Determination of Remaining Life of Rotating Machines in Shipboard Power Systems by Modeling of Dielectric Breakdown Mechanisms

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***Abstract*—This paper presents a model to simulate electrical trees in dielectric materials. The model accounts for the characteristic tree patterns and the partial discharges associated with the propagation of trees. This simulation model is used as basis to develop a diagnostic tool to determine the remaining life of insulation materials by relating the fractal dimension of the tree to the supply voltage and material properties. Simulation results are presented to show the performance of the prognosis method.**

I. Introduction

Since the first electrical power system was installed on the USS Trenton in 1883, Shipboard Power Systems (SPS) have undergone a multitude of technological advancements with the most recent innovative drive aimed at an All-Electric Ship (AES). Presently, the AES is a notional concept and this paper looks at the health monitoring of winding insulation systems of rotating machines on the ship. The unique characteristics of the AES that make the research findings presented in this paper compelling have been discussed extensively in [1]. In particular, it is envisaged that there would be increased electromagnetic coupling of the devices on the ship due to the limited space which also leads to structural deformation of cables resulting accelerated aging and degradation of insulation systems. The reduced cable lengths of devices on ships also reduce their damping capabilities and could lead to more pronounced over-voltages during transients and thus faster degradation of machines winding insulations. The AES is also projected to incorporate power electronic conversion devices for power conversion purposes. These devices produce high frequency current and voltage components as a result of their switching action that have been reported to cause increased aging of cables [2].

Health monitoring for power apparatus has evolved to the point that it is currently possible to test and monitor machines without interrupting their operation. Generally, condition monitoring is performed with a view to determine the Remaining Useful Life (RUL) and assess winding condition of the rotating machines, to prioritize maintenance by determining a maintenance schedule based on need, to commission devices and to determine root causes of failure [3]. Several methods are available for condition monitoring and can be divided up into two main classes: online and offline methods. Offline monitoring has come to be associated with machine testing for failure and incipient faults. Online testing is akin to health monitoring of rotating machines without interrupting operation. Online monitoring is often preferred to offline testing because no outage is required, the stress levels do not exceed regular stress levels during normal operation, it is easy to collect information from sensors monitored on machines and online monitoring can help facilitate predictive maintenance. Online monitoring is, however, expensive to setup due to the cost of sensors monitored on devices for fault data acquisition. In the past, failure diagnosis and failure prediction for rotating machines was done by experts and sometimes by way of visual inspection. Presently, there are several software systems that can extract information from data about devices. These expert software modules come in either offline or online types to automatically carry out data analysis.

Common offline methods for testing stator and rotor winding insulation systems include insulation resistance tests, Polarization and Depolarization Current (PDC) tests, DC and AC high potential tests, dissipation factor tests and offline Partial Discharge (PD) tests. Online monitoring for rotating machines include, but are not limited to, thermography, online-PD monitoring, vibration monitoring, air-gap monitoring, voltage surge analysis and current signature analysis [3]. This paper proposes a new approach to online PD analysis for the purposes of predicting the time to failure of rotating machine insulation systems. To develop the method, we first present a new approach to modeling electrical trees. After presenting this micro-view of insulation degradation, we would present a formulation that enables the calculation of the time to breakdown of insulation which forms the basis for the proposed new method for online PD monitoring

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II. MODIFIED DIELECTRICS BREAKDOWN MODEL

