International Journal of
Science and Engineering Investigations
vol. 2, issue 19, August 2013
ISSN: 2251-8843

# Partial Discharge Localization in Stator Winding of Generators using Multi-Conductor Transmission Line Model

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***Abstract***-Partial discharges (PDs) are a major source of insulation failure in power generators. Techniques for locating a PD source are of major importance in both the maintenance and repair of a generator. In this paper a wide band MTL model of generator winding employed to best simulate propagation of partial discharge signals in generators and precisely locate the source of partial discharge in the winding. The MTL model is briefly reviewed and the related equations of the model are reformulated to easily simulate application of a PD signal at any location along the winding. Using Matlab software is developed to calculate the windings resonance frequencies and the magnitudes of over voltages occurring between different coils along the winding. Comparing these results with the experimental results, accuracy of this model and the related simulation is verified.  Propagation of PD signal in a high voltage generator (6kv/250kw) is simulated using the Multi-Conductor transmission line (MTL) model with frequency dependent parameters.

***Keywords-****partial discharge, generators, Multi-Conductor transmission line model*

## I. INTRODUCTION

Partial discharges (PD) are a major cause of insulation failure in power generators. If PD activity is not detected and ideally located before it develops into a full discharge, catastrophic failure can result and the resulting economic cost to the utility may be significant [1]. The actual cost depends on the location and importance of the generator, the availability and cost of alternative sources and / or routes of power and the capital cost of repair or replacement. On-line condition monitoring of power generators is advisable and ideally this should include immediate detection of increased PD activity and location of the discharge [2]. Depending on the severity and location of a discharge the generator will either be taken out of service immediately or at a convenient time or will be kept in service with increased monitoring [3]. Early work on PD location assumed the generator behaved like a capacitive network, but further studies indicate this is only valid over a limited frequency range and is inadequate for studying PD propagation [4]. A recent paper modeled each section of the winding as a lumped circuit that takes into account capacitance, inductance and resistive and dielectric losses [5]. This was valid when the dominant PD frequencies are up to a few hundred kHz, but is inadequate in the MHz region. This paper describes how a model based on multi-conductor transmission line theory can be used to simulate a generator winding over a frequency range from a few hundred kHz to a few tens of MHz. A wide frequency range is necessary because the spectra needed to describe the various types of partial discharges observed on a power generator can extend from tens to hundreds of kHz for a surface or interface type PD and from hundreds of MHz to a few GHz for a small bubble void [6]. model suitable for the latter was beyond the scope of this research because of the difficulties associated with the design and experimental validation of such a model and also because PD pulses of (1 – 100) ns duration have minimal destructive power and are of limited practical significance. As a compromise, the model proposed in this paper is suitable for simulating the propagation of PD pulses of duration 100ns- 10ms. This is appropriate for most practical cases. Representing a generator winding by a lumped circuit model requires a resolution appropriate for the chosen frequency. For example, previous research [7] has shown that representing each coil in the winding by a lumped PI circuit model is valid up to a few hundred kHz. To correctly model the winding at higher frequencies requires that each turn in the coil (and hence the entire winding) is modeled as a circuit unit. The electrical parameters of the winding are calculated on a per turn basis and the entire winding is represented by distributed multi conductor transmission line (MTL) model. The generator winding is considered as a single input multiple outputs system, where the input is the PD signal and the outputs are the current signals at the measuring terminals. FFT are calculated from all possible PD locations to the line-end and neutral-end measuring terminals using a simulation program developed in Matlab. Simulation results show that the poles in the Functions derived from the FFT contain information about the location of discharge [2][3][8].

## II. MTL MODEL

Multi-conductor Transmission Line (MTL) theory deals with a network of N conductors coupled all together, characterized by its inductance matrix, [L] and capacitance matrix [C] that are distributed parameters. In the MTL model, windings parameters are considered as distributed parameter and winding behavior is described by transmission line equations. MTL model for turns of one coil is depicted in the figure 1. Base on the theory of multi conductor transmission line model, the generator windings are combination of a set of transmission lines. These lines are geometrically in parallel, however electrically in series [9][10].

