Direct interaction between partial discharge and temperature on epoxies: phenomenological life models

INSTITUTE OF PHYSICS PUBLISHING JOURNAL OF PHYSICS D: APPLIED PHYSICS
J. Phys. D: Appl. Phys. **35** (2002) 33–39 PII: S0022-3727(02)23456-7

Direct interaction between partial discharge and temperature on epoxies: phenomenological life models

M Di Lorenzo del Casale and R Schifani

Università di Palermo, Dipartimento di Ingegneria Elettrica, Viale delle Scienze, 90128 Palermo, Italy

Received 29 March 2001, in final form 11 June 2001
Published 11 December 2001
Online at stacks.iop.org/JPhysD/35/33

Abstract
In this paper the final results of basic research regarding the ageing process of insulations due to partial discharge (PD) activity under different thermal conditions are reported. According to the IEC publication 792-1 (IEC 1985 *IEC Report Publication* 792-1), the effects of a direct interaction between PD and temperature on material performance has been studied. We used, a simple electrode system with a flat cavity and an epoxy resin widely employed in high-voltage insulation apparatus to perform lifetime tests.

On the basis of a previously performed analysis of the ageing mechanisms taking place in different materials, simple phenomenological life models are proposed in this work, giving a new approach to the problem that appears to be a useful tool for future application on electrical components. For this purpose, first the interaction between the temperature and PD was modelled, then a suitable PD quantity, depending on the energy wasted in the specimen during the ageing, was chosen to be assumed as a stress function in the inverse power law.

1. Introduction

Users and manufacturers of electrical power equipment are showing increasing interest in multi-factor functional testing of the related insulation systems in order to validate the assessment of their service performance. Indeed, there is not much literature concerning this subject so that many researchers have concentrated their best efforts to study the dielectric ageing phenomena on elementary insulation systems under multistress conditions in accelerated ageing tests [1–5]. It should be emphasized that the degree of insulation deterioration is actually dependent on the applied stress factors or factors of influence (voltage, temperature, mechanical and so on) and on their interaction as well, that could in principle accelerate or slow down the ageing rate due to the nonlinear phenomena involved with respect to a single applied stress. This matter is widely emphasized in the IEC publication 792-1 [1] in terms of 'the realistic modelling of service aging in a functional test, and the concern that tests be as simple and practical as possible'.

The ageing of insulating materials due to electrical field and thermal multistress has been extensively studied and modelled [6–9], but when a defect is present then partial discharge (PD) inception generally increases the degradation rate. In this case, even if the PD phenomenon can be considered as an affect of the applied electric field (primary stress), the temperature was found to assume the function of an indirect ageing factor mostly in changing the PD activity [10–14]. Furthermore, when an epoxy material is considered, a thermal stress which is lower than its material glass transition temperature should be considered for practical purposes, in order to keep its mechanical consistency as requested in service conditions. Actually, the latter may be a working state for many similar insulations employed in electrical machine manufacture, where PDs can be found during the service life.

Studies on PDs have been generally approached by means of digital measurement systems [15–17], mainly in order to post-process the data acquired. Making use of these new technologies, it was recently evidenced that PD ageing mechanisms in epoxy resins as well as their related degradation effects in a simple dielectric configuration test, radically change at temperatures higher than the ambient [18, 19]. Taking into account this basic concept, the main purpose of

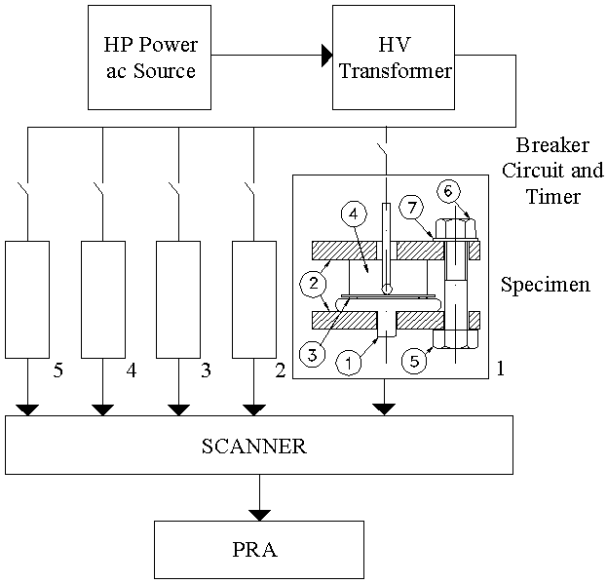

Figure 1. Specimen and HV test circuit. Cigrè Method II test cell: 1, plane electrode; 2, acrilic plate, 3, kapton spacer; 4, moulded sphere electrode with a specimen; 5, polycarbonate bolt; 6, polycarbonate nut; 7, nylon washer.