A. Background

Experimental investigations of electrical treeing indicate that the growth of tree channels is associated with partial discharges (PD) in the dielectric materials. The actual mechanism of growth has been explained by several physical processes including electron avalanches [4], electromechanical fracturing [5] and photo-degradation [6]. From the point of view of a simulation model that can generate the electrical tree structures, a number of approaches have been suggested to account for the characteristic patterns of growth and the growth dynamics. The NPW model, named after its inventors, Niemeyer, Pietronero and Weismann was the first model to suggest that the tree channels were created by an advancing boundary of an injected charge fluid from the tree tip. The model associated the branching patterns observed during tree growth to a stepwise development in which the next branch to be added to the structures is chosen at random from pre-specified growth direction. Each growth direction has a failure probability proportional to E^n, where E is the local electric field along the bond and n is an unknown exponent normally fixed at values between 1.5 and 2. For computations, the NPW model assumes that local failure occurs immediately after the local electric field exceeds a critical level. Below this level, tree extension in the pre-specified direction is not possible. Experimental observation, however, suggests that there is high electric field, mostly, at the tips of the growing trees and, to a lesser extent, within the tree channels due to space charges. The high electric field induces damage generating events in the insulation and over time the tree extends in the direction where the insulation material has been damaged the most. Including this stepwise damage process into the NPW model suggests that there is a critical damage level where local failure is possible. This constitutes the modification to the NPW model called the Discharge Avalanche Model (DAM) which avoids the difficult-to-explain power law associated with the NPW model. The DAM modification to the NPW model accounts for the stochastic nature of tree propagation by using random values for the physical characteristics of the dielectric material. DAM, however, does not account for PD in the tree channels. Several models have been proposed to account for PD with most associating a PD activity to the damage processes that occurs when there is a local breakdown. In this paper, we propose a new approach to electrical treeing modeling by representing the growing tree as a set of contiguous charged spheres. This idea has been suggested in [7] to describe PD in a static electrical tree. The model proposed in this paper extends this idea into a dynamic tree by using DAM to extend the tree whilst accounting for the PD activity in the tree channels by way of charge transfers between the charged spheres.

B. Proposed Model

The proposed model represents the tree as a highly conductive path from the point of initiation to any tree tip. This is illustrated in Figure 1. Figure 1 also shows darkened circles representing charged spheres that are imagined to be interspersed and contiguous within the tree. By calculating the voltages and charges between the spheres and all points of possible tree extensions, the electrical tree can be advanced from the tree tip to the ground plane. The number of points of possible tree extension is limited in this simulation method to 5 as a compromise between computation effort and accuracy of representation. The calculation of charges is based on the Charge Simulation Method (CSM) which uses image charges to account for the ground electrode plane. The charge on each sphere is calculated by the superposition principle to reflect the voltages at each point in the dielectric material. Tree growth is based on the DAM model by the accumulation of damage energy in the specified direction. The damage energy is assumed for simplicity to be proportional to the electric field in the specified path and is given in Equation (1) below where $D(E)$ is the damage energy calculated for an electric field E, α is the constant of proportionality associated with Equation (1), $V(x)$ is the potential at location x with units of joule-meter per volts

$$D(E) = \alpha\left(V(x_1) - V(x_2)\right) \tag{1}$$

The damage process is calculated and accumulated until it reaches a critical level, at which time a local breakdown is taken to have occurred and a new sphere is added to the tree to represent a tree link. When there is a local failure of the dielectric material, voltage between the points of failure are modified to account for the breakdown. This modification is carried out by assuming a simple model of low resistance path between the points of failure as shown in Figure 1. The charges on each spheres associated with a local breakdown are modified to account for the voltage changes. The charge transfer that occurs during the breakdown process is assumed to be associated with a PD activity in this model. To calculate the charge transfer during the PD event associated with the breakdown process, the superposition principle is used to relate the voltage of any two spheres involved in breakdown to the charges of all spheres in the tree (including the two spheres involved in the breakdown) as shown in Equation (2).

$$\begin{aligned}(x_{11} - x_{11}')Q_1 + (x_{12} - x_{12}')Q_2 + \ldots + (x_{1n} - x_{1n}')Q_n &= V_1 \\ (x_{21} - x_{21}')Q_1 + (x_{22} - x_{22}')Q_2 + \ldots + (x_{2n} - x_{2n}')Q_n &= V_2\end{aligned} \tag{2}$$

In Equation (2), x_{11} is the voltage contribution of the sphere with charge Q_1, x_{12} is the charge contribution at the point location of charge Q_1 due to charge Q_2 and x_{11}' is the voltage contribution of the image charge associated with the sphere of charge Q_1. The terms x_{11} and x_{12} in (2) are calculated by (3) and (4) where d_0 is the diameter of influence of the charge, r is the distance between the points, ε_0 is the permittivity of free space and ε_r is the relative permittivity for the medium.

