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A Contribution to Everlasting Electrical Insulation for DC Voltage: PD-Phobic Materials

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ABSTRACT This paper focuses on the design of insulating materials candidate from DC-supply applications, proposing viable solutions that may increase the defect-tolerance of an insulation system and avoid the presence of highly energetic phenomena, specifically partial discharges, which can cause premature insulation breakdown. It is shown that, in principle, polymeric materials for DC insulation can be structured, possibly through nanotechnology, to avoid partial discharge inception in steady state even in UHVDC cables and high-field design insulation systems, which would exclude partial discharge degradation from the aging factors that can affect insulation reliability and life. This approach may provide basic tools to design DC insulation having electro-thermal life and reliability of virtually unlimited extent, thus of so-called PD-phobic materials.

INDEX TERMS Cables, electro-thermal life, HVDC, insulation reliability, nano-filled materials, partial discharge (PD), partial discharge inception voltage (PDIV), polymeric materials.

I. INTRODUCTION

Electrical insulation is a key component for the reliability of any electrical apparatus because it is the primary cause of premature breakdown, thus the main factor associated with apparatus life and reliability, as well as safety. Increasing life and reliability and optimizing design to reach minimum insulation volume have impact on insulating material properties and manufacturing processes.

The electro-thermal design of an electrical insulation stems from data obtained from accelerated life testing performed in laboratory, and it uses probabilistic models to extrapolate the specified life at some levels of stresses that the insulation will have to withstand during operation [1]. Unfortunately, a number of elements can affect insulation reliability, causing premature failures. Those can be addressed to manufacturing, on-field commissioning and, particularly, the rising harsh electromagnetic environment that insulation systems are going to meet in service. Indeed, he presence of defects and/or unexpected types of supply waveforms differing from the sinusoidal AC supply may incept highly energetic degradation phenomena and increase drastically aging rate [2]–[6].

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Examples of supply voltage waveforms which are rapidly replacing/overlapping to AC sinusoidal are those provided by power electronics (including AC/DC and AC/AC converters), and DC which are becoming more and more common not only in HV transmission, but also in HV and MV renewable links and MV supply of transport vehicles.

Electric life behavior in AC and DC, design field and relevant partial discharge inception voltage, PDIV, are discussed in Sections 2 and 3, highlighting how the field magnitude in insulation and defects may differ between AC and DC, depending on material properties and temperature. This may activate PD at significantly different voltage and field levels, in the same defect, whether the insulation system is supplied in AC or DC. In section 4, the dependence of PDIV on material properties is modelled. It provides a drive for the development of insulating materials having the purpose to operate below PDIV in DC steady state, even with defects that might be able to incept partial discharges. In this way, the concept of PD-phobic materials for DC applications is introduced for the first time as an electrical insulation property.

II. LIFE AND DESIGN FIELD IN ELECTRICAL INSULATION

In AC the electrical field in cavities or defects inside insulation depends on the permittivity ratio. For a flat cavity, the amplification factor is given approximately by [7]:

$$f_{AC} = \frac{E_c}{E_b} = \frac{\varepsilon_{rb}}{\varepsilon_{rc}} \tag{1}$$

where ε_{rc} and ε_{rb} are relative permittivity and E_c and E_b are electric field, in cavity and insulating material, respectively. For a cavity containing gas and a typical polymer for HV insulation, f_{AC} can be about 2, thus the field in air is two times that in insulation. Since permittivity is almost invariant with temperature, and almost a constant for a broad range of materials used as electrical insulation (e.g. $\varepsilon_{rb} = 2.1$-3.5), the field in a defect does not vary significantly with temperature and it is characteristic of categories of insulating materials.

In DC the situation is drastically different, because the field in a defect depends on conductivity, γ, and the amplification factor for a flat cavity is:

$$f_{DC} = \frac{E_c}{E_b} = \frac{\gamma_b}{\gamma_c} \tag{2}$$

Insulating materials can be modified easily (changing base compound, blend, adding nanofillers) to vary conductivity (but not permittivity) even of orders of magnitude. As the electric field in cavities or defects depends on conductivity ratio, the more the conductivity in an insulating material is smaller than that of the medium in the cavity, the lower the electric field in the cavity will be. Unlike permittivity, conductivity displays broad variation with temperature, T, and, to minor extent, with electric field, E [8], [9]. Equation (3) is often used to describe an exponential temperature and field dependence of conductivity is:

$$\gamma\,(T, E) = \gamma_0\, exp(\alpha(T - T_0))\; exp\,(\beta\,(E - E_0)) \tag{3}$$

where γ_0 is the conductivity at a reference temperature T_0 (in °C) and a reference electric field E_0 (in kV/mm). The temperature dependence of conductivity is delivered by the temperature coefficient α (in °C^{-1}) whereas β (in mm/kV) represents the field dependency coefficient.