In this step two different modeling techniques may be used:

1) To model each coil with a multi-conductor transmission line. Each turn also can be modeled as an extended transmission line.
2) To model each coil in form of an extended single conductor transmission line.

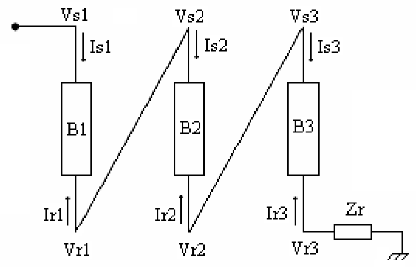

Fig.1. Winding model with three turns in series connection.

For developing the model a single turn is considered as the basic element of analysis. Fig. 1 shows an electrical machines winding with three turns in series connection. In the figure, $Z_r$ is the impedance for representing the terminal conditions: short and open circuit. The voltage $V_{s1}$ is the surge at the beginning of the winding.

Surge impedances and coefficient of propagation can be estimated by comparison of these two models. The following equations are the result of this comparison [11-13].

$$Z_i = \frac{1}{v_s \left[ c_0^i + c_1^i + 2k \left\{ 1 - \cos\left(\frac{\omega a}{v_s}\right) \right\} \right]} \tag{1}$$

$$\gamma = \frac{1}{v_s d} \sqrt{\frac{\omega}{2\sigma\mu}} + \frac{\omega \tan\delta}{2v_s} + \frac{j\omega}{v_s} \tag{2}$$

Where
K: inter-turn capacitance
a: Turns average length
d: disks gap
$v_s$: velocity

The first and second terms in the (2) are representing the skin effect and the dielectric losses respectively. σ, μ and d are the conductivity, permeability and the winding coils gap respectively. The details of modeling and the parameters estimation for an inhomogeneous winding (realizing frequency dependent parameters) are discussed in [14].

## III. PD INJECTION

According to the figure 1 we have this telegraphs equations:

$$\frac{\partial V_t}{\partial x} = -L\left(\frac{\partial I_t}{\partial t}\right) \tag{3}$$

$$\frac{\partial I_t}{\partial t} = -C\left(\frac{\partial V_t}{\partial x}\right) + C_0 \frac{\partial E_0}{\partial t} \tag{4}$$

In (3) and (4), $V_t$ and It are the voltage and current vectors. The order is equal to the number of turns in a coil. L and C are square matrices of the inductances and capacitances in the coil while $E_o$ and $C_o$ denotes the excitation function and capacitance from one turn to the static plate. To study the PD phenomena the excitation function don't exist so in the (4):

$$\frac{\partial E_0}{\partial t} = 0 \tag{5}$$

By solve the (3) and (4) and by insertion of (5), one can obtain following equations:

$$V_i(x) = A_i \exp(-\Gamma(\omega)x) + B_i \exp(\Gamma(\omega)x) \tag{6}$$

$$I_i(x) = \frac{1}{z_i}[A_i \exp(-\Gamma(\omega)x) - B_i \exp(\Gamma(\omega)x)] \tag{7}$$

Equations (6) and (7) are 2N equation and contain 2N undefined parameters ($A_i$ and $B_i$). By using the terminal conditions.

