# Partial Empirical Model of the Multifactor Aging of High Voltage Insulation

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## INTRODUCTION

Aging of high voltage (HV) polymeric insulation has been studied extensively for several decades. The exposure of insulating materials to electric fields, impact of mechanical and thermal stress, chemical processes, and other factors result in deterioration of physical characteristics of insulation with time. This inevitably leads to the breakdown of insulation [1]. Estimation of lifetime of electric insulation is quite straightforward for cases when the multifactor aging rate of insulation is equal to the sum of aging rates of the insulating material under influence of each factor. However, experimental evidence shows that multifactor aging rate is often significantly higher then the sum of individual rates [2].

The experimental measurements of aging rate are much easier to perform when influence of each factor is studied separately. The task of transition from such experimental data to the estimation of lifetime of multistressed electric insulation is addressed here. The partial empirical model of multifactor aging proposed here assumes that the interdependence of the aging factors is constant during all operation time.

## BACKGROUND

Electric strength of material is one of major characteristics of high voltage insulation, and it can be used as a measure of

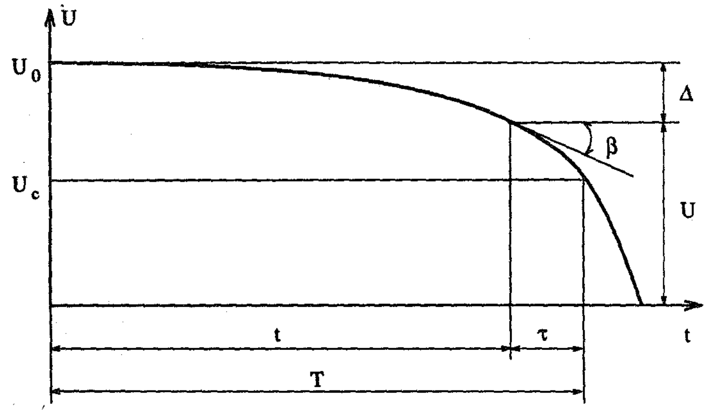


Figure 1: Curve of degradation of insulation under the influence of one factor.

aging. The electric strength of insulation at any moment of time $t$ can be characterized by its breakdown voltage $U = U(t)$ or by its depth of degradation

$$\Delta = U_0 - U, \tag{1}$$

where $U_0 = U_{t=0}$ is an initial electric strength of the material, and $t$ can be considered age of insulation. Then, using Figure 1, rate of degradation $\nu$ can be found as

$$\nu = \frac{d\Delta}{dt} = -\frac{dU}{dt} = \tan\beta. \tag{2}$$

Using this notation, electric strength can be expressed as

$$U = U_0 - \int_0^t \nu \, dt. \tag{3}$$

In Figure 1 the expected remaining life is $\tau = T - t$ , where $T$ is the evaluated lifetime of insulation from the start of operation to the point when electric strength $U$ is lower then the critical electric strength $U_c$. For $N$ factors acting simultaneously but assumed to be independent, the combined rate of degradation is a sum of individual factor rates:

$$\nu = \sum_{i=1}^{N} \nu_i. \tag{4}$$

Determination of $\nu_i$ in (4) is complicated due to interdependence of the aging factors. Usually, such interdependence accelerates the rate of degradation. For example, lamination due to periodic deformation of thermoreactive insulation intensifies processes of partial discharges and their destructive effects.

COMBINED RATES OF DEGRADATION

Theoretically, influence of each factor on the rate of degradation can be independent, in which case, each component in (4) is minimal and equal to a single-factor rate of degradation for this factor $\nu_{i\,min}$. The combined rate of degradation would be minimal in this case:

$$\nu_{min} = \sum_{i=1}^{N} \nu_{i\,min}. \qquad (5)$$

Analysis of the fastest degradation processes allows to extract maximal value of the rate of degradation $\nu_{i\,max}$ for each component. This value will correspond to the case of maximal interdependence of the $i$-th factor with the rest $N-1$ factors. The maximal possible combined rate of degradation will the be represented as

$$\nu_{max} = \sum_{i=1}^{N} \nu_{i\,max}. \qquad (6)$$

In general, $\nu_i$ consists of the two parts: the part $\alpha i$ of $\nu_{i\,max}$, which depends on the degree of interdependence of the $i$-th factor with other factors and the part $(1-\alpha_i)$ of $\nu_{i\,min}$. Then, for $i$-th component

$$\nu_i = \alpha_i \nu_{i\,max} + (1-\alpha_i)\nu_{i\,min}, \qquad (7)$$

where $0 < \alpha_i \leq 1$. The parameter $\alpha_i$ is equal to 0 if the factors are independent, and equal to 1 if the interdependence of the factors is maximal.

EVALUATION FORMULAS

The process of decreasing of the electric strength of insulation under the influence of one aging factor can be approximated with (8) [3].

$$U_i = U_0(1 - t/T_i)^{1/n_i}, \qquad (8)$$

where $n_i$ and $T_i$ are empirical constants. For such approximation, it is sufficient to find $U_0$ and two values of the breakdown voltage $U_i'$ and $U_i''$ corresponding to the two exposure times of the insulation to the $i$-th aging factor $t_1$ and $t_2$, accordingly. Then,

$$n_i = \ln(1 - t_1/T_i)/\ln(U_i'/U_0), \tag{9}$$

and the value of $T_i$ can be found from a solution of a transcendental function in (10) under the condition that $F(T_i) = 1$.

$$F(T_i) = \frac{\ln(U_i'/U_0)}{\ln(U_i''/U_0)} \cdot \frac{\ln(1 - t_2/T_i)}{\ln(1 - t_1/T_i)}. \tag{10}$$

Differentiation of (8) produces:

$$\nu_{i\,min} = -\frac{U_0}{n_i \tau i}(1 - t/T_i)^{-1+1/n_i} = -\frac{U_0^{n_i}}{n_i \tau_i} U_i^{1-n_i}, \tag{11}$$

where $U_i$ is an estimated electric strength in the moment of time $t$ when only the $i$-th factor is present.