Design of an insulation systems is generally made resorting to accelerated life tests on objects as much representative as possible of the final product, applying then simple models to extrapolate to design filed and life, at selected failure probability, and to adapt the dimensions to the product size (dimensional or size effect [1], [9]). The most typical model used to extrapolate test data and determine the design electric field is the inverse power law, which is inserted in a probabilistic framework using the Weibull distribution (valid for electrothermal and mechanical stress). The resulting probabilistic life model, for electric stress, linearized by log-log transformation, has expression [10], [11]:

$$\log\left(t_{F,P}\right) = \log\left(K_P\right) + \log\left(t_R\right) - n\log\left(E\right) + n\log\left(E_R\right) \tag{4}$$

where P is failure probability, $K_P = -\left(\log\left(1-P\right)^{1/\beta_t}\right)$, t_F (or L), is life, E_R is a reference electric field, t_R the corresponding life, and n is the voltage endurance coefficient, VEC. Often, E_R coincides with the higher test field, that is the initial breakdown field (electric strength) of the insulation system, i.e. $E_R = E_S$. This life model holds at a constant temperature. The design field of an insulation system, E_D, can be then estimated for the requested failure probability, P, operating temperature and life (L_D).

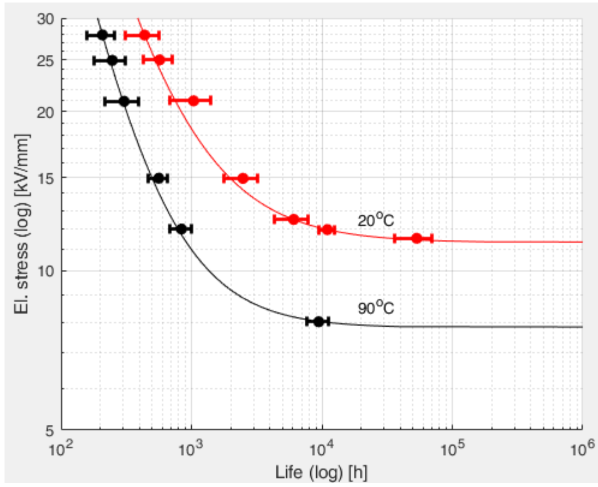

FIGURE 1. Thermo-electrical threshold life lines: experimental results (from XLPE specimens) and fitting to life model (5). Failure probability 63.2%. Test temperatures 20 and 90°C. After [14].

Compatibly with the maximum allowable dimension for the electrical apparatus (e.g. HV cable), insulation can be designed to provide any chosen life at fixed reliability ($R = 1 - P$). It is common experience that cables taken from service after decades of operation do not show any significant aging effect, and the same holds for other electrical apparatus, as transformers or generators [12], [13]. This leads to speculate that:

- The insulation design field is generally conservative, which means that there is the possibility of extremely long electro-thermal life
- Breakdown, including premature failure, is mostly due to defects embedded in insulation as a result of manufacturing, assembly and/or installation processes.

Supporting the speculation of a conservative design, it is shown in [14] that accelerated life tests can be modelled according to (from (4)):

$$\log\left(t_{F,P}\right) = \log\left(K_P\right) + \log\left(t_R\right) - n\log\left(\frac{E - E_T}{E_R - E_T}\right) \tag{5}$$

where E_T is the electrical threshold, indicating possible threshold values for cross-linked (XLPE) cables in the interval 12 to 8 kV/mm in the insulation temperature range 20 to 90°C, see Fig. 1. Hence, it may likely occur that choosing a design field from the linear extrapolation of the inverse power model, referring to (4), can provide values of field which are, indeed, below the threshold for electrical aging (depending on insulating material and manufacturing technology).

In addition to that, thermal aging is generally lower than that considered for the design, due to thermal cycling which establishes a mean temperature lower than the thermal

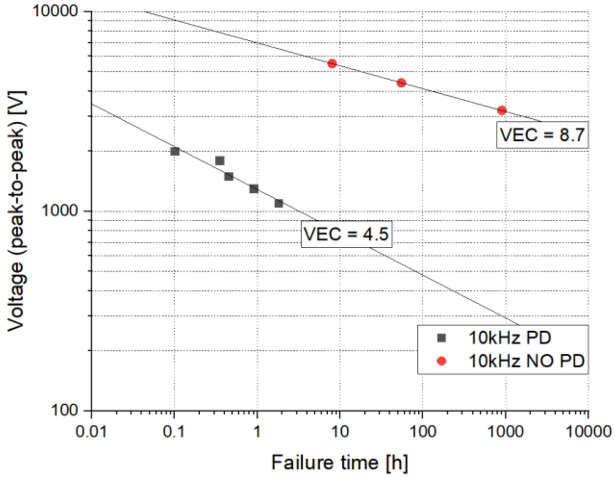

FIGURE 2. Evidence of life reduction due to partial discharge occurrence for enameled wires aged under AC voltage, at high frequency (10 kHz), without and with PD. The life points have failure probability 63.2%. The value of the voltage endurance coefficients, VEC, that is, n in (4) are reported.

class, and the fact that the latter is generally underestimated [15], [16].

