-based powders having $13 < \gamma < 17$. The relation J/Eis shown for measurements on several powders used in polymer-based grading material. The relation σ/E is shown for percolated silicone rubber with three different fillers: this is plotted log/log, giving a nice upwards curve just as we are used to seeing (i.e. the power-law is not enough). At high frequency (e.g. many kilohertz) there is high loss in any nonlinear conductive grading that is able to grade power frequency and the high frequency acceptably. A two-layer system, with a first part that have higher conductivity, then a second part extending beyond this with normal conductivity, is a way to avoid the intense heating at the slot/end join. Alternatively, capacitive grading systems could be tried. It is mentioned that a combined SiC and ZnO filler can have electrical properties similar to those of ZnO, but better thermal conductivity.

[Tay06] [My Licentiate thesis.] About 0.5 kV/mm seems the maximum stress in grading simulations based on real applied voltages. But bear in mind that this is in a labmodel with a PTFE tube, known to have lower capacitance (and therefore less current collected) per unit length.



Figure 7: 'Typical voltage-current curves' for some SiC-loaded tapes. [These lack detail on the area or length of the cross-section through which the current flows. von-Roll's test method (SIB1407) specifies a 40 mm radius tube, i.e. 127 mm circumference, so about 10 μ A corresponds to the 2 μ A/inch so much used in [Eme96] .] From fig. 8 of [Con05].

[**Omr08**] Slot semiconductor conductivity from 1×10^{-2} S/m to 1×10^{-5} S/m, field-independent.

[Var07] Again, looking at small nonlinear conductivities, for reducing stresses within materials used mainly as insulators; fields are therefore much higher and currents much lower than in grading materials.

Its fig. 7 shows some current waveforms, whose shape is similar to that from our SiC material measurements; it seems to be just the result of a sinusoidal capacitive term and a conductive non-sinusoidal term approximately symmetric around voltage peaks, i.e. stateless, with conductivity at a time depending on that time's voltage.

[Dav07] The 'apparent resistivity of the stress grading coating' is $r = r_0 \exp(-\beta |\partial U/\partial x|)$, i.e. $\sigma = \sigma_0 \exp(n|E|)$.

[Min07] [An ABB paper.] FEM models of stress-grading region, mainly for surface potential.

"The stress grading layer consists of a non-linear material. The resistivity depends mainly on the field strength and is also affected by voltage frequency.

According to the material test results, the resistivity of the stress grading tape can be represented by the following equation:

 $\rho = \rho_0(f) \exp(-kE),$

where k is a positive constant and $\rho_0(f)$ is a positive value, which is dependent on the voltage frequency. Its value for power frequency voltage is a few times higher than that for 1 kHz voltages.

The dependence of the permittivity of the stress grading material on the electrical stress was neglected in the simulation. The frequency influence on the permittivity





(a) J/E for various filler powders, in PTFE-walled cell, $10\,{\rm mm}$ radius and $15\,{\rm mm}$ height.

(b) σ/E for percolated silicone rubber composites: A is SiC 40 % vol.; B is a smaller SiC grain and some ZnO, 45 % vp.; C is a commercial ZnO filler.

Figure 8: Electrical properties of some filler powders and composites. From [EC06].

was considered and different values of relative permittivity were used in the simulation. For example, the relative permittivity of 8 and 6 were used for the power frequency voltage and 1 kHz voltages, respectively.

The maximum calculated stress along the surface in the field grading region at 8.5 kV, 50 Hz sine-wave voltage is 270 V/mm. The value increases to 380 V/mm and 550 V/mm at 1 kHz sine-wave and pulse voltages, respectively.

A surface stress of 600 V/mm is commonly considered to be the value at which surface sparking could occur ... For a short distance, e.g. 20 mm, the value was much higher than the above value."

A table is given, of maximum stress in the grading, V/mm, with varied peak and form of the applied voltage:

Peak vo	ltage	4.0kV	8.5kV	11.3kV
50Hz sine		200	270	291
250Hz sine		260	333	368
1kHz sine		300	380	411
1kHz 100us	pulse	350	440	467
1kHz 17us	pulse	440	506	551
1kHz 5us	pulse	490	550	600

The following was given as a response to a question about the model parameters and the appropriateness of Eva's thesis to the material. It confirms that the machine end-winding grading is pretty high concentration SiC:

"Det B-stage SiC-baserade fältstyrande band som diskuteras i ISH-artikeln är för roterande maskiner och är FULLT med SiC limmat på en bärare. I min avhandling diskuterar jag SiC blandat i en polymermatris. I det senare fallet påverkar tunna skikt av polymer mellan SiC-kornen egenskaperna, som därför skiljer sig från B-stage bandet."

B Details of measurement data

Measurements on a single type of SiC-based B-stage epoxy tape (vonRoll Isola, item 217.01, supplied by ABB motors) are studied here. This and a SiC-based paint (Dold) are the only stator-winding grading substances we have used in any laboratory work; only the tape gave any good consistency of results, presumably mainly due to a more consistent thickness than was possible with the paint.

