Partial Discharge Location in Transformers through Application of MTL Model

S. M. H. Hosseini, M. Ghaffarian, M. Vakilian, G. B. Gharehpetian, F. Forouzbakhsh

***Abstract*--In this paper a wide band MTL model of transformer winding employed to best simulate propagation of partial discharge signals in transformers 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 disks 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 transformer (50MVA, 220/35 kV), is simulated using the Multi Conductor Transmission Line (MTL) model with frequency dependent parameters (tanδ , ε).**

***Keywords:* Partial Discharge, Transformers, Multi Conductor Transmission Line model.**

I. INTRODUCTION

IN electrical power markets, the reliability of power systems is one of the most important concerns of the power system operators, since it has the main role in continuation of the customers' service without any disturbance. Many customers are willing to pay higher rates to have a reliable service without interruption. Thus the utilities need to improve their reliability. And 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 is 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. Additionally there is no need to equipments that simulate the high voltage stress on the insulation. After 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 modeled with high accuracy. PD signals contain a wide frequency range that expands 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.

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II. PD FREQUENCY CONTENT

Two real PD signals that are measured on a 20 kV distribution transformer and on a 420 kV power transformer respectively (after de-nosing or separation noise from the measured signals) are depicted in the Fig. 1. Using the Matlabs FFT function, frequency content of these signals is calculated and shown in Fig. 2. As it can be examined from these frequency analysis results, obtained for both transformers, two main zones of frequency content for PD in power and distribution transformer exists; one below 1MHz and the other one between 7 to 9 MHz. Therefore the transformer winding modeling must employ models to be valid for a wide frequency range such as MTL model.

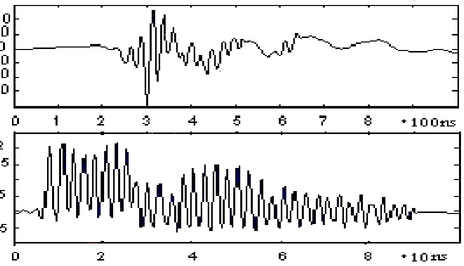

Fig. 1. Recorded PD pulse after de- noising,
(a) 20kV distribution transformer (b) 400kV power transformer

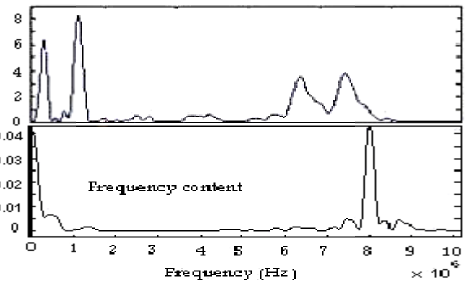

Fig. 2. Frequency spectrum of PD pulse showed in the figure1

III. TRANSFORMER WINDING MODELING

Transformer modeling methods [2-5] can be classified to Gray Box or parametric modeling and Black Box models.

The Gray Box models can be used by designers to study the resonance behavior of transformer winding and the distribution of electrical stresses along the transformer windings.

As a result, in the design stage, the Gray Box model has privileges to the Black Box model. The Gray Box models can be categorized as: "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 Gray and Black Box models [4]. 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 [2-5] and also on only the homogenous transformer windings ignoring the frequency dependency of the winding insulation parameters [4, 8]. While, [10] addressed in a general form application of MTL to transformer modeling.

A. 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 disk is depicted in the figure 3. 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.

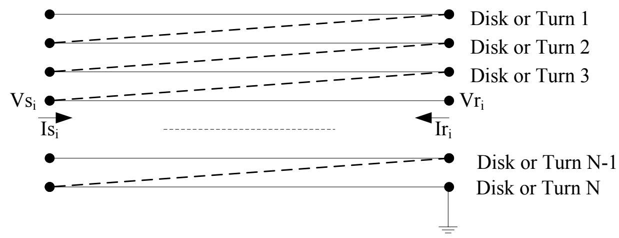

Fig. 3. Multi-conductor transmission line model

Surge impedances and coefficient of propagation can be estimated by comparison of these two models. The following equations are the result of this comparison [8-11].

$$z_i = \frac{1}{v_s\left[C_0^{(i)} + C_1^{(i)} + 2K\left\{1 - \cos\left(\frac{\omega a}{v_s}\right)\right\}\right]} \quad (1)$$

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

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 disks gap respectively. The details of modeling and the parameters estimation for an inhomogeneous winding (realizing frequency dependent parameters) are discussed in [10].