III. PARTIAL DISCHARGE INCEPTION IN DC AND AC AND IMPACT ON AGING RATE

A factor which can accelerate drastically insulation aging, thus causing premature breakdown, is partial discharges, PD. They are highly energetic electronic avalanches occurring in cavities or low-density defects present in an insulation, and mostly unavoidable due to manufacturing or assembling processes of electrical insulation systems [8], [17].

The effect of PD is increasing the aging rate at the defect location, so that the slope of the life line is significantly affected and life is shortened [18], [19]. As an example, Fig. 2 reports experimental results of life tests, fitted to model (4), performed without and with the presence of PD, under AC sinusoidal voltage at 10 kHz. The former tests were made in insulating oil, to avoid PD, the latter in air. As can be seen, the voltage endurance coefficient, n in (4), is halved when PD occur, i.e. goes from 8.7 to 4.5, which can cause dramatic life reduction compared to design life (e.g. in Fig. 2 life decreases of 5 orders of magnitude at 2 kV_{PP} if PD occur). It can be expected that under DC the aging rate due to PD will be lower than under AC, due to the much lower repetition rate of DC PD, thus the decrease of n will be less significant, but PD will anyway affect life duration also under DC [20].

An approximate, deterministic estimate of the partial discharge inception field in a cavity embedded in an insulation is given by, [21]:

$$E_i = 25.2p\left(1+\frac{8.6}{\sqrt{2pr}}\right)\left[\frac{V}{m}\right] \tag{6}$$

where r is the cavity radius (or height) and p is the gas pressure inside the cavity. However, PD phenomena have stochastic nature associated to the availability of a free electron and recombination path [20], but (6) can provide a valuable estimate of a minimum PD inception condition.

Hence, partial discharge inception voltage depends on cavity size, cavity medium (generally air) and its pressure, besides insulation thickness and geometry. Under AC the only way to increase PDIV in an insulation is to reduce defect size. Actually, $PDIV_{AC}$ could be increased changing the medium in the defect/cavity injecting a matter having higher permittivity than air, or increasing gas pressure, but this is beyond insulating material development. Referring to DC, (2) indicates that the smaller the conductivity in the insulating material, the lower the electric field in the cavity and, thus, the higher the electric field for PD ignition, i.e. $PDIV_{DC}$.

Expressions for $PDIV_{AC}$ and $PDIV_{DC}$, and their ratio, can be simply obtained resorting to the classic equivalent circuit generally used to describe PD occurrence (*abc* circuit), and assuming a deterministic discharge process, [22], [23]:

$$\frac{PDIV_{DC}}{PDIV_{AC}} = \frac{|Z_c(\omega)|}{|Z_b(\omega)|+|Z_c(\omega)|}\cdot\frac{R_b+R_c}{R_c} \tag{7}$$

where Z and R are the impedance and the resistance representing the capacitive and resistive characteristics of the cavity (suffix c) and the insulation (suffix b) in their lumped element model [22]. At power frequency (50 or 60 Hz), the effect of insulation and cavity gas resistance can be neglected with respect to capacitance, hence (7) becomes:

$$\frac{PDIV_{DC}}{PDIV_{AC}} = \frac{\varepsilon_{rb}}{\gamma_b}\cdot\frac{\gamma_b h_c+\gamma_c(h_s-h_c)}{\varepsilon_{rb}h_c+\varepsilon_{rc}(h_s-h_c)} \tag{8}$$

being h_s the insulation thickness and h_c the height of the cylindrical cavity embedded in the insulation.

The ratio between $PDIV_{DC}$ and $PDIV_{AC}$, calculated from (8), is reported in Fig. 3 as a function of temperature, for different values of γ_0 and α (refer to (3)) whereas air conductivity is assumed to be constant. Fig. 3 refers to results obtained for a multi-layer specimen made by three cross-linked polyethylene, XLPE, layers, where the one in the middle is punctured, and having a cylindrical cavity with mean height $h_c = 400\ \mu$m. It can be seen that, depending on γ_0 and α, $PDIV_{DC}$ can become significantly higher than $PDIV_{AC}$ at any operation temperature, but also lower. Specifically, the smaller the conductivity and the temperature coefficient α, the higher $PDIV_{DC}$ will be compared to $PDIV_{AC}$, as a function of temperature.

