PD LOCATION IN TRANSFORMER WINDING BY USING A MTL MODEL

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Abstract: To locate accurately the occurrence of a partial discharge in a power transformer winding, a wide frequency band model of the winding is required. In this paper a wide frequency band Multi Conductor Transmission Line model (MTL) is employed to simulate the propagation of PD signal in transformer windings. The MTL model is briefly reviewed and the related equations of the model are reformulated to easily simulate occurrence of a PD signal along the winding. Software is developed in Matlab to calculate the windings resonance frequencies and the magnitudes of over-voltages occurring between different disks along the winding. Then propagation of PD signal in a power transformer (900MVA, 525kV), is simulated using the (MTL) model with frequency dependent parameters. Also this method is employed to model the laboratory transformer winding.

1 INTRODUCTION

Partial discharge signals are very short duration current pulses. Although they don't seem dangerous at the beginning, because their energy are very low, however in long term these PDs weaken the insulation system and finally can cause a permanent fault. One of the possible sources of failure in a power system is power transformer.

The consequences of occurrence of failure in a transformer can be very catastrophic. Among the causes of an electrical failure in transformer, internal insulation breakdown is the most prevalent one and partial discharges are the most important reason for this kind of failure. If PDs are not detected and located accurately they can convert to full discharges and result in a permanent electrical insulation break down in transformer. PD detection can be done using on-line and off-line methods. PD detection that uses on-line methods, have several benefit such as; increasing the system reliability, reducing the outage time, and improving the safety.

No additional equipments are needed to simulate the high voltage stress on the insulation. Beside detection of PDs in a power transformer, its location in the winding is very important. To study the PD signals propagation in a winding, the winding should be modelled with high accuracy. PD signals contain wide frequency band components that expand to several hundred kilo hertz [1]. Therefore in this paper PD signal propagation is studied by employing the appropriate model that is accurate in the range of several Mega Hertz.

2 TRANSFORMER MODEL

Transformer modeling methods [2-7] can be classified to "RLC Ladder Network Model" and "MTL Model". The fundamental elements of the Ladder Network model are the lumped R, L and C elements. The frequency limitation for the validity of this model is in the range of a few hundred kHz. In order to extend this range to a few MHz, it is necessary to use a turn-to-turn modeling procedure instead of disk-to-disk modeling. This procedure will result in a large scale system, which would be difficult to simulate and to analyze such a sophisticated system.

The other solution to this problem is the application of the hybrid model which can be built by a combination of other models [5]. In this model, due to application of a Black Box approach, the order of the network is reduced substantially. However there is no transient voltage distribution information available along the winding in a Black Box model. To overcome this problem a method will be introduced in this paper which is based on the Multi-conductor Transmission Line (MTL) theory. Using this theory, the number of equations and the size of the memory required for the calculation decreased significantly.

In addition, because of using the distributed parameters, the model accuracy will be expanded over MHz frequency range.

The published works on frequency dependent modeling of transformer is more focused on the RLC Ladder Network model in past. While the published works on MTL modeling is mostly concentrated on modeling of electrical rotating machines [6] and also on only the homogenous transformer windings ignoring the frequency dependency of the winding insulation parameters [4],[8]. While reference no. [9] addressed in a general form application of MTL to transformer modeling.

2.1 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 behaviour is described by transmission line equations. MTL model for turns of one disk is depicted in the Fig. 1. Base on the theory of multi conductor transmission line model, the transformer windings are combination of a set of transmission lines. These lines are geometrically in parallel, however electrically in series.

In this step two different modeling techniques may be used:

a. To model each disk with a multi-conductor transmission line. Each turn also can be modeled as an extended transmission line.

b. To model each disk in form of an extended single-conductor transmission line.