Knowledge of time functions $U_i = f(t)$ (as shown in Figure 2) for each factor allows to determine corresponding values of $\Delta_i, \tau_i$, and $\nu_i$ for each moment of time (see Figure 2a).

If the aging factors are independent, then

$$\Delta(t) = \sum_{i=1}^{N} \Delta_i(t), \tag{12}$$

which allows to find the expected remaining life from the following equation:

$$U_0 - \Delta(t) = \sum_{i=1}^{N} \int_t^{\tau} \nu_i dt. \tag{13}$$

The equation (13) must be solved using numerical techniques.

The rate of degradation $\nu_i$ under the conditions of maximal interdependence of the aging factors is defined by actual electric strength $U$ (see Figure 2b). Then, maximal rate of degradation can be found from (11) by substituting the evaluated breakdown voltage $U_i$ with the actual breakdown voltage $U$ at a given moment of time. This is equivalent to the transition from the point

A of the real time $t$ to the point B of evaluated time $t_e$. Since $t_e > t$, this transition results in the additional depth of aging $\Delta_i'$ and increased value of $\beta_i(t)$.

For a general case of multifactor aging of insulation, the combined rate of aging can be derived from (4), (7), and (11), and it is described by (14).

$$\nu = \sum_{i=1}^{N}\Big[\frac{(1-\alpha_i)U_0}{n_i T_i}\Big(1-\frac{t}{T_i}\Big)^{\frac{1-n_i}{n_i}} + \frac{\alpha_i U_0^{n_i}}{n_i T_i}U^{1-n_i}\Big], \qquad (14)$$

in which coefficients $\alpha_i$ can be determined experimentally. Integration of (14) by time yields expression for the breakdown voltage for each moment of time $t$:

$$U = U_0 - U_0\int_0^t \sum_{i=1}^{N}\Big[\frac{(1-\alpha_i)}{n_i T_i}\Big(1-\frac{t}{T_i}\Big)^{\frac{1-n_i}{n_i}} + \frac{\alpha_i U_0^{n_i-1}}{n_i T_i}U^{1-n_i}\Big]dt. \qquad (15)$$

Equation (15) can be solved only by using numerical techniques.

## Conclusions

The expressions for estimation of speed of degradation processes have been derived here on the basis of proposed multifactor stress degradation model. The degradation process is considerably faster when the aging factors are interdependent. Use of proposed expressions requires multifactor experiments with each specific type of insulation. Following work will demonstrate correspondence of the proposed theoretical approach with experimental data.

## References

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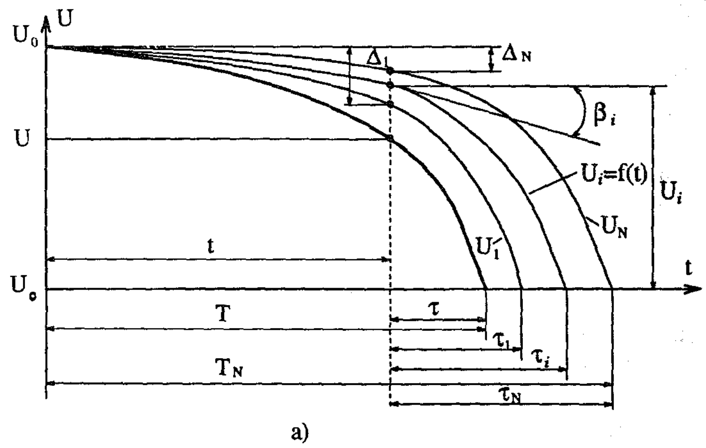

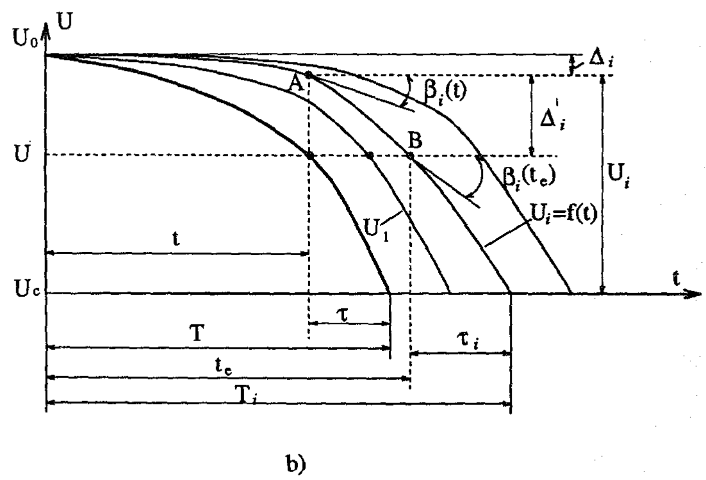

Figure 2: Components of (a) minimal and (b) maximal rates of degradation.