A simplified expression can be derived from (8) where the dependence on cavity size can be exploited. It must be highlighted that since defect dimensions are generally unknown in insulation, the ratio between the measured $PDIV_{AC}$ and $PDIV_{DC}$ can provide indication on cavity dimensions. This will be a fundamental information for insulation system design and manufacturing technology, as well as for material development. Considering reasonable limits for permittivity and conductivity ratios, and cavity size (i.e. cavity height

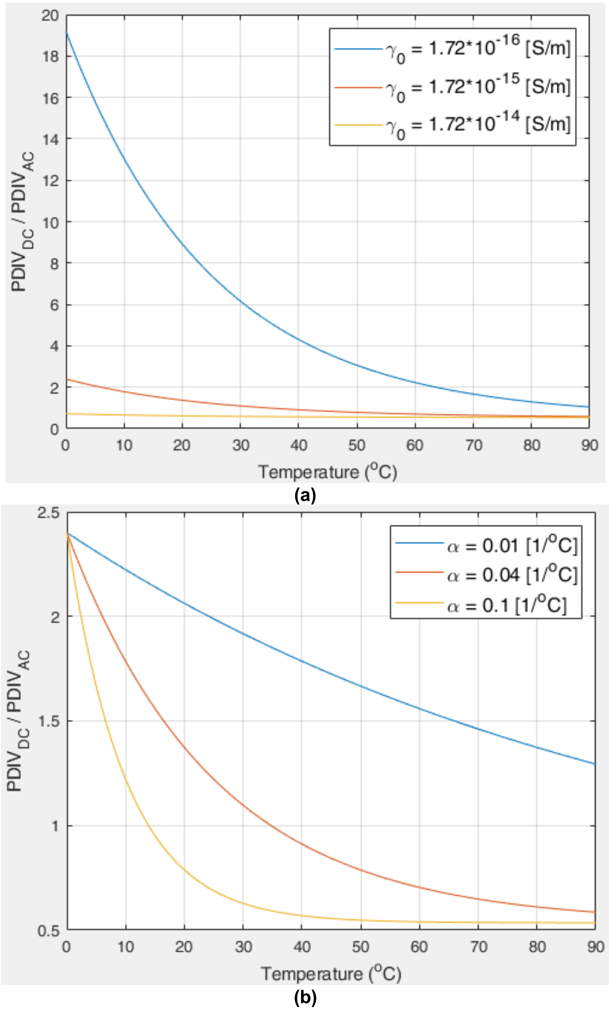

FIGURE 3. Ratio of PDIVDC to PDIVAC as function of temperature, (a) varying γ_0 with constant temperature coefficient ($\alpha = 0.04$ °C^{-1}) or (b) at constant γ_0 ($\gamma_0 = 1.72$E-15 [S/m]), for a specific defect size. ($h_c = 400\ \mu$m). Equation (8).

cannot exceed the thickness of the entire specimen):

$$\varepsilon = \frac{\varepsilon_{rc}}{\varepsilon_{rb}} = \frac{1}{f_{AC}} \leq 1$$
$$\gamma = \frac{\gamma_c}{\gamma_b} = \frac{1}{f_{DC}}$$
$$h = \frac{h_c}{h_s} < 1$$

Equation (8) can be rewritten as:

$$\frac{PDIV_{DC}}{PDIV_{AC}} = \frac{\frac{h_c}{h_s - h_c} + \frac{\gamma_c}{\gamma_b}}{\frac{h_c}{h_s - h_c} + \frac{\varepsilon_{rc}}{\varepsilon_{rb}}} = \frac{\frac{h}{1-h} + \gamma}{\frac{h}{1-h} + \varepsilon} = \frac{h(1-\gamma) + \gamma}{h(1-\varepsilon) + \varepsilon} \quad (9)$$

Equation (9) is a function of the three variables: h, ε and γ, so that some inference on cavity size can be obtained from the PDIV ratio. Fig. 4 shows an example where the PDIV ratio is represented as a function of temperature and for various defect thicknesses, according to (9). It is noteworthy that increasing temperature PDIV$_{DC}$ decreases because of the increase of insulation conductivity (refer to (3)). The temperature dependence of PDIV$_{AC}$ is negligible, according to the approximate model considered here, but the dependence of PDIV$_{DC}$ on cavity thickness becomes less and less significant as long as conductivity is low. This seems quite interesting in the light of DC insulation system design. A kind of forgiveness in terms of defect size seems, indeed, envisaged for DC supply.