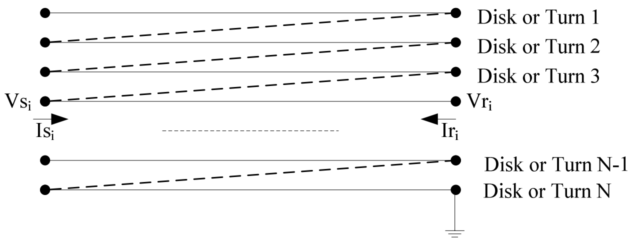

Figure 1: Multi-conductor transmission line model

Surge impedances and coefficient of propagation can be estimated by comparison of these two models. The following equations are the result of this comparison [7-9].

$$z_i = \frac{1}{v_S[C_0^{(i)} + C_1^{(i)} + 2K\{1 - \cos(\frac{\omega a}{v_S})\}]} \tag{1}$$

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

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

The first and second terms in the equation 2 are representing the skin effect and the dielectric losses respectively. σ, μ and d are the conductivity, permeability and the winding disks gap respectively. The details of modeling and the parameters estimation for an inhomogeneous winding (realizing frequency dependent parameters) are discussed in [9].

2.2 Pd injection

According to the Fig. 4 we have this telegraphs equations:

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

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

In equations 3 and 4, V_t and I_t 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_0 and C_0 denote 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:

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

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

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

$$I_S(i+1) = I_R(i) \qquad \text{For} \quad i=1 \quad \text{to} \quad n-1 \tag{8}$$

$$V_S(i+1) = V_R(i) \qquad \text{For} \quad i=1 \quad \text{to} \quad n-1 \tag{9}$$

2n-2 equations are available. For 2 other equation, the bushing of transformer can be simulated by a capacitance C_B connected at the line-end. By respect to the Cs (stray capacitance of the source power) Then,

$$I_S(1) = jw(C_B + C_S)V_S(1) \tag{10}$$

If the neutral end is at earth potential,

$$V_R(n) = 0 \tag{11}$$

If a PD current pulse I_{PD} is injected into the Kth turn of the winding, 8 and 9 are modified when i=k-1:

$$I_S(k) = I_R(k-1) + I_{PD} \tag{12}$$

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 transformer terminals.

2.3 Pd Location

PD location using the MTL model was studied in several papers [1], [10- 11]. In this section the equations 6 and 7 are reformulated, using the terminal conditions. The unknown parameters; A_i and B_i are considered as unknown vectors therefore:

$$[\mathrm{A}][\mathrm{X}] = [\mathrm{B}] \tag{13}$$

$$\begin{bmatrix} & & \\ & A & \\ & & \end{bmatrix} \begin{bmatrix} \\ X \\ \\ \end{bmatrix} = \begin{bmatrix} \vdots \\ \vdots \\ I_{PD} \\ \vdots \end{bmatrix} \tag{14}$$

$$I_S = \frac{1}{z_1}\left(x_1 - x_2\right) \tag{15}$$

$$I_N = \frac{1}{z_n}\left(x_{2n-1} \times a(n,2n-1) - x_{2n} \times a(n,2n)\right) \tag{16}$$

$$[X] = \frac{[A]^*}{|A|}[B] \tag{17}$$

$$x_1 = \frac{\overset{*}{a}_{1k} \times z_{k+1} \times z_k \times I_{PD}}{|A|} \tag{18}$$

$$x_2 = \frac{\overset{*}{a}_{2k} \times z_{k+1} \times z_k \times I_{PD}}{|A|} \tag{19}$$

$$x_{2n-1} = \frac{\overset{*}{a}_{2n-1k} \times z_{k+1} \times z_k \times I_{pd}}{|A|} \tag{20}$$

$$x_{2n} = \frac{\overset{*}{a}_{2nk} \times z_{k+1} \times z_k \times I_{PD}}{|A|} \tag{21}$$

$$\frac{I_S}{I_N} = \frac{z_n}{z_1} \times \frac{\overset{*}{a}_{1k} - \overset{*}{a}_{2k}}{\overset{*}{a}_{2n-1k} \times a(n,2n-1) - \overset{*}{a}_{2nk} \times a(n,2n)} \tag{22}$$

As it appears from the equation 22, the frequency spectrum of I_S/I_N depends only on the location of PD and the windings parameters. In the above equations it is assumed that in the matrix A, the voltage equations placed at first (at the top) and then current equations placed below them. The measured current by HFCT (bushing end) is related to the Is according to the equation 23. So $\frac{I_{HFCT(BUSHING)}}{I_{HFCT(NEUTRAL)}}$ is also related to the PD location.

$$I_{HFCT}(Bushing) = \left(\frac{C_B}{C_B + C_S}\right) I_S(1) \tag{23}$$

Fig. 2 and Fig. 3 show the PD measurement circuit and the transformer winding equivalent model for PD location respectively. In addition flowchart of the developed program which is based on the MTL modeling theory is shown in Fig. 4. There are one loop for frequency and one loop for sensitivity analysis in order to realize the loss factor variations and at the end; the location of PD is evaluated.