this paper has been to define a life modelling procedure that can lead to an estimate of the material lifetime in laboratory controlled test conditions that are as simple and practical as possible. This goal has been pursued by observing the variation of PD related quantities by making use of digital measurement techniques. The first step was to study and model the interaction between temperature and PD activity, in order to give an in-depth description of the model formulation that is in agreement with the inverse power law, e.g. a generally used mathematical function that relates 'a function S of the applied stress and the lifetime D (here expressed in hours) of the material'

$$D = \frac{k}{S^n} \tag{1}$$

where k and n are constants that depend on the particular material under test.

Following the idea that all degradation phenomena are always linked to the wasted energy, a model has been produced by assuming the energy dissipated inside the specimen under test to be a primary stress function, contrary to the case where the applied voltage V (V) is assumed in the same role.

Obviously, the results here reported cannot be extrapolated directly to complex insulating systems, where the PD process and its interaction with temperature can be different from the one found here, but we think that they could be considered as a useful and necessary starting point for future research work exploring epoxy-based electrical apparatus when, for mechanical purposes, a high material glass transition temperature T_g is requested.

2. Specimens and experimental testing procedure

A Bakelite bisphenolic epoxy resin: EA 920KA/EA 920KB, generally used for impregnation processes in electrical machine manufacture, has been used in this research. This epoxy resin has its glass transition temperature in the range between 120 °C and 140 °C [20]. The employed test cell assembly was a CIGRE specimen holder (Method II) depicted in figure 1 together with a sketch of the high-voltage (HV) testing circuit (following IEC Standard No 270, 1981). The test cell reproduces a sphere–plane electrode configuration, including in the middle, an air-filled flat cavity. Therefore, it has to be pointed out that the original air gap thickness of the CIGRE was modified by 0.250 mm to have mainly a pulsive discharge activity during all the life tests that, indeed, can be detected by conventional pulse detectors as shown in [12]. Furthermore, the testing system allows the ageing of more specimens in parallel. Each specimen was connected to the test voltage by a mechanical connection that, externally triggered by an electronic protection, opens the broken-down specimen branch without interrupting the test for the remaining specimens. The HV test system is computer controlled, which also saves the times-to-breakdown value of each specimen. To obtain the different testing temperatures, the test cell was immersed in a silicon oil bath, wherein the temperature was regulated by means of a controller together with a PT100 thermoresistance. A uniform temperature distribution inside the oil bath was ensured by an external pump arrangement.

The testing procedure was based assuming the specimen time-to-breakdown under 50 Hz sinusoidal voltage, V, of 30 kV, 24 kV and 20 kV as end point criteria. Furthermore, for each voltage amplitude, three temperatures T were applied, e.g. 30 °C, 55 °C and 80 °C, thus giving nine test conditions for various combinations of the above thermal and electrical stresses. The choice of the above stress levels was due to a compromise between the operating times of a research laboratory. PD digital measurements were performed by an instrument that works as a statistical discharge phase analyser with the aid of an external personal computer [16]. Discharge pulses, appearing on the measuring RLC impedance (180 kHz resonance frequency), were first filtered to remove any power frequency component, then they were amplified by a wide-band three-stage amplifier (30–800 kHz). The amplification factor was adjusted to provide the wanted dynamic range, with a maximum sensitivity of 1 pC. At the end of the acquisition phase, all the data were saved in compressed files.

The study proposed in this paper is based on the periodical acquisition of the pulse discharge amplitude, e.g. the external apparent charge $q(i)$, of their inception phase angle $\varphi(i)$ and of the instantaneous test voltage value, for an acquisition time (Δt) equal to 10 s. Therefore, several quantities could be evaluated off-line from the above PD data by means of a physical and statistical analysis software developed in the laboratory.

3. Temperature effects on PD ageing

A plot of the mean times-to-breakdown obtained as the arithmetic mean of the values of seven samples tested under the same conditions is presented in figure 2 [5]. The obtained experimental time-to-breakdown values present a standard deviation, σ%, with respect to their mean value in the range of 10–30%. It is possible to observe a tendency of the lifetime to increase with increasing applied temperature under the same voltage, as was already observed for other different epoxy

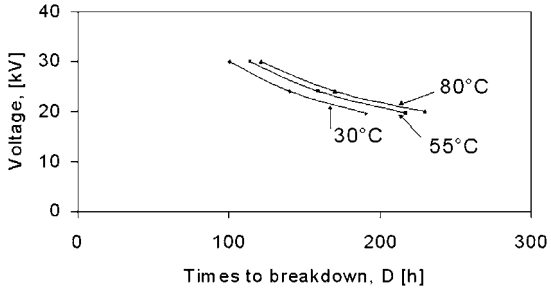

Figure 2. Voltage versus time-to-breakdown at constant temperatures.