Even if the above mathematical description has the inherent weakness to treat a stochastic phenomenon like PD by a deterministic approach, it can provide a clear picture of what it can be expected regarding PD inception under DC steady state. It must be highlighted that materials play a fundamental role in minimizing the possibility of PD occurrence in defects of a DC insulation (in steady state). Fig. 3, indeed, indicates that even relatively small reduction of conductivity can increase significantly PDIV$_{DC}$ and its ratio to PDIV$_{AC}$. Thus, an insulation system which may suffer PD under AC due to defects, can become PD-phobic under steady-state DC, that is, operate below the inception of PD even at high design electric fields and in the presence of cavities of considerable dimensions.

It is noteworthy that this does not mean that the insulation system will not suffer PD at all during life if designed below PDIV$_{DC}$. Indeed, since during voltage transients (such as energization and voltage polarity inversion) the electric field in a defect will be driven by permittivity, as under AC, and it will be dependent fully on conductivity only in steady state [24]–[26]. Hence, if the design field of a DC insulation is larger than PDIV$_{AC}$, PD may occur during transients in insulation defects. Since the duration of a transient is proportional to the ratio of permittivity to conductivity, the smaller the conductivity, the longer the transient, thus the time at which electric field will be permittivity-driven and PD can potentially occur. Hence, while DC insulation can be operated most of the life in the absence of PD, some PD can occur during each transient. Those should therefore be limited in number as much as possible or, otherwise, design must take into account the potential small amount of life reduction that each transient can subtract to operation life upon PD inception. As an example, the cumulative aging model described in [27] could be used for this estimation.

IV. MATERIAL DESIGN FOR A PD-PHOBIC ELECTRICAL INSULATION

The concept of PD-phobic insulation brings to design and tailoring of insulating materials for DC insulation. They can be modified purposely depending on the use, i.e. under permanent DC, in the presence of numerous transients, or even in the case, as forecasted by Flexible-DC approach, where the insulation can be submitted alternatively to AC or DC fields.

In any of the above conditions, materials can be optimized to raise as much as possible the threshold for PD inception and forgiveness to the presence of defects in the insulation.

Materials as XLPE can be modified to considerably vary conductivity (as reported also by recent patents [28], [29]), but the highest capability to modify conductivity comes from

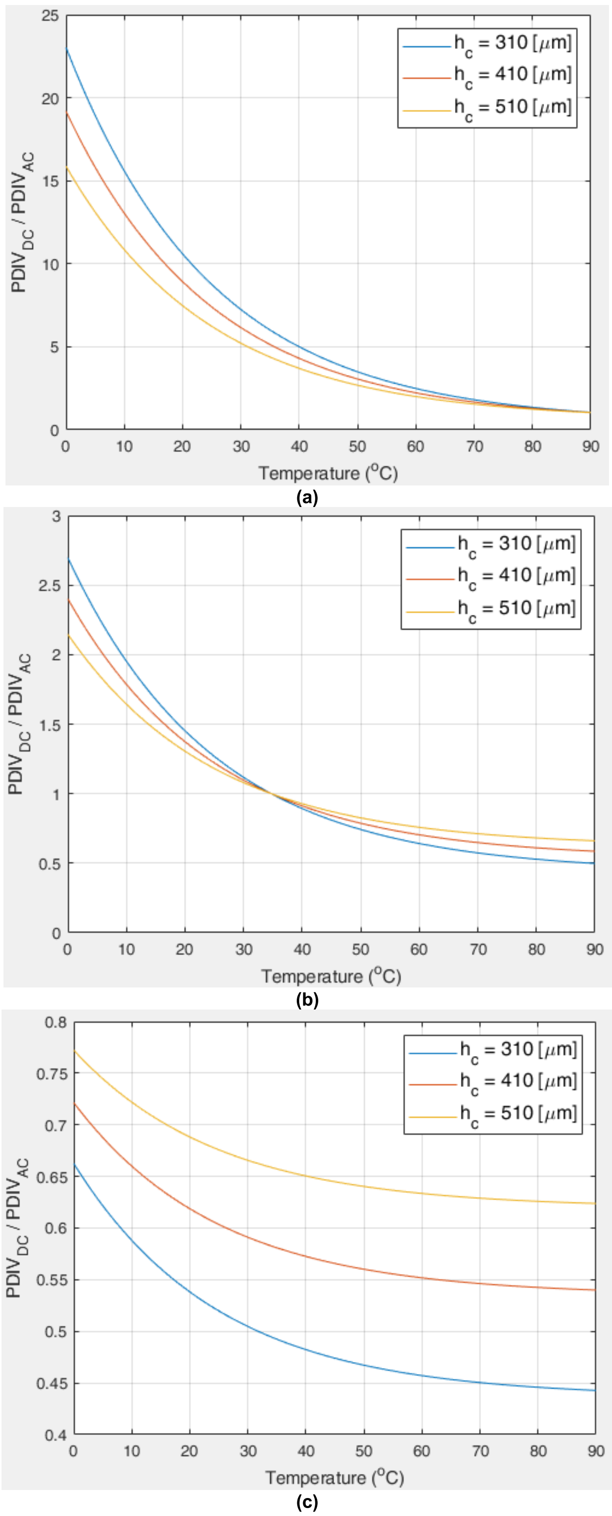

FIGURE 4. Variation of PDIVDC/PDIVAC with cavity thickness, h_c, as a function of temperature, according to (9) for a constant temperature coefficient α = 0.04 °C^{-1}. (a) γ_0 = 1.72E-16 [S/m], (b) γ_0 = 1.72E-15 [S/m] and (c) γ_0 = 1.72E-14 [S/m]).