Several lengths of the material were used, with the intention of getting an estimate of the effect of electrode contacts and extraneous capacitances. For each chosen length, only one test specimen was used: it would have been good to have had several specimens of each length, to distinguish variations in results due to variation in the applied material (thickness, exact length, material variation, tightness) from variations due to the different chosen lengths.

SiC-based rubber materials as used in cable accessories should *not* be assumed to have very similar properties to this SiC-loaded epoxy tape; the tape is heavily loaded with SiC, whereas the material in the accessories may be more weakly loaded.

B.1 Test object

The main material-based measurements were made on four short tubular lengths of the tape. A PFTE tube of outer radius 15.3 mm and inner radius 10 mm was used as a support for the tape, during and after curing. This is the same tube as was used in the simple laboratory test bars, but its outer radius is slightly less here because there is not the tightly fitting inner conductor. Copper-tape electrodes were put on the PTFE tube before the tape was applied: between the facing electrode surfaces the lengths of the four pairs of electrodes were intended as 10 mm, 20 mm, 40 mm and 80 mm. After application of all the parts, and curing, the measured values were closer to 11 mm, 21 mm, 40 mm and 80 mm. The stress-grading tape was applied half-lapped according to the manufacturer's specification, with the tape and electrodes overlapping by 20 mm. The whole assembly was cured at 160 °C for 2 hours. The final thickness of the cured tape layer was about 0.5 mm. Around the thin electrodes, the PTFE tube and the tape, there was only air, i.e. there was no conductor within the tube.



Figure 9: The four tape samples on their PFTE support tube

B.2 Measurement instruments

DC measurements were made with voltages applied across one sample at a time, from a Keithley 3 kV variable supply. The current in the circuit was measured with a Keithley 617 electrometer.

AC measurements were made with an IDA200 dielectric spectroscopy system. Using an external Trek $30 \, \text{kV}$ amplifier, the applied voltage could reach the $24 \, \text{kV}$ needed for stressing the 80 mm sample with the same mean electric field as $3 \, \text{kV}$ on the 10 mm sample, but this voltage was not possible in combination with the highest frequencies due to the amplifier's 50 mA current limit and the capacitance of the screened HV flexible cable. The missed measurement point, along with another point where the IDA200 system reported an electrometer overload, have been replaced with NaN (not a number — omit from plots).

B.3 Measurement sequences

DC measurements were made at 500 V increments up to $3 \, \text{kV}$. The current measurement was taken after the value was seen to settle. There was never a really constant value of current: even with low applied field there was an rapid decline for some seconds (charging the capacitances in the surrounding insulation?) followed by a slow decline, and at the highest fields there ended up being an increase in current after some seconds of the initial decrease, perhaps due to warming. The current just after the main decline was recorded as the DC value.

AC measurements were made with increasing voltage in the outer loop, and with an inner loop of log-spaced decreasing frequencies from 100 Hz to 100 mHz with three points per decade. One set of measurements was made with the same voltage applied to each of the four lengths of sample, taking 500 V increments up to 3 kV as with the DC measurements. Another set was made where the mean electric field across each of the lengths was the same as that across the 10 mm sample in the previous set; this required up to 24 kV for the 80 mm sample.

An initial AC measurement was also made between the 10 mm-spaced electrodes, along the bare surface of the PTFE tube before applying the tape, at frequencies from 0.1 Hz to 1 kHz and voltages of 100 V and 200 V. This was done to give an idea of the stray capacitances involved in the later measurements (it's a pity this wasn't done on all the lengths).

When interpreting AC measurment results it should be borne in mind that fundamental frequency values (e.g. C') are of limited relevance when harmonic components are tens of percent of the fundamental; harmonic components are therefore plotted too.

B.4 Direct current

B.5 Alternating current: varied V and f

B.5.1 Capacitance of a 10 mm gap, bare or graded

From the AC measurement on the 10 mm gap without tape applied, the capacitance was about 2 pF and loss factor about 1/200, as shown in figure 11. Such values are below the measurement system's intended range, whose minimum is around 10 pF. The plots are simply to show that losses are small, capacitances are small and nearly constant with frequency, and the clip placement makes about a 30% difference to the 10 mm



Figure 10: DC measurements on four lengths of SiC grading tape, each taken on three occasions; also, a fitted equation.

gap's capacitance. The harmonic content had amplitudes of only about 10^{-4} of the fundamental.

Now the measurement is across the same gap, but with the stress-grading tape applied and cured as described in section B.1. Looking initially at the fundamental-frequency components of the measured current, normalised by voltage amplitude and frequency to give the familiar C' and C'' values, figure 12 can be compared to the bare case of figure 11.