B. PD Injection

According to the figure 3 we have this telegraphs equations:

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

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

In (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):

$$\frac{\partial E_0}{\partial t} = 0 \quad (5)$$

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

$$V_i(x) = A_i \exp(-\Gamma(\omega)x) + B_i \exp(\Gamma(\omega)x) \quad (6)$$
$$I_i(x) = \frac{1}{z_i}[A_i \exp(-\Gamma\omega x) - B_i \exp(\Gamma(\omega)x)] \quad (7)$$

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

$$I_S(i+1) = I_r(i) \quad \text{For i=1 to N-1} \quad (8)$$
$$V_S(i+1) = V_r(i) \quad \text{For i=1 to N-1} \quad (9)$$

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. Then,

$$I_S(1) = -j\omega C_B V_S(1) \quad (10)$$

If the neutral end is at earth potential,

$$V_r(N) = 0 \quad (11)$$

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

$$I_S(k) = I_r(k-1) + I_{PD} \quad (12)$$

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.

C. PD Location

PD location using the MTL model was studied in several papers [1, 12, 13]. In this section the (6) and (7) are reformulated, using the terminal conditions. The unknown parameters; A_i and B_i are considered as unknown vector (X), x_i is element of vector X, $a(i,j)$ and $a^*(i,j)$ are the elements of A and A^* respectively. By writing the equations one can obtain:

$$[A][X] = [B] \quad (13)$$

$$\begin{bmatrix} & & \\ & A & \\ & & \end{bmatrix} \begin{bmatrix} \\ X \\ \\ \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ \cdot \\ \cdot \\ \cdot \\ I_{PD} \\ \cdot \\ 0 \end{bmatrix} \quad (14)$$

$$I_S = \frac{1}{z_1}(x_1 - x_2) \quad (15)$$

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

By multiplying A^{-1} into (13) and by replacing A^{-1} with its equal value, $\frac{[A]^*}{|A|}$, on can obtain (17):

$$[X] = \frac{[A]^*}{|A|}[B] \quad (17)$$

$$x_1 = \frac{a^*(1,k) \times z_{k+1} \times z_k \times I_{PD}}{|A|} \quad (18)$$

$$x_2 = \frac{a^*(2,k) \times z_{k+1} \times z_k \times I_{PD}}{|A|} \quad (19)$$

$$x_{2N-1} = \frac{a^*(2N-1,k) \times z_{k+1} \times z_k \times I_{PD}}{|A|} \quad (20)$$

$$x_{2N} = \frac{a^*(2N,k) \times z_{k+1} \times z_k \times I_{PD}}{|A|} \quad (21)$$

$$\frac{I_S}{I_N} = \frac{z_N}{z_1} \times \frac{a^*(1,k) - a^*(2,k)}{a^*(2N-1,k) \times a(N,2N-1) - a^*(2N,k) \times a(N,2N)} \quad (22)$$

As it appears from the (22), the frequency spectrum of I_s/I_N depends only on the location of PD and the windings parameters (values of $a(i,j)$ and $a^*(i,j)$ are only depended to winding structural parameters and location of PD determined that which of them are related to the frequency spectrum of I_s/I_N. In the above equations it is assumed that in the matrix A, the voltage equations placed at first (at top of matrix) and then current equations placed below them.

The 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.

IV. CASE STUDY AND SIMULATION RESULTS

Based on application of the above algorithm, a program is developed in the Matlab domain. That algorithm is applied to the inhomogeneous transformer windings, 50MVA, 220/30kV, the high voltage winding of this transformer contains 56 disks, the first 6 pair disk are interleaved and the next 22 pair disk are inverted type.

Realizing the disks dimensions as presented in the table 1, this winding is called inhomogeneous from structural point of view [5, 10]. The transformer related dimensions and coefficients are shown in the fig. 5 and 6 and in the tables 2 and 3 [5, 10].