materials as polypropylene (PP) that are compounded, and the addition of nanofillers, which can grade the value of conductivity and its thermoelectrical dependence for any specific purpose.

TABLE 1. Mean values of conductivity after 24 h polarization at 30 kV/mm and 20°C, its temperature coefficient α (refer to (3)), and dielectric strength for two types of base polypropylene compounds (PP1 and PP2), and three types of nanofilled materials, i.e. PP1N1, PP1N2 and PP2N1.

Material code	Conductivity (S/m)	Dielectric strength (kV/mm)	α (°C^{-1})
PP1	1.15E-16	369	0.12
PP1N1	5.7E-15	377	0.03
PP1N2	5.7E-16	308	0.13
PP2	1.6E-15	394	0.06
PP2N1	4.8E-17	488	0.07

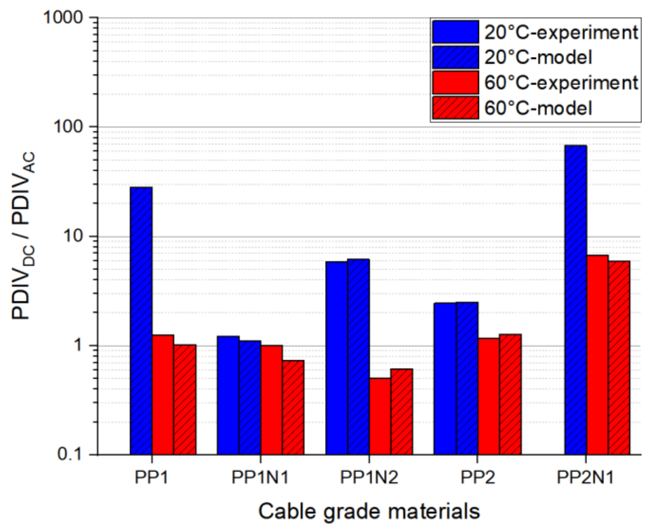

FIGURE 5. Experimental and estimated values of PDIVDC/PDIVAC for multi-layer specimens made of PP1, PP1N1, PP1N2, PP2 and PP2N1 at 20 and 60°C (Table 1) (refer to (8) and (3)). The defect had radius 3.5 mm and average height 400 μm. Due to the high values of DC PD at 20°C it was not possible to apply a large enough voltage during PDIV testing of PP1 and PP2N1 materials, thus the corresponding experimental values could not be reported in this Fig.

Table 1 reports data from two types of PP compounds, PP1 and PP2, which have been nanostructured with the addition of 1% wt (PP1N1 and PP2N1) and 2% wt (PP1N2) silica nanofiller [30].

The tested specimens consisted of press-molded slabs with a thickness of 0.4 mm (average value). All specimens were dried for 24h in a vacuum oven at 80°C before testing.

PDIV measurements were performed, both under AC and DC voltage, using three-layer specimens where the central layer had a punctured hole which could be varied in dimensions, i.e. radius and height. The latter variation was obtained changing the central layer.

Fig. 5 reports the results of $PDIV_{DC}$ to $PDIV_{AC}$ ratio for PP1 and PP2, as well as for the three nanofilled materials (PP1N1, PP1N2 and PP2N1), at 20 and 60°C, compared with the estimation from the model of (8) and (3). The defect had a radius of 3.5 mm and an average height of 400 μm.

As can be seen, there is a good fitting between model and experimental results, even if the experimental values of $PDIV_{DC}$ for PP1 and PP2N1 could not be obtained at 20°C (too high-test voltage). On the whole, it comes out clearly that materials having lower conductivity always feature a higher $PDIV_{DC}$ value (or $PDIV_{DC}/PDIV_{AC}$ ratio), even when the defect is significantly large. They can tend to the concept of ''PD-phobic'' materials. This holds also under full load, as long as the temperature coefficient, α, is low. However, when α is increased, the advantage of a very low reference conductivity (γ_0) is lost, and the $PDIV_{DC}$ drops considerably: see e.g. PP1N2. Specifically, the addition of nanofillers reduces both conductivity and the temperature coefficient, α, in PP2N1, which displays very large values of the ratio between $PDIV_{DC}$ and $PDIV_{AC}$ even at high temperatures. This material would, therefore, become an interesting candidate to manufacture PD-free cables, in DC steady state, even in the presence of significantly large defects.