$$x_{11} = \frac{3}{4\pi\varepsilon_0\varepsilon_r d_0} \tag{3}$$

$$x_{12} = \frac{1}{4\pi\varepsilon_0\varepsilon_r r} \tag{4}$$

The calculation above is done for all charged sphere added to the tree tip. The voltages after the breakdown process are based on the idea that the physical branch between the tree tip and branch end before breakdown is a highly conductive medium. Equation (2) is then converted into two simple linear equations with two unknowns to be solved during each tree extension. To account for PD within the tree branches that have already broken down, the electric field between all tree branches are calculated and the tree branch with the maximum electric field greater than the critical field is reduced to a value below the critical field. The charge transfer required is solved by using the superposition to obtain two linear equations by similar reasoning as discussed earlier. After this process is carried out for all tree branches with electric field greater than the critical field, the process is started again with a new instantaneous voltage level. The new instantaneous voltage level is propagated throughout the tree by the assumption of highly conductive tree channels. With the voltages prescribed at each point of the tree, the charges required on each sphere is calculated by similar reasoning based on the superposition of voltages. This results in linear equations whose size increases with each added tree branch. The approach used in this paper to obtain accurate solutions at each simulation step is by successive relaxation beginning with a single sphere (preferably the sphere at the point of initiation of the tree). A single sphere results in a simple equation that gives the charge required to calculate the voltage at the specified point of the sphere while maintaining all other charges fixed. After obtaining the charge, a second sphere is added to obtain two linear equations with two unknowns and continues until all charges are accounted for. The whole process is illustrated in the flow chart shown Figure 2.