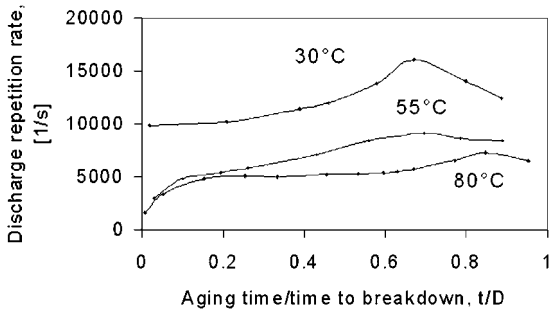

Figure 3. Discharge repetition rate against the ratio between time t and time-to-breakdown D at the inspected temperatures under 30 kV.

resin systems [11, 21], but with a different geometric test cell assembly. This stressed the idea of the characteristic performance of such epoxy materials. Therefore, it could be inferred that under PD stress, the application of temperatures higher than the ambient and lower than a fraction of the related T_g (°C), appears not to be detrimental conditions for the material's lifetime. This could probably be explained with a major epoxy softening, that reduces the related erosion action of the PD charges impinging on the epoxy surface [21]. In contrast, the use of a temperature higher than the above fraction of T_g would reverse this tendency because the resin becomes less homogeneous and loses its mechanical characteristics, especially in the proximity of its glass transition temperature. Actually, in [11, 19] it was experimentally demonstrated for different epoxy materials used in a CIGRE I test configuration, that a maximum exists for the lifetimes when the ratio between the testing temperature T (°C) and the material glass transition temperature T_g is around 0.70–0.80, thus letting us believe that a parabolic dependence between the applied voltage and T/T_g may be inferred. In this experimental work, the temperature inspected was set in the 0.2–0.65 range of T/T_g.

The off-line analysis of the acquired PD data let us obtain some information regarding the ageing processes that take place in the resin. The most evident temperature effect was a decrease of the discharge repetition rate, figure 3, and an increase of PD amplitudes, as shown in figure 4. A very similar temperature effect on PD behaviour has already been observed, in an increasingly evident way, in another cavity geometry, in particular an epoxy embedded spherical void under a uniform electric field [22]. This peculiarity was ascribed to an increase of the material work function with temperature, and it could probably be generalized for epoxy materials. For a flat cavity, the time evolution of PD activity with temperature is shown in

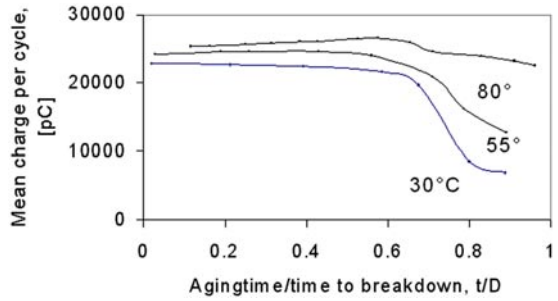

Figure 4. Mean negative charge per cycle against t/D at the inspected temperatures under 30 kV.

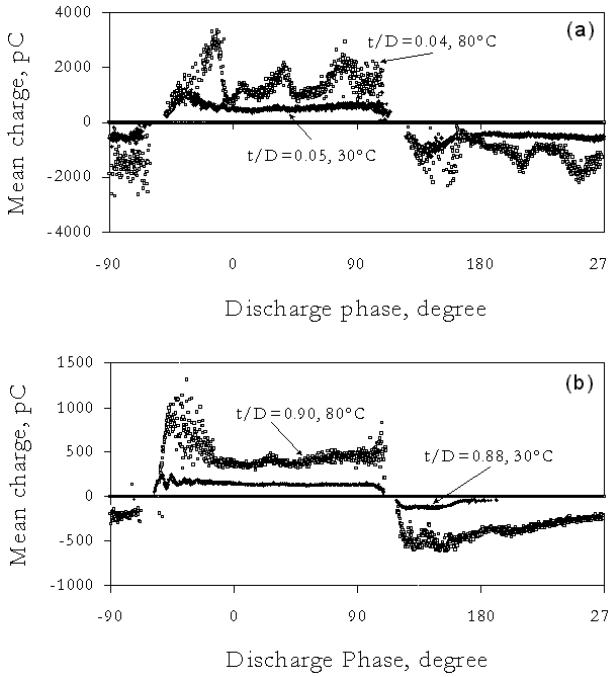

Figure 5. Charge phase distribution, $H_{qm}(\varphi)$, at various temperatures and for various t/D values.

figure 5 in terms of mean charge-phase distribution $H_{qm}(\varphi)$. Near the breakdown, it is possible to observe a negative charge reduction, that is more evident at 30 °C, and a resin surface effect could be claimed in this phenomenon [23].