With subtraction of the estimated capacitance due to the surrounding air, note that the extra capacitance due to a constant ε_r of the stress-grading material would be about $\varepsilon_0(\varepsilon_r - 1) \times 2\pi \times 15.5 \,\mathrm{mm} \times 0.5 \,\mathrm{mm}/10 \,\mathrm{mm}$, which would be about a 0.15 pF increase if the material had $\varepsilon_r \approx 4.5$ as the main epoxy-mica insulation has.

B.5.2 Fundamental frequency views, as C, G and I

A well-controlled voltage source gives low harmonic content. In our measurements, the 3rd and 5th harmonics were the strongest distortion of the voltage, at maximum amplitudes each of around 4% of the fundamental component. A linear measurement object has only a fundamental-frequency current component in response to a single frequency excitation. Because many dielectrics being approximately linear in their working range of fields, a lot of ideas have been built up based on the fundamental frequency. Even though the materials considered here are far from linear, it is interesting to see how they 'appear' in the classic fundamental-frequency views. One aspect that is still relevant is



Figure 11: Capacitance and loss measured across the 10 mm gap *without* stressgrading tape present. Two low voltages were used, 100 V and 200 V. Two placements were used of the crocodile clips from the measurement system: 'near' has the clips standing out parallel to each other from the electrodes, and 'far' has them connected from opposite ends with thin wires.



Figure 12: Capacitance and loss measured across the 10 mm gap with stress-grading tape present. The downturn of C' values at low frequency is probably due to slight phase-errors together with the very much greater current due to C''.

the loss: if the applied voltage *is* sinusoidal, then only (in-phase) fundamental frequency components of the current will have a non-zero power dissipation over a whole cycle.

Conductivity: I_1/E_1 Comparison of the four lengths, each with the same mean applied electric field, allows possible effects of electrodes and of the lapped tape to be seen.



Figure 13: Capacitance and loss measured across the 10 mm gap with stress-grading tape present, with subtraction of 2 pF from C'

Fundamental currents: $\Re\{I_1\}$, $\Im\{I_1\}$ The directly measured quantity is current, which in the previous paragraphs has been 'normalised' by amplitude and sometimes also by frequency. Here it is shown directly, split into real (lossy, in phase with applied voltage) and imaginary ('capacitive') components.

- **B.5.3** Harmonic currents
- **B.5.4** Peak currents, w.r.t. E and f
- **B.5.5** Waveforms: i(t), i(v(t))

Rather than dealing with a single index — e.g. magnitude of component n, real or imaginary part of component n, peak value of current — the full picture can be seen, as a function of time or of frequency. In the following it should be borne in mind that the measurement system records only the frequency-domain components from fundamental up to eighth harmonic, so even the time-domain waveforms shown here have been, in effect, filtered. It has been observed from many objects that the frequency components beyond about the 7th harmonic become much more small and 'noisy' (variation between different applied amplitudes and frequencies) than the 1st, 3rd and 5th (which usually hold most of the detail, for symmetrical objects); this inherent filtering by the measurement system is therefore not likely to affect the useful information in the results.



Figure 14: Capacitance C' for the four samples, with varied applied stress E.



Figure 15: Capacitance C' for the four samples, with varied applied voltage V.



Figure 16: Capacitance C' for the four samples, with varied frequency.



Figure 17: Loss C'' for the four samples, with varied applied stress E.



Figure 18: Conductivity G(f) representation of figure 17, for the four samples, with varied applied stress E.



Figure 19: Fundamental-frequency current's quadrature component $\Im\{I_1\}$, a different view of figure 17's C', for the four samples, with varied applied stress E.



Figure 20: Fundamental-frequency current's in-phase component $\Re\{I_1\}$, a different view of figure 17's C'' for the four samples, with varied applied stress E.



Figure 21: Third harmonic relative magnitude $|I_3|/|I_1|$, for the four samples, with varied applied stress E.



Figure 22: Fifth harmonic relative magnitude $|I_5|/|I_1|$, for the four samples, with varied applied stress E.



Figure 23: Peak current $\hat{I}(t)$ for the four samples, with varied applied stress E.



Figure 24: Peak current $\hat{I}(t)$ after removal of the fundamental capacitive current $\Im\{I_1\}$, for the four samples, with varied applied stress E.



Figure 25: Peak current $\hat{I}(t)$ for the four samples, with varied applied voltage V.



Figure 26: Peak current $\hat{I}(t)$ for the four samples, plotted against applied stress E.



Figure 27: Peak current $\hat{I}(t)$ after removal of the fundamental capacitive current $\Im\{I_1\}$, for the four samples, plotted against applied stress E.



Figure 28: Waveforms i(t) for the 10 mm sample, at f = 21 Hz with varied applied stress E.



Figure 29: Waveforms i(t) for the 10 mm sample, at $E \approx 200 \text{ V/mm}$ with varied frequency.

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Figure 30: Lissajous figures, i(t)/v(t), for the 10 mm sample, at f = 21 Hz with varied applied stress E.



Figure 31: Lissajous figures, i(t)/v(t), for the 10 mm sample, at $E \approx 200$ V/mm with varied frequency.

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