$Ir_1 = -Is_2$ ، $Ir_2 = -Is_3$ ، $Vr_1 = -Vs_2$ ، $Vr_2 = -Vs_3$ و $-Ir_3 = Vr_3 / Zr$ (8)

2N-2 equations are available. For 2 other equation can be simulated by a capacitance $C_B$ connected at the line-end. Then,

$$I_{(s1)} = -j\omega c_B v_{(s1)} \tag{9}$$

If the neutral end is at earth potential,

$$V_{r(N)} = 0 \tag{10}$$

If a PD current pulse $I_{PD}$ is injected into the kth turn of the winding, (8) is modified when i=k-1:

$$I_s(k) = I_r(k-1) + I_{PD} \tag{11}$$

Whit this set of terminal equation applied to (6) and (7), one can calculate the coefficients ($A_i$ and $B_i$) and then by use of them the current due to PD pulse can be calculated in the generator terminals.

$$\begin{bmatrix} I_{s(1)} \\ 0 \\ \vdots \\ 0 \\ I_{PD} \\ 0 \\ \vdots \\ 0 \\ I_{R(n)} \end{bmatrix} = \begin{bmatrix} \\ \\ \\ \\ [Y] \\ \\ \\ \\ \\ \end{bmatrix} \begin{bmatrix} V_{s(1)} \\ V_{s(2)} \\ \vdots \\ \vdots \\ V_{s(k)} \\ \vdots \\ \vdots \\ V_{s(n)} \\ V_{R(n)} \end{bmatrix} \tag{12}$$

Where [Y] is a $(n+1)\times(n+1)$ matrix.

If matrix [Y] is inverted and re-arranged, it is possible to get.

$$\begin{bmatrix} I_{s(1)} \\ V_{s(2)} \\ V_{s(3)} \\ \vdots \\ V_{s(k)} \\ \vdots \\ \vdots \\ V_{s(n)} \\ V_{R(n)} \end{bmatrix} = \begin{bmatrix} & & \\ & [T] & \\ & & \end{bmatrix} \begin{bmatrix} V_{s(1)} \\ 0 \\ \vdots \\ \vdots \\ I_{PD} \\ \vdots \\ \vdots \\ 0 \\ I_{R(n)} \end{bmatrix} \tag{13}$$

Hence, if the line-end voltage, the neutral-end current and the PD current are known all other voltages and currents can be calculated.

## IV. CALCULATION OF MODEL PARAMETERS

MTL model parameters consist of capacitance, inductance, resistance and conductance matrices. They depend on conductors and insulations geometry and characteristics, geometrical dimensions of the generator, winding type and position of each winding [10][11].

### A. Capacitance

There are various capacitances between different conductors. The capacitance between two adjacent turns in a coil can be calculated by assuming parallel plate capacitor approximation as: [12]

$$C_T = \frac{\varepsilon_{\circ}\varepsilon_P \times \pi D_m (w + t_P)}{t_P} \tag{14}$$

Where $D_m$ is the winding diameter, $w$ is the width of the conductor in axis direction, $t_p$ is paper thickness in both sides of the conductor, $\varepsilon_0 = 8.85\times10{-}12$ F/m and $\varepsilon_p$ is the relative permittivity of paper.

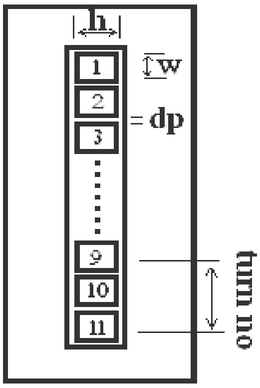

Fig.2. The structure of the generator winding

### B. Inductance

In evaluating inductance, it is assumed that the magnetic flux penetration into the laminated iron core is negligible at frequencies above 1 MHz [7]. The inductance is calculated by assuming the winding consists of loss-less multi-conductor transmission lines surrounded by a homogeneous insulator. Hence [4]:

$$[L][C] = [C][L] = \mu\varepsilon[I_n] \tag{15}$$

Where $\mu$ and $\varepsilon$ are the permeability and permittivity of the insulation and $I_n$ is the unit matrix. If no high frequency magnetic flux penetrates the iron core, the winding can be regarded as a conductor in free space surrounded by insulation. The inductance due to the flux external to the conductor ($L_n$) can be calculated using [3]:

$$[L_n] = \frac{\varepsilon_r}{c^2}[c_n]^{-1} \tag{16}$$

Where [Cn] = capacitance without insulation, er = relative permittivity of insulation and c = velocity of light in free space. At high frequencies, the flux internal to the conductor also creates an inductance [4]

$$L_i = \frac{R_s}{2\pi f} \tag{17}$$

Where $R_S$ is the resistance due to the skin effect and f is the frequency. The total inductance is given by

$$[L] = [L_n] + L_i\,[I_n] \tag{18}$$

### C. Resistance

In resistance calculation, the skin effect at high frequencies is taken into account. The resistance per unit length of conductor is given by

$$R_s = \frac{1}{2(d_1 + d_2)}\sqrt{\frac{\pi f\,\mu}{\sigma}} \tag{19}$$

Where $d_1$, $d_2$ = cross-sectional dimensions of rectangular conductor, m = permeability of conductor, s = conductivity and f = frequency.

### D. Conductance

The conductance (G) is due to the capacitive loss in the insulation. It depends upon the frequency f, the capacitance C and the dissipation factor $\tan\delta$.

$$\begin{cases} [G] = 2\pi f\ [C]\tan\delta \\ \tan\delta = 0.07\left(1 - \dfrac{6}{7}e^{-(0.308f\times10^{-6})}\right) \end{cases} \tag{20}$$

The parameters of MTL model are determined based on numerical field analysis methods (e.g.finite element method), by using maxwell software.

Fig.3. The coil of 6kv generator tested

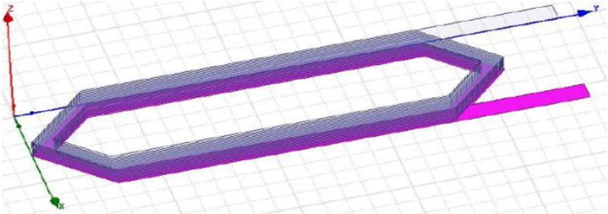

Fig.4. Three-dimensional shape of the winding 6kv simulation in Maxwell software

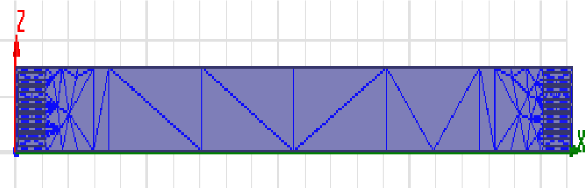

Fig.5. Shape mesh two-dimensional of the coil

## *V.* COMPARISON OF MEASURED AND COMPUTED RESULTS

The simulation study has been carried out on a simple 16coil multi-conductor transmission line as shown in Figure 1 with predefined circuit elements as listed in Table 2. The various PD currents that flow through the neutral point due to the Dirac-shaped discharges (atdifferent site-of origins), are calculated by using the MATLAB software.

TABLE I .PARAMETERSOF THE MACHINE UNDER TEST

| | | |
|---|---|---|
| Rated voltage | 6000 | v |
| Rated power | 250 | kw |
| Rated speed | 1500 | r.p.m |
| Rated frequency | 50 | hz |
| Winding Connection | star | --- |
| Number of turns per phase | 176 | --- |
| Number of coils per phase | 16 | --- |
| Number of turns in a coil | 11 | --- |
| Conductor dimensions | 11.5*236 | mm |

TABLE II .PARAMETERSOF THE COIL UNDER TEST

| | L(mH) | R(ohm) | $C_S$(PF) | $C_g$(PF) |
|---|---|---|---|---|
| Real | 17.2 | 0.35 | 30 | 1331 |
| Estimated | 17.7 | 0.4 | 27.94 | 1253 |

The calculated current signals are then fed into a software implementation of the algorithm for PD localization as previously described. The first PD current used is that with the source located at the 2nd section Line away from the neutral point.Figure.7,8 and 9 is a comparison between the measured current spectrum and the estimated current spectrum.