Another parameter studied was the net energy consumed in the specimen due to discharge activity. The energy fed from the source to the specimen with an apparent discharge pulse $q(k)$ occurring at time $t(k)$ of the applied voltage $v(k)$, derives from the relation

$$e_i(k) = v(k)q(k). \tag{2}$$

This apparent energy can be positive or negative, e.g. energy can go from the source to the specimen or *vice versa*, while that wasted inside the specimen is always positive. Furthermore, considering the net value of the energy fed from the source to the specimen W_i during the acquisition time Δt, it is possible to write for all the related n discharges

$$W_i = \sum_{k=1}^{n} e_i(k) = \sum_{k=1}^{n} v(k)q(k). \tag{3}$$

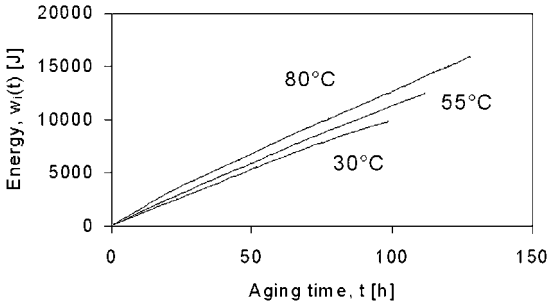

Figure 6. Energy function $w_i(t)$ versus the ageing time t under 30 kV sinusoidal voltage (50 Hz), at testing temperatures of 30 °C, 55 °C and 80 °C.

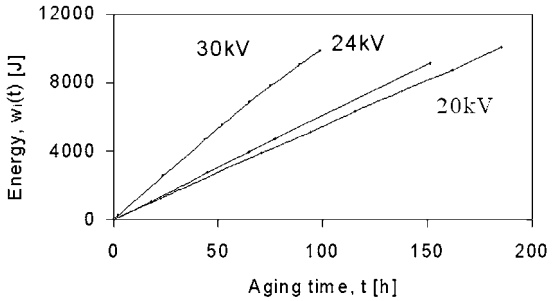

Figure 7. Energy function $w_i(t)$ versus the ageing time t under 30 kV, 24 kV and 20 kV sinusoidal voltage (50 Hz) at 30 °C constant temperature.

After that, the energy W_i was evaluated and divided by Δt, then we get the mean discharge power dissipated P_m during the same time. In this experimental work, as already observed, the PD activity goes only with small changes during the first 70–80% of the specimen life. Afterwards a decrease in discharge number of negative polarity occurred until breakdown. This fact produced an almost constant performance of P_m during a life test. Therefore, integrating P_m versus t in agreement with the following

$$w_i(0,t) = w(t) = \int_0^t P_m \, \mathrm{d}t \tag{4}$$

and assuming the starting time of the test as 0, the energy $w(t)$ was numerically evaluated as a function of the ageing time t. In figure 6 a typical behaviour of $w_i(t)$ until the breakdown is shown for the inspected temperatures and at 30 kV, while in figure 7 a similar plot is shown, but performed at constant temperature and varying the voltage. The first obvious remark we can put forward, is that this energy function can be numerically considered as almost linear with time:

$$w_i(t) = mt \tag{5}$$

this should imply that it is a zero crossing straight line, then characterizable by a constant angular coefficient m (or power coefficient) which has the dimension of watt. The second remark regards the stochastic nature of m (having a different value for each tested specimen under the same conditions) and the increasing value trend with temperature together with the related times to breakdown, when the applied voltage is constant.

Table 1. Average power coefficient at different voltage and temperatures.

V (kV)	T (°C)	m (W)	σ (%)
20	30	52.3	4.0
	55	58.5	6.1
	80	61.3	7.4
24	30	63.2	4.2
	55	68.8	6.5
	80	69.3	8.1
30	30	82.42	8.6
	55	94.67	9.7
	80	95.40	12.7

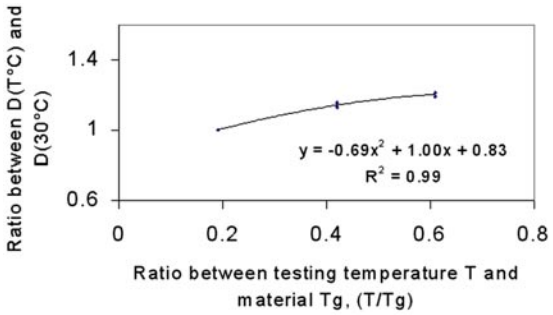

Figure 8. The ratio of the mean lifetime at temperature T (°C) and the corresponding value obtained at 30 °C, $D(T)/D(30)$, versus T/T_g for all the voltage values used in the experiment.