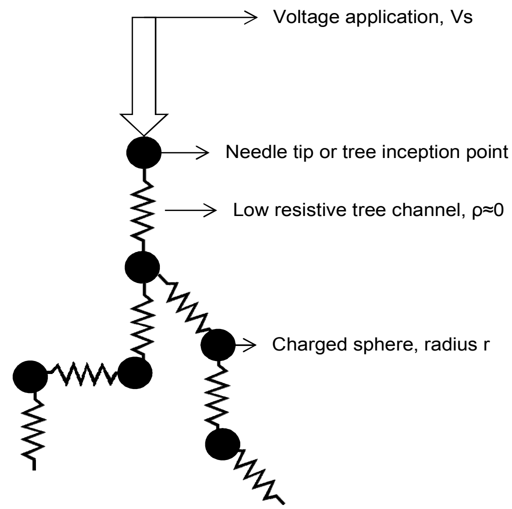

Figure 1. Illustration of electrical tree model

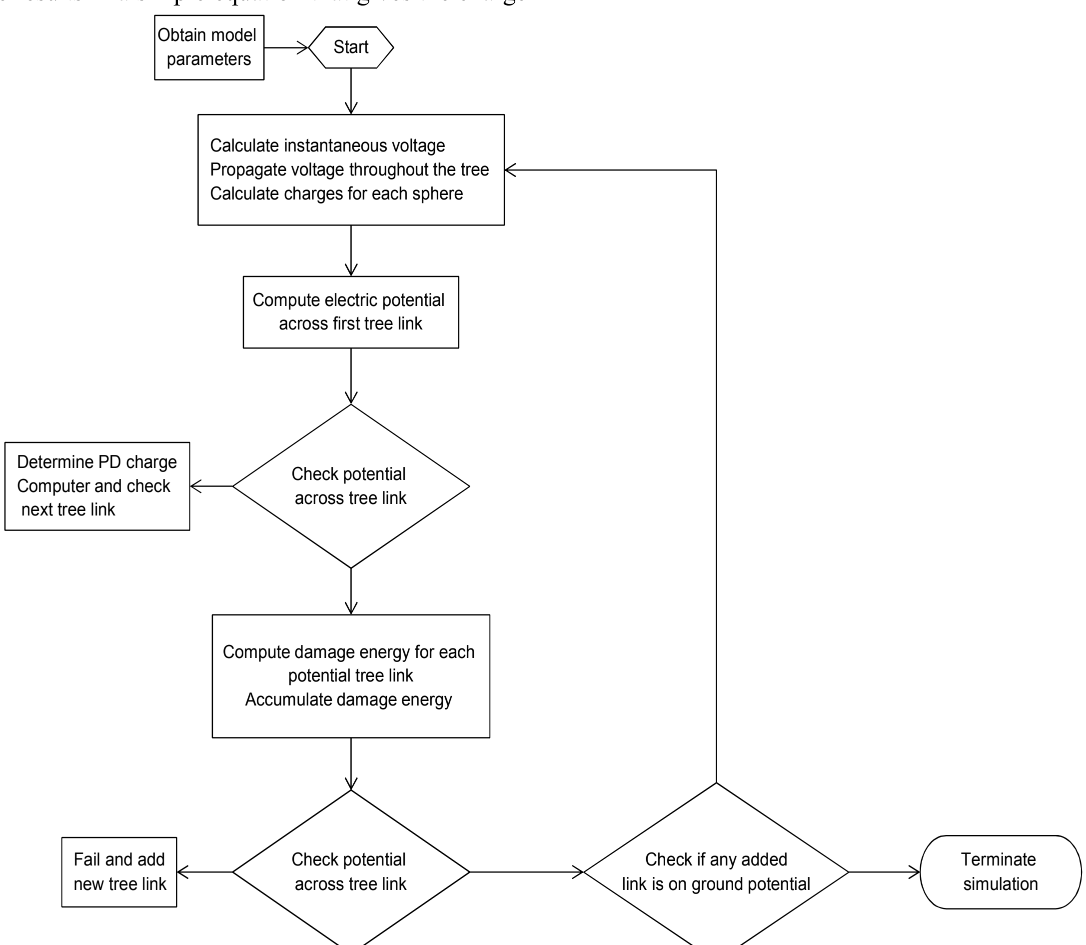

Figure 2. Flow chart illustrating the simulation process

TABLE I. MODEL INPUT PARAMETERS

PARAMATER NAME	TYPE OF PARAMETER
Applied voltage	External input
Applied voltage frequency	External input
Permittivity of free space	Universal constant
Relative permittivity	Material constant
Material hardness	Material constant
Critical damage	Material property
Critical field	Material property
Channel conductivity	Material property
Electrode spacing	Simulation parameter

C. *Simulation Results*

Simulations using this model have been carried out in MATLAB to assess model assumptions using different values for the model parameters listed in Table 1. Three types of model parameters are listed in the table for material dependent parameters, parameters associated with the external inputs to the breakdown process and computer simulation parameters. Voltage values above 5 kV were used for all simulation results. The supply frequency was fixed for the simulations reported in this paper at 60 Hz. The dielectric strength and relative permittivity for insulation materials can be obtained from manufacturers and for the material whose breakdown is modeled in the figures, was found to be 15.7 kV/mm and 4.8 respectively. The material hardness can be obtained from manufacturers and was fixed at 75 for this work. The material hardness guides the choice of critical damage energy that is used in the proposed model. The channel conductivity should be low values below 0.001 for good results. The remaining parameters are simulation parameters which affect the accuracy of numerical computations. Some of the figures generated with the model are illustrated in Figure 3, Figure 4, Figure 5 and Figure 6. The figures were generated to simulate the conditions of a needle plane experiment with the same separation distance of 0.1 mm. The fractal dimension and the time to breakdown are shown for each of the figures generated by the model in Figure 7. The fractal dimension is calculated by the box counting method for a grid size of 0.01 mm. It is seen that there is a similar relationship between the time to breakdown and the applied voltage as between the fractal dimension and applied voltage. The relation is, however, highly nonlinear. The next section discusses an approach to model the relationship between the time to breakdown and the characteristics of the tree.