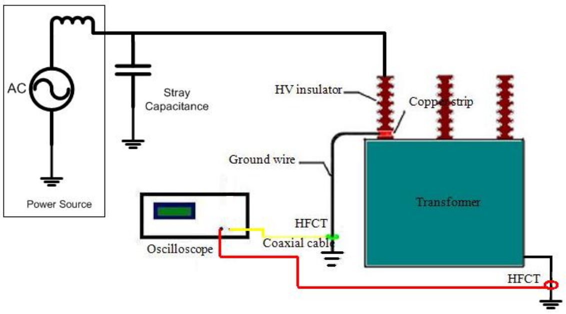

Figure 2: PD measurement circuit for PD location

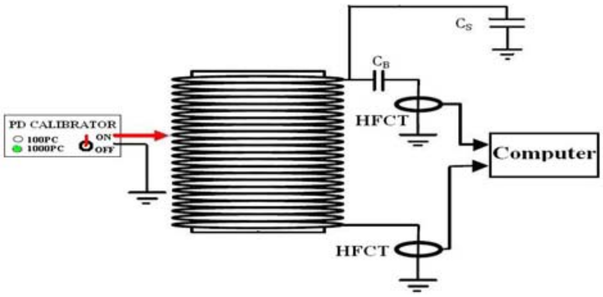

Figure 3: Transformer winding equivalent model

3 SIMULATION RESULT

Based on application of the above algorithm, a program is developed in the Matlab domain. That algorithm is applied to the homogeneous transformer windings, 900MVA, 525kV, Shell type. The high voltage winding of this transformer contains 12 disks. The transformer related dimensions and coefficients are shown in tables 1.

Assume a sinusoidal power supply with the amplitude of E_0 and angular frequency of ω is applied on the transformer. Transformer winding is modeled by using the frequency dependent transmission line model. The final goal in this section is to determine the resonance frequencies and the location of PD along the winding. The Fig. 5 show the calculated over voltages between transformer disks [10], has demonstrated the accuracy of this modeling method.

By injecting the PD calibrator signal to the different part of the winding, frequency content of Is and In is calculated. Fig. 6 shows the frequency spectrum of PD calibrator signal and fig. 7 shows Frequency spectrum of Is. As it appear in the Fig. 7 as the PD location become closer to the top of winding (where the **Is** is measured) the amplitude of **Is** will increase and the frequency spectrums peak of the **Is** move toward the higher frequencies as PD location become closer to the bushing end. This process is reverse for **In** and is shown in the Fig.8. The above results are true because as PDs propagate in the winding it lose higher frequency content very soon.