A synthesis of the m values found is shown in table 1, where the arithmetic mean value (performed on seven specimens tested under the same conditions) and the related standard deviation coefficient $\sigma\%$ are reported.

4. Modelling temperature effects on PD activity

To model the material life performance, varying the applied voltage and temperature as previously outlined, a suitable function S of the stresses imposed on the material must be chosen. In particular, we must take into account by S of either the effect of PD and the indirect effect of temperature T. Furthermore, this should be performed by a mathematical formulation that returns S equivalent values able to reproduce lifetimes D in agreement with equation (1); e.g. when S increases, D should decrease. Therefore, for modelling purposes, the first step consists of identifying the primary stress for the material that may be directly linked to the presence of PD, e.g. the applied voltage V or the angular coefficient m. Then the temperature effect can be quantified by a suitable mathematical function of the testing value T, and of the material glass transition temperature of the epoxy under test, T_g, that is, in other words, of the ratio T/T_g. The data of figure 2 are presented in such a way in figure 8 for every voltage used as the ratio between the mean lifetime at T (°C), and the corresponding lifetime at 30 °C, against T/T_g. Then we see that while in figure 2 a distinction can be put forward between the temperature, applied voltage and lifetime, now all the data are dependent only on T and leave the voltage appearing as an invariant parameter. The resulting curve can be fitted by the following parabolic function in order to consider the decreasing

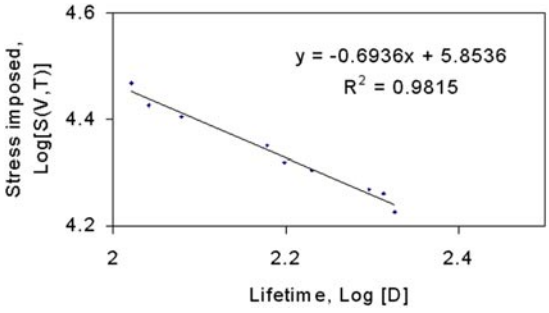

Figure 9. Function $S = V/C(T/T_g)$ of the stress imposed versus time-to-breakdown.

life trend above 0.7–0.8 of T_g:

$$C\left(\frac{T}{T_g}\right) = \frac{D(T)}{D(30)} = k_1\left(\frac{T}{T_g}\right)^2 + k_2\left(\frac{T}{T_g}\right) + k_3$$
$$= -0.69\left(\frac{T}{T_g}\right)^2 + 1.00\left(\frac{T}{T_g}\right) + 0.83 \qquad (6)$$

where, k_1, k_2 and k_3 are parameters depending on the epoxy material under test, and are obtained by a linear regression method with an R^2 factor of correlation equal to 0.99.

5. Experimental life data modelling

5.1. Voltage stress

If a function of the equivalent stress imposed on the material is proposed here as $S(V, T) = V/C(T/T_g)$ with physical dimensions of volts, and plotted versus the times-to-breakdown in figure 9, then it is possible to see that all the data are now well approximated by a straight line in a log–log plot, where the y-axis stands for $\log[S(V, T)]$ and the x-axis for $\log[D]$ with D expressed in hours. The validity of the 'inverse power law' can be inferred [24] and applying the linear regression techniques, the following numerical model was obtained with a R^2 factor of correlation equal to 0.98

$$D = k\left(\frac{V}{k_1(T/T_g)^2 + k_2(T/T_g) + k_3}\right)^{-n} = 2.72E + 8S^{-1.44}. \qquad (7)$$

Therefore, it could be pointed out that the 'inverse power model', most widely employed for single stress [25], can be applied in the multi-stress ageing studied here, by choosing a suitable function of the stress imposed, but the constants to be experimentally determined now become five, e.g. k, k_1, k_2, k_3 and n. In particular, three life tests must be performed at three temperatures to isolate the parabolic dependence of the lifetimes upon temperature, that is k_1, k_2, k_3. Finally, the other two life tests require the evaluation of k and n. Indeed, it has to be pointed out that the n values are a little lower than the usual values encountered in the literature. This fact may be the result of the exponential form of the chosen function of the voltage (e.g. the ratio of V with $C(T/T)$), while usually only the V value is used.