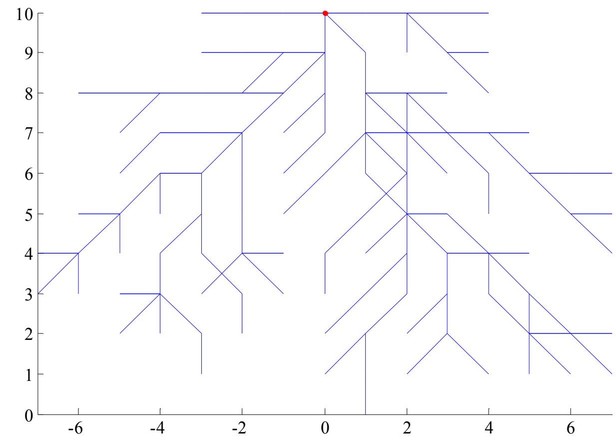

Figure 3. Tree simulation at 10 kV for grid spacing of 0.1 mm

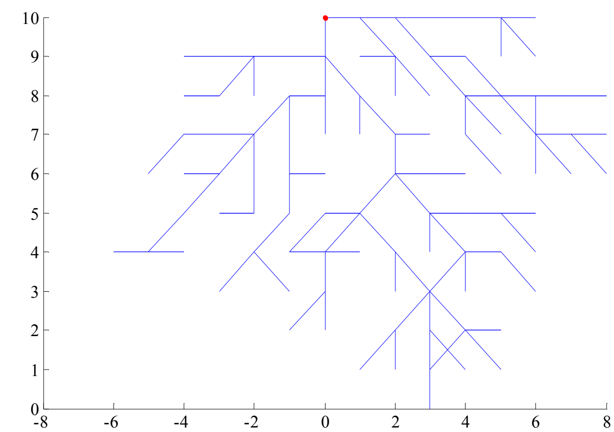

Figure 4. Tree simulation at 20 kV for grid spacing of 0.1 mm

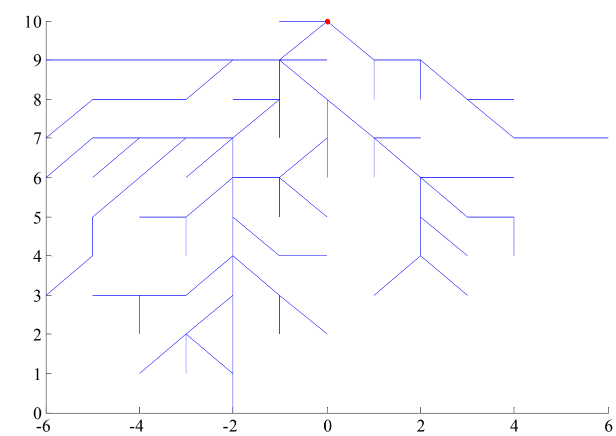

Figure 5. Tree simulation at 30 kV for grid spacing of 0.1 mm

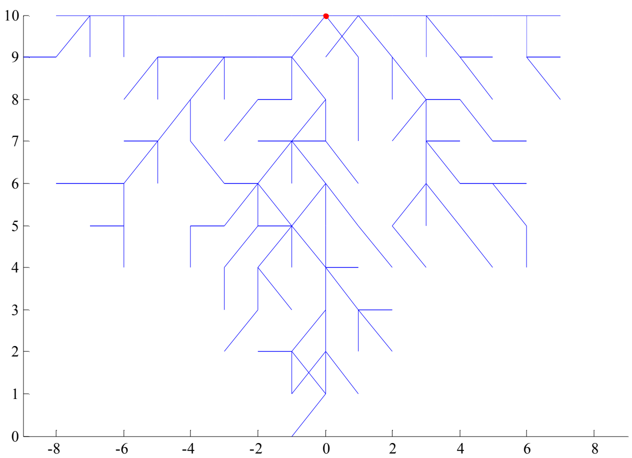

Figure 6. Tree simulation at 40 kV for grid spacing of 0.1 mm

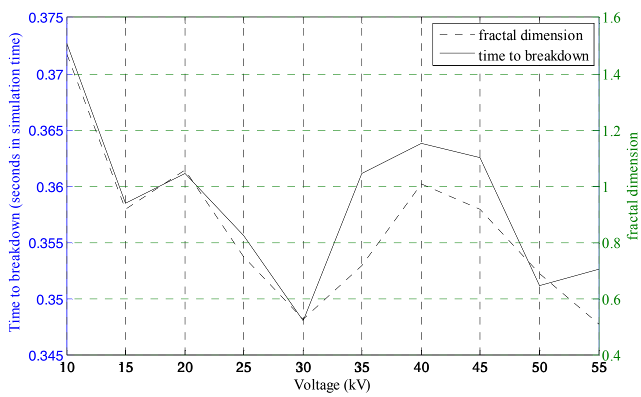

Figure 7. Plot of time to breakdown and fractal dimension as a function of applied voltage

III. MACRO-MODEL TO DETERMINE TIME TO BREAKDOWN

It has been established that the growth rate and time to failure can be related to the characteristics of the tree, material properties and other parameters of the breakdown process such as the supply voltage. The simulation results of Fig. 7, show this correlation for supply voltage, time to breakdown and fractal, albeit a nonlinear relationship. The results presented in [8] and shown in (5) present a fundamental relationship that relates some material properties and other parameters to the breakdown time. Based on this formulation, we propose (6) as an empirical relationship that can be used to determine the time to breakdown of insulation materials.