Fig.6. Schematic machin with the coil under test

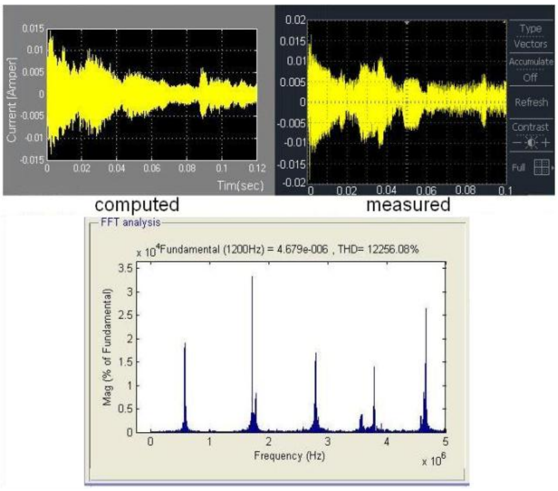

Fig.7. The comparison between the current spectrum of the simulated and measured, when PD be injected at Line1.

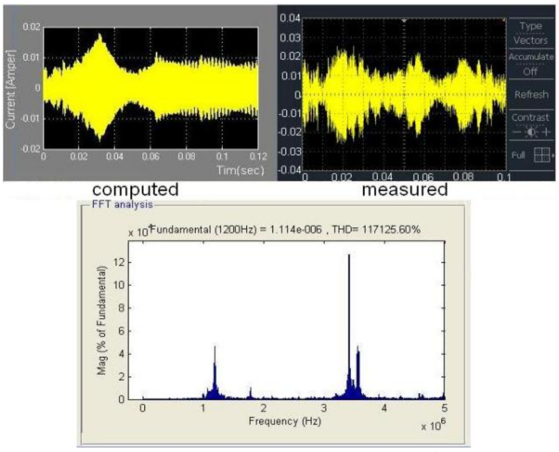

Fig.8. The comparison between the current spectrum of the simulated and measured, when PD be injected at Line6.

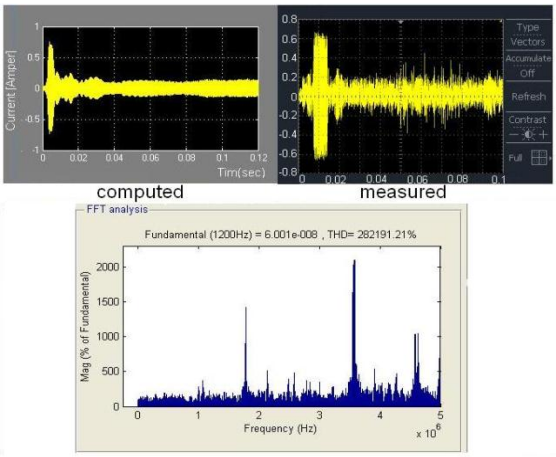

Fig.9. the comparison between the current spectrum of the simulated and measured, when PD be injected at Line10.

TABLE III. THE COMPARISON BETWEEN ACTUAL POSITION AND THE ESTIMATED POSITION OF MEASURED PD (DEPENDING TO THE NODE)

| $PD_S$ | Real position | Estimated position |
|---|---|---|
| $PD_1$ | 1 | 2 |
| $PD_2$ | 6 | 6 |
| $PD_3$ | 10 | 10 |

## VI. CONCLUSION

An algorithm for generator partial discharge localization has been developed in this paper. The MTL model equations are reformulated to apply the PD simulated signal along the winding for investigation of PD location. The approach is based upon frequency spectrum analysis of PD current signals. The algorithm initially estimates the parameters of the generator from the poles of the discharge frequency spectrum. The position of a PD source can then be deduced by calculating the PD current waveforms with the source simulated at various locations within the generator. These waveforms are then compared to the observed waveform to determine the closest match. This algorithm does not require any predetermined information about the generator. The PD site-of-origin is determined purely from a measured PD current. Simulation and experimentation both show promising results.

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