The deterministic model proposed above cannot satisfactorily describe the ageing behaviour of insulation systems, because it is actually characterized by a random nature of the lifetime D. Therefore, assuming that the epoxy lifetimes under constant stress follow a Weibull distribution, a statistical life modelling approach can be usefully investigated [3].

Table 2. Weibull parameters of the lifetimes for each stress level.

$S(V, T)$ (V)	α (h)	β	CVM
20 000	199	1.95	0.0216
17 182	204	1.98	0.0233
16 353	210	2.05	0.0230
24 000	150	1.97	0.0194
20 619	168	2.02	0.0227
19 624	192	2.15	0.0318
30 000	106	1.98	0.0152
25 773	127	2.12	0.0386
24 530	130	2.19	0.0165

The epoxy resin lifetimes can be described by the Weibull distribution function $F(t; S(V, T))$ under constant stress $S(V, T)$

$$F(t; S(V, T)) = 1 - \exp\left[-\left(\frac{t}{\alpha}\right)^{\beta}\right] \qquad (8)$$

where t is the time to failure, α and β are the scale and shape parameters of the Weibull function, both depending on the stress. The scale parameter is defined as the failure time for a probability of 63.2%, indeed this represents the time at which $F(\alpha) = 1 - (1/e) = 0.6321$. Therefore, the expression of α can be given by the model considered above, and from equations (1) and (8), it follows that

$$F(D, S(V, T)) = 1 - \exp[-k^{-\beta}D^{\beta}S(V, T)^{n\beta}] \qquad (9)$$

which represents the probability distribution for both the failure times at fixed stress, and the electrical equivalent stresses at constant time [26].

A rough estimate of β can be obtained by evaluating the shape parameter of the Weibull distribution for the times to breakdown obtained for constant values of $S(V, T)$. In table 2 they are reported together with the results of the related Cramer von Mises (CVM) test, that gives an index of the validity of the Weibull data fitting [27]. As can be observed, the values of β at different stress levels are very similar. Therefore, on the basis of this result and considering that the same PD ageing phenomenon was always observed at different voltage levels and as reported in the literature [3, 26], the hypothesis of assuming β constant and equal to the mean of the values obtained at different stress levels (e.g. $\beta = 2$) could be acceptable. Furthermore, for a fixed probability $F(D; S)$ to the time-to-failure D and for a given value of the stress function, from a mathematical point of view the life model could be written as follows

$$D = \left(\frac{\ln(1 - F(D, S))}{-k^{-\beta}S(V, T)^{n\beta}}\right)^{1/\beta} \qquad (10)$$

and substituting in equation (10) the values reported in (7), the result is

$$D = \left(\frac{\ln(1 - F(D, S))}{-10.07E - 18S(V, T)^{2.9}}\right)^{1/2}. \qquad (11)$$

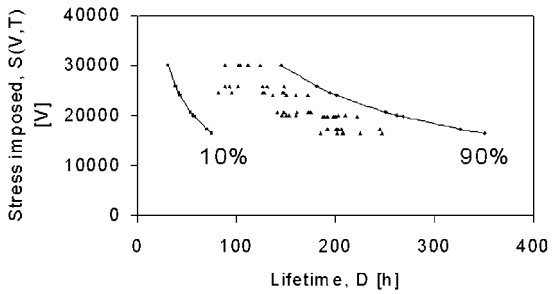

Figure 10. Experimental data and electrical life curves at 10% and 90% failure probability.

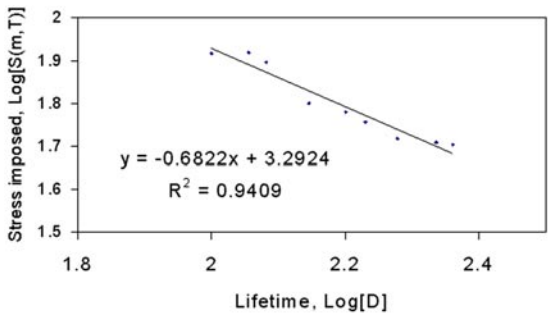

Figure 11. Function $S = m/C(T/T_g)$ of the stress imposed versus time-to-breakdown.

The experimental data and the electrical life curves at a failure time probability of 10% and 90% are shown in figure 10 and it is possible to observe that they include all the data obtained here. Obviously, the parameters present equation (10) are experimentally evaluated as for (7).