$$t_g = \left(\frac{L_c}{L_b}\right)^{df}\left(\frac{hN_b}{kT}\right)\exp\left(\frac{U_0 - \alpha C_0 \pi \varepsilon E^2}{kT}\right) \quad (5)$$

$$t_g^1 = \alpha (D_s)^{df} \exp\left(D_m - \beta V^2{}_s\right) \quad (6)$$

In (5), U_0 is the initial energy barrier for molecular breakdown of the bonds in the dielectric material, αC is the volume of material activated in the direction of the applied field, E is the local field strength dependent on the applied voltage, kT, is the boltzmann's constant and T is the temperature in Kelvins, hN_b, is the Planck constant multiplied by the number of bonds in a given tree branch and L_c/L_b is the ratio of critical length over which breakdown proceeds exponentially and the instantaneous length of the tree branch farthest away from the tree tip. The equation in (6) is based on Equation (5) and is proposed as a model to determine the time-to-breakdown of a dielectric material undergoing breakdown. Equation (6), however, uses parameters that are more easily accessible by replacing the (L_c/L_b) term by the separation distance between the electrodes in a needle plane experiment, D_s. The second term is replaced with a constant, α, to be determined experimentally. Inside the exponential, the initial energy barrier is replaced by a parameter in the proposed electrical tree model, the critical damage energy, D_m. The local electrical field is replaced by the supply voltage, V_s and a constant, β, to be determined experimentally. df is the fractal dimension whose value can only be determined after an examination of a failed tree. The proposed RUL model can be determined by empirical curve fitting for any dielectric material. Figure 8 is the result of such curve fitting for simulation data based on the proposed electrical model discussed in section II. There is generally a closer fit for voltage values in the middle of the figure with a divergence on the extremes of voltages.

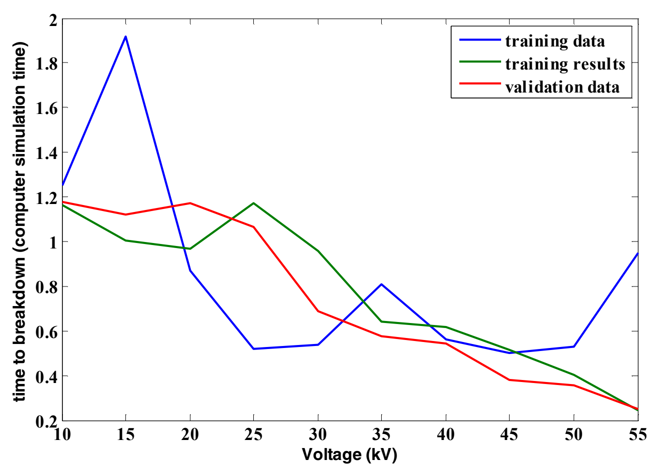

Figure 8. Determination of macro model

IV. CONCLUDING REMARKS

This paper has presented a new model for electrical tree simulation based on a modification of the DAM model with an application of the CSM to determine PD during the growth of electrical trees. It has been shown that there is a relationship between the time to breakdown and the parameters of a growing tree that can used in practical application for machine diagnostic purposes. Figure 9 shows the relationships between the maximum PD and the PD count for the entire duration of breakdown as well as the supply voltage for computer simulation using the proposed model. It is seen that with increasing applied voltage, the maximum measured PD during tree growth increases, which is expected. The PD count, however, has an interesting relationship which is confirmed experimentally from testing carried out during our studies in dielectric breakdown mechanisms. Some of the results of actual breakdown testing are shown in Figure 10 and Figure 11 for maximum apparent charge, measured in volts, and PD count. The plot in Figure 10 is for the maximum apparent charge per applied voltage cycle (60 Hz) for an entire tree propagation and complete breakdown at applied voltage of 8 kV. Figure 11 is the PD count per cycle for the same period as Figure 10. We find these correlations useful since the macro model presented in section III and the relationship between PD and voltage as shown, by way of computer simulation and experimental measurement, indicates a way to use PD measurements to determine the RUL of machine insulation systems particularly on SPS where due the unique circumstances generally on ships, and particularly for the AES, PD is presumed to be a major source of degradation.

However, as Figure 8 suggests, the macro model may be applicable only for a range of voltages for each material type. Further work would be required to determine the fractal dimension since this value must be known for the model to be applicable on practical level.