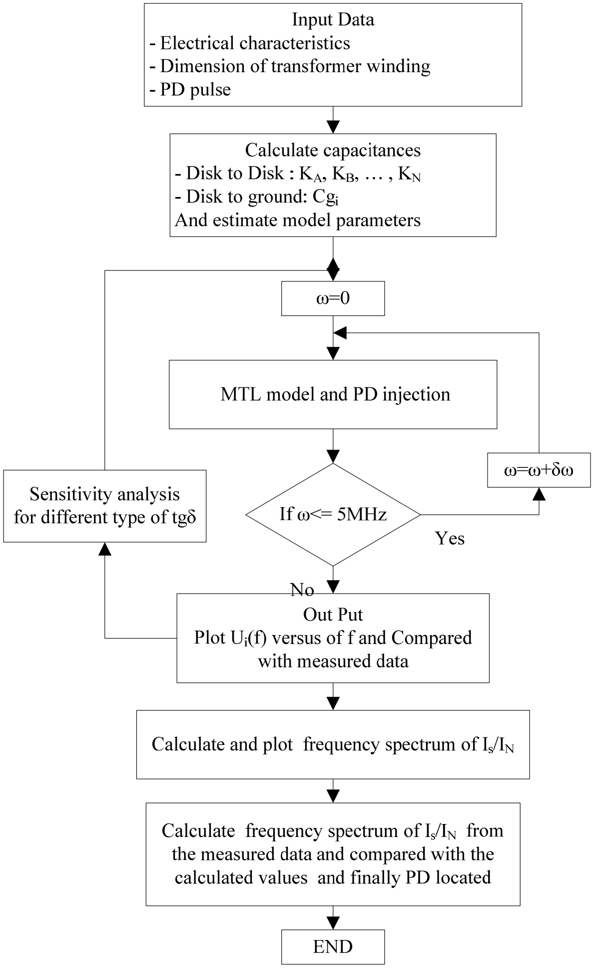

Figure 4: Algorithm MTL model and PD injection

4 LABORATORY TEST MODEL

By injecting PD simulated signal of a PD calibrator to different part of a laboratory winding it was shown that if the location of PD be far from the measurement point, most of the signal will be lost. Fig. 9 shows the Experimental test set up. Fig. 10 shows the recorded signal and Fig. 11 shows the frequency content of the measured signals.

Fig. 10 shows how the magnitude of the signal is attenuated and deformed while passing the winding. In addition, Fig. 11 shows the frequency content of these measured signals at different turns of the winding is determined. As it shown when PD source is located in a turn close to the sensor (in this case signal was measured through the winding lead) the measured signal has a wide frequency band, while if the PD source is located in a turn far from the sensor, the measured signal will have a limited frequency band. Using PD calibrator set to 1000pc, the PD pulse is injected to each node along the winding and the results are recorded. Using Matlab FFT, the frequency content of the measured signal is computed.

As shown in this figures when a PD pulse is passing through the winding, the magnitude and the frequency content of the signal will be reduced relatively. By heeding to the frequency related to maximum amplitude in the frequency spectrum, PD in the winding can be located.

5 CONCLUSION

In this paper a wide band MTL based model is employed for transformers to study the PD location along the winding of a transformer. The MTL model equations are reformulated to apply the PD simulated signal along the winding for investigation of PD location. The winding of a high voltage power transformer, 900MVA, 525kV, is simulated by using the MTL model with frequency dependent parameters and then by comparing the result with the measured signals, the accuracy of the model is verified.

Using this model, the PD propagation in the winding is studied and it is shown that by frequency spectrum of I_s and I_N, the location of PD pulse in the winding can be found. This method is employed to locate the PD in a laboratory winding. The results show how the signal magnitude is attenuated and its shape is deformed. In addition, the frequency content of the measured signal when PD is injected to different turns of the winding are computed.

Table 1: Dimensions and characteristics

Number of disks	$m = 12$
Turn average length	$a' = 6.83$m
Disk turns	N^i = 17,17,21,23,21, 23,23,23,17,21,21,17
Dielectric coefficient	$\varepsilon_r = 2.5$
Dielectric loss coefficient	$\tan\delta$ = Fix and frequency dependent
Surge velocity	$\upsilon_s = 184\ m/\mu.s$
Conductor conductance	$\sigma = 5 \times 10^{7}\ {}^{s}\!/\!{}_{m}$
Permeability	$\mu = \mu_0 = 4\pi \times 10^{-7}\ {}^{H}\!/\!{}_{m}$
Disks gap	d = ٣.٥٥ mm
Disk to disk capacitance	$\overset{(i)}{C}_m = 4016\ p.F$
Disk to ground capacitance	$\overset{(i)}{C}_g = 28\ p.F$
Inter-turn capacitance	$K^{(i)}$ =160 pF/m
Conductor static plate	$\overset{(1)}{C}_0$ = 34.6 pF/m $\overset{(1)}{C}_1$ = 3.9 pF/m