5.2. Energy stress

Following the idea that all the degradation phenomena are always related to wasted energy, a model has been produced by assuming the primary stress to be the energy dissipated inside the specimen under test. The PD energy function in section 3 was represented by the power coefficient m that can be considered as a stochastic quantity related to PD activity. Therefore, following the same modelling approach as used before, the stress function could now be defined as

$$S(m, T) = \frac{m}{C(T/T_g)}. \tag{12}$$

Obviously, the dimension of S is now watts, with $C(T/T_g)$ having no physical dimension. The first difference that appears with respect to the previous assumption of $S(V, T)$ as the stress function is that now we have a different value of $S(m, T)$ associated with each specimen tested under the same external conditions of V and T. However, reporting the mean values versus the related times-to-breakdown in a log–log plot, the data are well fitted by a straight line, as shown in figure 11. Again the inverse power model validity can be inferred when an epoxy material is subjected to PD and temperature. Applying linear regression techniques, the following numerical model was obtained, with an R^2 value equal to 0.94

$$D = 67.1E + 3S^{-1.46}. \tag{13}$$

Table 3. Weibull parameters found for each stress range.

Stress $S(m, T)$ (W)	α (h)	β	CVM
$41.9 \leqslant S(m, T) \leqslant 52$	204	1.84	0.0221
$53.3 \leqslant S(m, T) \leqslant 59.7$	197	1.90	0.0293
$60.1 \leqslant S(m, T) \leqslant 68.9$	150	1.96	0.0302
$69 \leqslant S(m, T) \leqslant 104.1$	109	2.14	0.0409

The statistical validation of the model described above, in which two stochastic quantities are present (the lifetime D and the stress function S of the PD energy), was performed by means of a Weibull analysis. Therefore, if we consider all the $S(m, T)$ values found in the experiment and we arrange them in (for example) four subfamilies following a decreasing order value, then the related experimental lifetime data were fitted by a Weibull function of which the scale parameter α and the shape parameter β were evaluated together with the CVM test data and shown in table 3. As can be seen, the α parameter, e.g., the lifetime at the probability of 63.2%, increases when the values of stress $S(m, T)$ decrease. Therefore, the results of the Weibull analysis are in agreement with those previously obtained by the life model based on the inverse power law.

6. Conclusions

The present work introduces an experimental approach to obtain phenomenological and statistical life models based on the inverse power law, which have been defined and discussed in this paper. The main goal was to describe the life behaviour of epoxy resin systems subjected to partial discharge activity under thermal conditions which were higher than the ambient temperature but lower than the material glass transition temperature. Furthermore, their soundness was supported by a validation procedure. In the case examined, even if PD phenomenon could be considered as an effect of the applied electric field, the temperature was found to assume the function of an indirect factor of ageing which attributed mostly to changing the PD activity.

The basic modelling concept was to choose a suitable quantity to be assumed as the stress function and that was most indicative of the real working conditions for the materials. After modelling the interaction between the temperature and PD activity, then the ratio of the applied voltage or of a function of the energy wasted inside the insulation as a consequence of PD to a function of the material glass transition temperature was assumed as the stress function.

Finally, the main conclusions can be stressed as follows.

For the divergent electric field configuration here employed, the PD characteristic pattern before the breakdown has been identified and the decreasing trend of the negative discharges can be assumed as an indicator of the incoming breakdown.

The energy consumed in the specimen for PD has been recognized as a stochastic quantity that has an almost linear trend with ageing time and that fruitfully can be used for modelling purposes. The major feature of this model is that it provides a means of connecting the physics and statistics of the breakdown process.

Obviously, the results reported here cannot be extrapolated directly to complex insulating systems, but we think they could

be considered as a useful and necessary starting point for future research work to be explored in epoxy embedded electrical components.

Acknowledgments

The present work was financially supported by MURST. Thanks are also due to Bakelite Gmbh for having supplied the epoxy resin tested here and to DuPont, Luxemborg, for the Kapton sample sheets.

References

[1] IEC 1985 The multi-factor functional testing of electrical insulation systems *IEC Report Publication* 792-1

[2] Schifani R and Gagliardo V 1995 Partial discharge patterns and aging phenomena at different temperatures in filled and unfilled epoxy, by a modified Cigrè setup, Method I *Proc. ICSD'95 (Leicester, UK, 10–13 July 1995)* pp 329–3

[3] Montanari G C 1995 Aging and life models for insulation systems based on PD detection *IEEE Trans. Dielectr. Electr. Insulat.* **2** 667–75

[4] Simoni L, Mazzanti G, Montanari G C and Lefebre L 1993 A general multi-stress life model for insulating materials with or without evidence of threshold *IEEE Trans. Dielectr. Electr. Insulat.* **28** 349–64