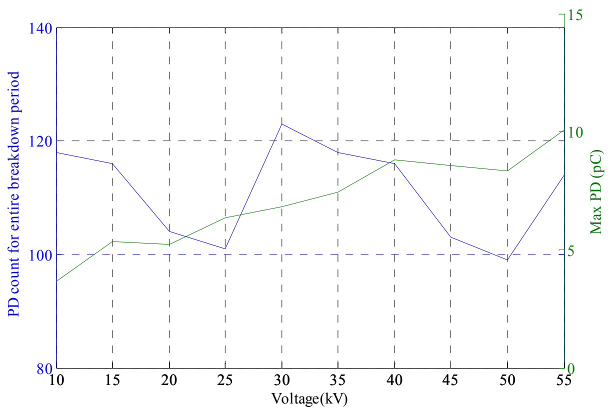

Figure 9. Plot of PD count and Maximum PD versus applied voltage

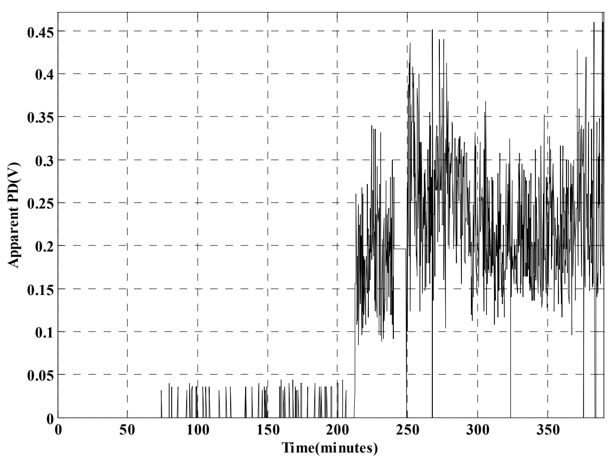

Figure 10. Maximum apparent charge of PD per cycle

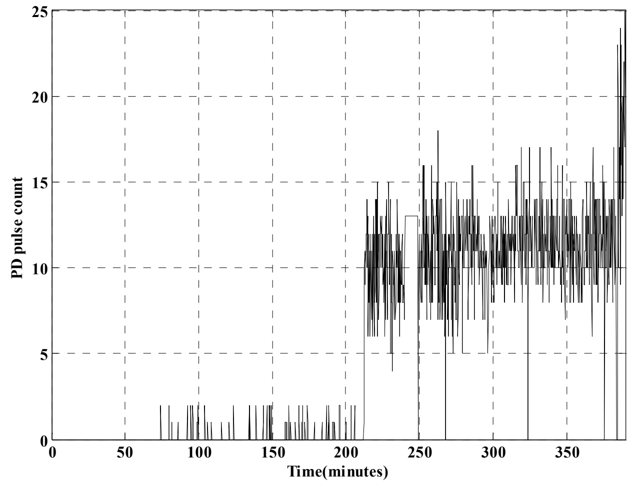

Figure 11. PD pulse count

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REFERENCES

[1] Y. Nyanteh, L. Graber, C. Edrington, S. Srivastava, D. Cartes, "Overview of simulation models for partial discharge and electrical treeing to determine feasibility for estimation of remaining life of machine insulation systems," Electrical Insulation Conference (EIC), 2011 , pp.327-332, 5-8 June 2011.

[2] N. H. Doerry, H. Fireman, “Designing all electric ships”, Proceedings of the Ninth International Marine Design Conference, 2006.

[3] G. C. Stone, E. A. Boutler, I. Culbert, H. Dhirani, ‘Electrical Insulation for Rotating Machines’ IEEE Series on Power Engineering, 2004, ISBN 0-471-44506-1.

[4] M. D. Noskov, M. Sack, A. S. Malinovski and A. J. Schwab, "Measurement and simulation of electrical tree growth and partial discharge activityin epoxy resin" J. Phys. D: Appl. Phys. 34 (2001) 1389–1398.

[5] L. A. Dissado, "Understanding Electrical Trees in Solids: From Experiment to Theory", IEEE Transactions on Dielectrics and Electrical Insulation Val. 9, No. 4; August 2002.

[6] M. D. Noskov, A. S. Malinovski, M. Sack, and A. J. Schwab, "Modelling of Partial Discharge Development in Electrical Tree Channels", IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 10, No. 3; June 2003.

[7] J. V. Champion and S. J. Dodd, "Simulation of partial discharges in conducting and non-conducting electrical tree structures", J. Phys. D: Appl. Phys. 34 (2001) 1235–1242.

[8] H. Z. Ding, B. R. Varlow, "Thermodynamic model for electrical tree propagation kinetics in combined electrical and mechanical stresses," Dielectrics and Electrical Insulation, IEEE Transactions on ,vol.12, no.1, pp.81-89, Feb. 2005.