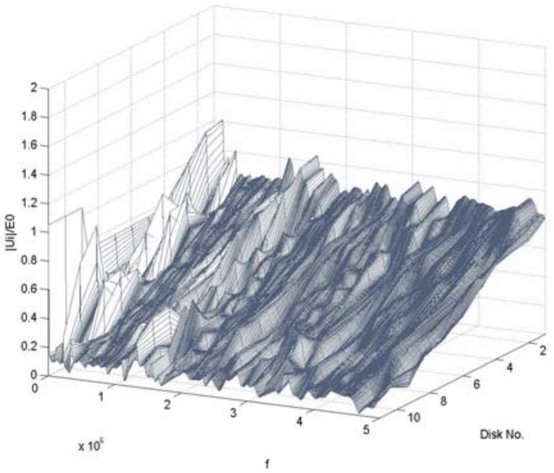

Figure 5: Over voltage between disks for tan δ=0.2

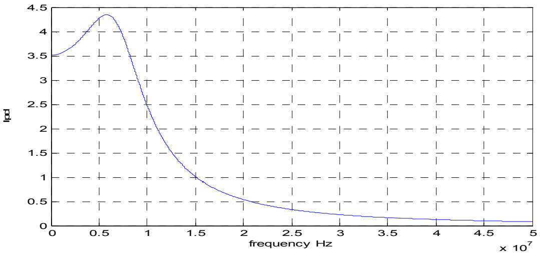

Figure 6: Frequency spectrum of PD calibrator signal

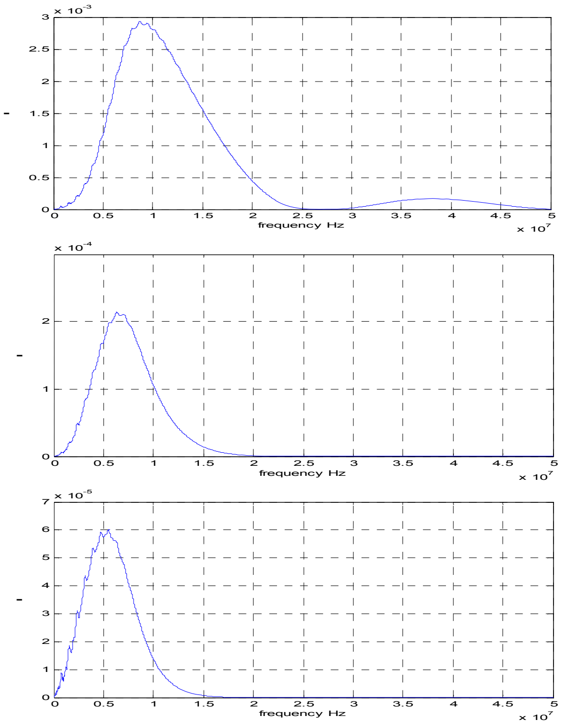

Figure 7: Frequency spectrum of Is when occurred in the disk Number 2, 6 and 10 respectively from up to down

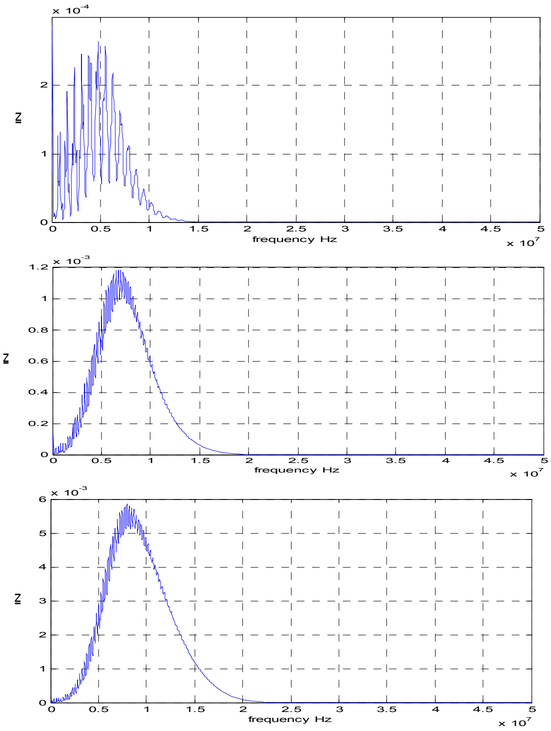

Figure 8: Frequency spectrum of In when PD occurred in the disk number 2, 6 and 10 respectively from up to down