[5] Di Lorenzo del Casale M, Romano P and Schifani R 2000 A life model for epoxy resins subjected to PD activity at different temperature *Proc. IEEE Conf. on Electrical Insulation and Dielectric Phenomena (Victoria, 15–18 October 2000)* pp 564–7

[6] Simoni L 1984 General equation of the decline in the electric strength for combined electrical and thermal stresses *IEEE Trans. Electr. Insulat.* **19** 45–52

[7] Ramu T S 1985 On the estimation of life of power apparatus insulation under combined electrical and thermal stress *IEEE Trans. Electr. Insulat.* **20** 70–8

[8] Fallou B, Burguire C and Morel J F 1979 First approach on multiple stress accelerated life testing on electrical insulation *CEIDP Annual Report* pp 621–8

[9] Crine J P, Parpal J L and Lessard G 1989 A model of aging of dielectric extruded cables *Proc. IEEE Int. Conf. on Conduction and Breakdown in Solid Dielectrics (Trondheim, Norway, July 1989)* pp 347–51

[10] Di Lorenzo del Casale M and Schifani R 2000 Investigation of temperature effect on an epoxy resin: aging due to partial discharges *Proc. IEE 8th Int. Conf. on Dielectric Materials, Measurements and Applications (Edinburgh, 17–21 September 2000)* pp 509–12

[11] Schifani R 1995 Temperature dependence of epoxy resistance to PD *IEEE Trans. Dielectr. Electr. Insulat.* **2** 653–9

[12] Di Lorenzo del Casale M, Mirelli G and Schifani R 1999 On PD insulation ageing under electrical and thermal multistress in Cigrè's method II: a methodologic approach *Proc. NORD-IS99 (Copenhagen, 14–16 June 1999)* pp 149–56

[13] Schifani R 1989 On a model for the comparative analysis of the ageing characteristics of epoxy resins subjected to internal discharges at various environmental temperatures *Proc. 3rd Int. Conf. on Conduction and Breakdown in Solid Dielectrics (Trondheim, Norway, 3–6 July 1989)* pp 456–60

[14] Gjaerde A C 1997 A phenomenological aging model for combined thermal and electrical stress *IEEE Trans. Dielectr. Electr. Insulat.* **2** 674–80

[15] Gulski E and Kreuger F H 1992 Computer-aided recognition of discharge sources *IEEE Trans. Electr. Insulat.* **27** 82–92

[16] Schifani R and Mirelli G 1998 A computer-aided instrument for pattern recognition of partial discharges *Proc. 9th Int. Symp. on Theoretical Electrical Engineering (Palermo, Italy, 9–11 June 1997) COMPEL* **17** 765–72

[17] Capponi G and Schifani R 1992 On partial discharge measurements in solid dielectrics by an automated system *IEEE Trans. Dielectr. Electr. Insulat.* **27** 106–13

[18] Di Lorenzo Del Casale M, Holbøll J T and Schifani R 2000 Partial discharge activity tests at different temperatures measured by Cigrè method II *IEEE Trans. Dielectr. Electr. Insulat.* **7** 133–40

[19] Di Lorenzo Del Casale M 2001 On multistress aging of epoxy resins, PD and temperature *IEEE Trans. Dielectr. Electr. Insulat.* **8** 299–303

[20] Di Lorenzo Del Casale M and Schifani R 2000 Investigation of temperature effect on an epoxy resin: aging due to partial discharges *Proc. IEE Int. Conf. on Dielectric Materials Measurements and Applications (DMMA 2000) (Edinburgh, 17–21 September 2000)* pp 509–12

[21] Gjaerde A C 1994 Multi factor aging of epoxy: the combined effect of temperature and partial discharges *PhD Thesis* Trondheim University, Norwegian Institute of Technology

[22] Schifani R, Romano P and Candela R 2001 On partial discharge mechanisms at high temperature in voids included inside an epoxy resin *IEEE Trans. Dielectr. Electr. Insulat.* **8**

[23] Hudon C and Bartnikas R 1990 Surface conductivity of epoxy specimens subjected to partial discharges *Proc. IEEE Int. Symp. on Electrical Insulation (Toronto, Canada, 3–6 June 1990)* pp 153–5

[24] IEEE 1987 *Guide for Statistical Analysis of Electrical Insulation Voltage Endurance Data* ANSI/IEEE Standard **930**

[25] Stone G C 1993 The statistics of aging models and practical reality *IEEE Trans. Dielectr. Electr. Insulat.* **28** 716–28

[26] Dissado L A and Fothergill J C 1984 *Electrical Degradation and Breakdown in Polymers* (London: Peregrinus)

[27] Lawless J F 1982 *Statistical Models and Methods for Lifetime Data* (New York: Wiley)