V. CONCLUSIONS

Is there any chance to go towards long-time lasting organic electric insulation if operated without partial discharges? According to forensic evidence, HV cables and transformers designed in the '70 keep working after 40 years without any need for maintenance actions, due to thermal and electrical stresses lower than the ones considered in their design (perhaps smaller than threshold stresses). Both the presence of a threshold, and the likely change of the prevailing electrical degradation mechanism close to design field, will translate into a final design of an insulation system which is generally very conservative. Therefore, reducing or eliminating the impact of highly energetic phenomena, as PD, during operating life may bring to very significant extension of life of DC insulation systems compared to the present design criteria or, in other terms, allow DC insulation systems to withstand electrothermal stress for many decades.

According to the model presented in the paper, if insulation materials can be modified to reduce their conductivity at the design field and maximum operating temperature, steady-state partial discharge inception voltage becomes significantly higher than the nominal voltages practically reached even with UHVDC transmissions. The dependence of PDIV on defect size can be hampered though an appropriate choice of the insulating material properties, highlighting that working on material design and technology is a must to obtain a new generation of MV and HV DC insulation systems that display high reliability and design electric field. This fits to the trend towards high-specific power electrical apparatus, which is becoming common not only in HV or UHV, but also in MV, especially in electrified transport.

REFERENCES

[1] G. C. Montanari and P. Seri, ''HVDC and UHVDC polymeric cables: Feasibility and material development,'' *IEEE Elect. Insul. Mag.*, vol. 35, no. 5, pp. 28–35, Sep. 2019.

[2] Y. Zhou, S. Peng, J. Hu, and J. He, ''Polymeric insulation materials for HVDC cables: Development, challenges and future perspective,'' *IEEE Trans. Dielectrics Electr. Insul.*, vol. 24, no. 3, pp. 1308–1318, Jun. 2017.

[3] *Guide to the Conversion of Existing AC Lines to DC Operation*, Cigré Work. Group, Paris, France, 2014.

[4] B. Sander, J. Lundquist, I. Gutman, C. Neumann, B. Rusek, and K.-H. Weck, ''Conversion of AC multi-circuit lines to AC-DC hybrid lines with respect to the environmental impact,'' CIGRE, Paris, France, Tech. Rep. B2-105, 2014, pp. 1–12.

[5] R. W. De Doncker, ''Power electronic technologies for flexible DC distribution grids,'' in *Proc. Int. Power Electron. Conf. (IPEC-Hiroshima-ECCE ASIA)*, Hiroshima, Japan, May 2014, pp. 736–743.

[6] G. C. Montanari, ''The potential impact of flexible DC transmission and distribution on insulated cables: Accelerated aging and premature failure,'' in *Proc. IEEE PES Asia–Pacific Power Energy Eng. Conf. (APPEEC)*, Macao, Dec. 2019, pp. 1–4.

[7] G. C. Crichton, P. W. Karlsson, and A. Pedersen, ''Partial discharges in ellipsoidal and spheroidal voids,'' *IEEE Trans. Electr. Insul.*, vol. 24, no. 2, pp. 335–342, Apr. 1989.

[8] L.A. Dissado and J.C. Fothergill, *Electrical Degradation and Breakdown in Polymers*. Stevenage, U.K.: Peregrinus, 1992.

[9] M. Marzinotto and G. Mazzanti, ''The statistical enlargement law for HVDC cable lines part 2: Application to the enlargement over cable radius,'' *IEEE Trans. Dielectrics Electr. Insul.*, vol. 22, no. 1, pp. 202–210, Feb. 2015.

[10] *IEEE Guide for the Statistical Analysis of Electrical Insulation Breakdown Data*, IEEE Standard 930/ IEC 62539, 2007.

[11] G. C. Montanari and M. Cacciari, ''A probabilistic insulation life model for combined thermal-electrical srresses,'' *IEEE Trans. Electr. Insul.*, vol. EI-20, no. 3, pp. 519–522, Jun. 1985.

[12] M. Joseph, B. Lantz, D. Byrne, S. Ziegler, and R. Hummel, ''Can cables last 100 years?'' in *Proc. Jicable*, Versailles, France, 2019, pp. 1–4.

[13] K. M. Furuheim, ''Aging of oil impregnated insulation paper of subsea HV cables in decades of service,'' in *Proc. Jicable*, Versailles, France, 2019, pp. 1–4.

[14] G. Montanari, ''Electrical life threshold models for solid insulating materials subjected to electrical and multiple stresses. I. Investigation and comparison of life models,'' *IEEE Trans. Dielectr. Electr. Insul.*, vol. 27, no. 5, pp. 974–986, Oct. 1992.