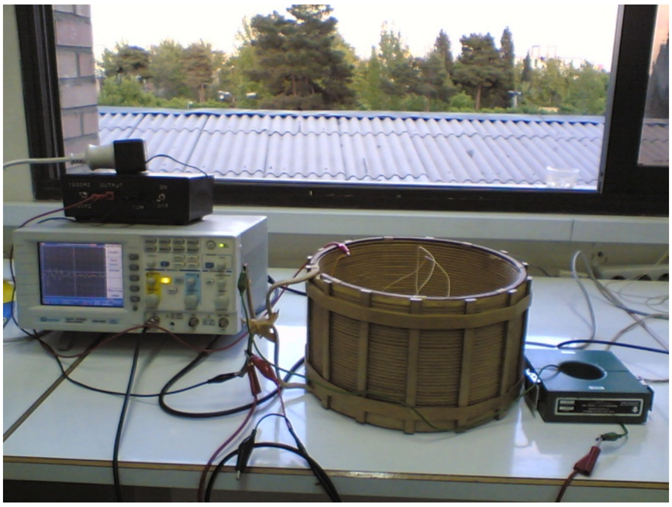

Figure 9: Experimental test set up for laboratory winding

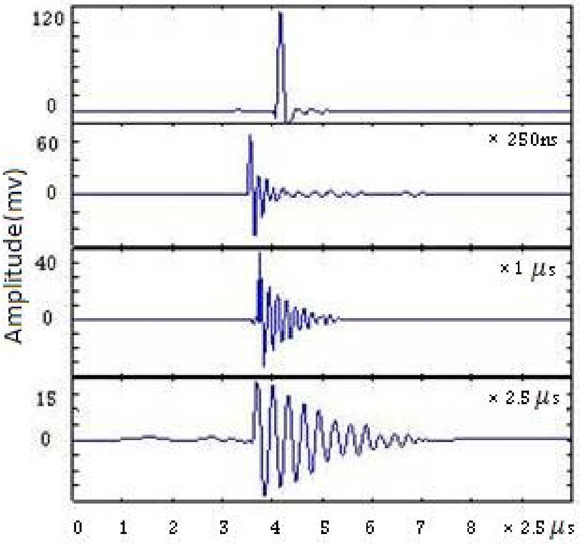

Figure10: PD pulse shape (PD calibrator pulse) - PD pulse after passing 6 turn - PD pulse after passing 12 turn - PD pulse after passing 33 turn (Respectively from top to down).

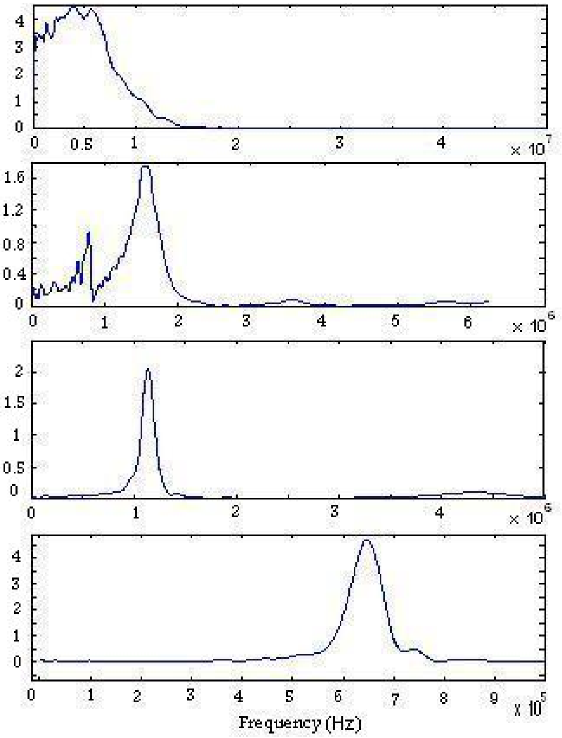

Figure11: Frequency content (PD calibrator pulse) - PD pulse after passing 6 turn - PD pulse after passing 12 turn - PD pulse after passing 33 turn (Respectively from top to down).

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