[15] M. A. Miner, ''Cumulative damage in fatigue,'' *J. Appl. Mech.*, vol. 12, no. 3, pp. 159–164, 1945.

[16] *Transformers: Basics, Maintenance, and Diagnostics*, U.S. Dept. Interior Bur. Reclamation, Denver, CO, USA, Apr. 2005.

[17] J. J. O'Dwyer, *The Theory of Electrical Conduction and Breakdown in Solid Dielectrics*. Oxford, U.K.: Clarendon, 1973.

[18] G. C. Montanari, ''Aging and life models for insulation systems based on PD detection,'' *IEEE Trans. Dielectrics Electr. Insul.*, vol. 2, no. 4, pp. 667–675, Aug. 1995.

[19] *Guide for the Statistical Analysis of Electrical Insulation Breakdown Data*, Standard IEC 62539, 2007.

[20] G. C. Montanari, ''A contribution to unravel the mysteries of electrical aging under DC electrical stress: Where we are and where we would need to go,'' in *Proc. IEEE 2nd Int. Conf. Dielectrics (ICD)*, Budapest, Hungary, Jul. 2018, pp. 1–15.

[21] L. Niemeyer, ''A generalized approach to partial discharge modeling,'' *IEEE Trans. Dielectrics Electr. Insul.*, vol. 2, no. 4, pp. 510–528, Aug. 1995.

[22] G. C. Montanari, R. Hebner, P. Seri, and H. Naderiallaf, ''Partial discharge inception voltage and magnitude in polymeric cables under AC and DC voltage supply,'' in *Proc. Jicable*, Versailles, France, 2019, pp. 1–4.

[23] P. Seri, L. Cirioni, H. Naderiallaf, G. C. Montanari, R. Hebner, A. Gattozzi, and X. Feng, ''Partial discharge inception voltage in DC insulation systems: A comparison with AC voltage supply,'' in *Proc. IEEE Electr. Insul. Conf. (EIC)*, Calgary, AB, Canada, 2019, pp. 1–4.

[24] F. H. Kreuger, *Industrial High DC Voltage: 1. Fields 2. Breakdowns 3. Tests*, Delft, The Netherlands: Delft Univ. Press, 1995.

[25] P. H. F. Morshuis and J. J. Smit, ''Partial discharges at DC voltage: Their mechanism, detection and analysis,'' *IEEE Trans. Dielectrics Electr. Insul.*, vol. 12, no. 2, pp. 328–340, Apr. 2005.

[26] P. Seri, R. Ghosh, L. Cirioni, and G. C. Montanari, ''Partial discharge measurements of DC insulation systems: The influence of the energization transient,'' in *Proc. IEEE Conf. Electr. Insul. Dielectric Phenomena (CEIDP)*, Richland, WA, USA, Oct. 2019, pp. 1–4.

[27] A. Cavallini, D. Fabiani, G. Mazzanti, G. C. Montanari, and L. Simoni, "Life estimation of DC insulation systems in the presence of voltage-polarity inversions," in *Proc. Conf. Rec. IEEE Int. Symp. Electr. Insul.*, Anaheim, CA, USA, Apr. 2000, pp. 473–476.

[28] J. Jow and A. Mendelsohn, "High-voltage direct current cable insulation and semiconductive shield," U.S. Patent 6 924 435, Aug. 2, 2005.

[29] J. K. Nelson, W. Zenger, R. J. Keefe, and L. S. S. Feist, "Nanostructured dielectric composite materials," U.S. Patent 7 579 397, Aug. 25, 2009.

[30] G. C. Montanari, P. Seri, H. Naderiallaf, A. Blume, G. Perego, C. Mazel, M. Paajanen, and M. Karttunen, "Adding nanofillers in polymeric insulating materials: So far so good? The case of polypropylene for DC cables," in *Proc. IEEE Electr. Insul. Conf. (EIC)*, Calgary, AB, Canada, 2019, pp. 1–4.

[31] W. Nelson, *Accelerated testing. Statistical Models, Test Plans, and Data Analysis*. New York, NY, USA: Wiley, 1990.

[32] G. C. Montanari, P. Seri, R. Ghosh, and L. Cirioni, "Noise rejection and partial discharge source identification in insulation system under DC voltage supply," *IEEE Trans. Dielectrics Electr. Insul.*, vol. 26, no. 6, pp. 1894–1902, Dec. 2019.

[33] G. C. Montanari, D. Fabiani, P. Morshuis, and L. Dissado, "Why residual life estimation and maintenance strategies for electrical insulation systems have to rely upon condition monitoring," *IEEE Trans. Dielectrics Electr. Insul.*, vol. 23, no. 3, pp. 1375–1385, Jun. 2016.

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