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

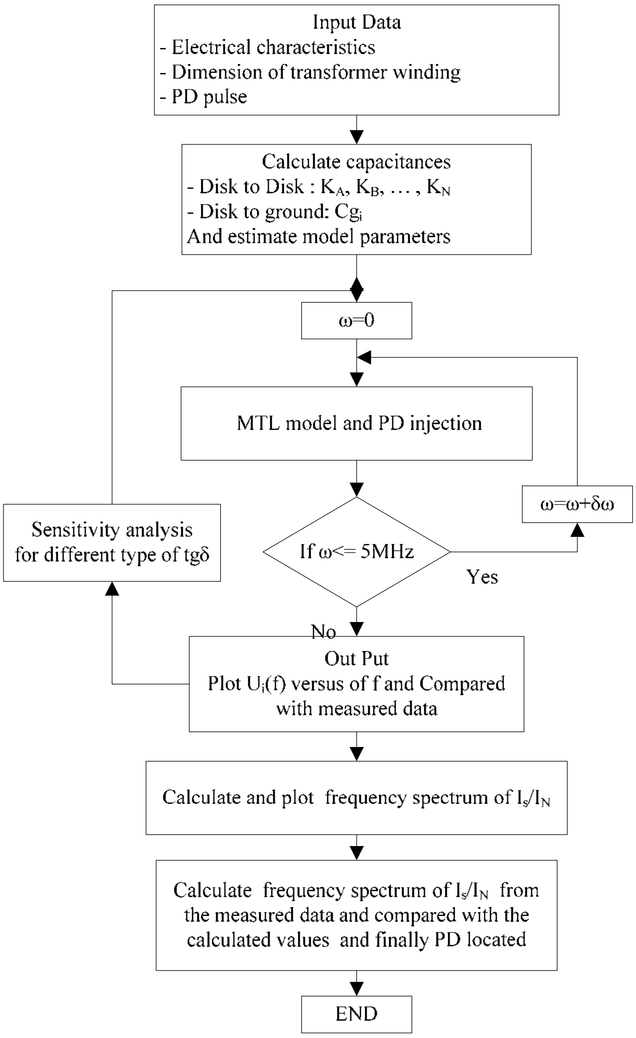

Fig. 4. Algorithm MTL model and PD injection

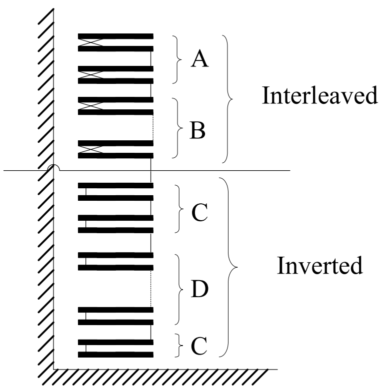

Fig. 5. Internal connections for the H.V winding of the transformer

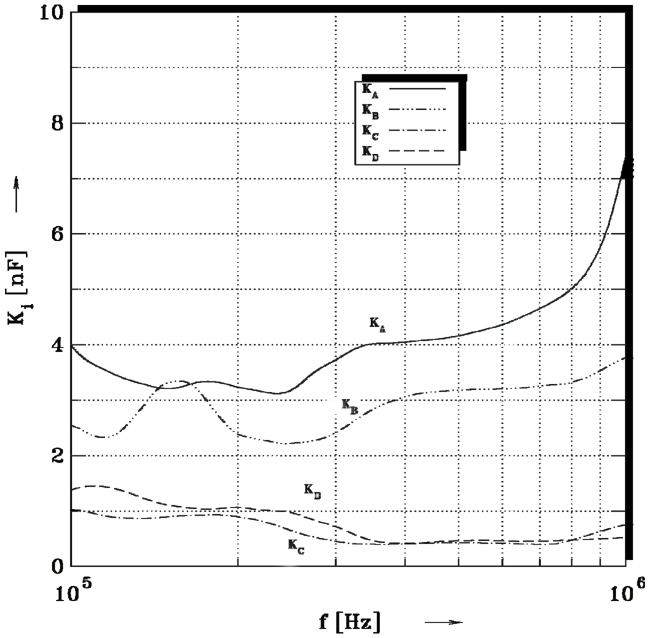

Fig. 6. Estimated capacitances of H.V winding
K_A, K_B, K_C, K_D: the disk to disk equivalent capacitances

Table 1. Dimensions of the double disks

	Winding type	Disks Numbers	From Disk *n* to *m*	Disk turns	width × height *mm* × *mm*
A	Interleaved	4	1-5	$13\frac{18}{20}$	15.0×3.0
B	Interleaved	8	5-13	$12\frac{18}{20}$	13.2×2.8
C	Inverted	4	13-17	$15\frac{18}{20}$	17.0×2.5
D_1	Inverted	28	17-45	$19\frac{17}{20}$	22.0×2.0
D_2	Inverted	9	45-54	$19\frac{18}{20}$	17.0×2.0
C	Inverted	3	54-end	$15\frac{18}{20}$	17.0×2.5
Σ		56		1005	

Table 2. Disk to disk and disk to grand capacitances calculated using analytical methods

Disk Capacitance				
Type	A	B	C	D
Nodes	28 -26	26 -22	22 - 20 , 2 - 1	20 - 2
Abbreviation	K_A	K_B	K_C	K_D
Value (nF)	4.47	3.05	0.31	0.32
Ground Capacitance: $C_g = 9\ P.F$				

Table 3. Dimensions and characteristics of the double disks

Number of disks	m =56
Turn average length	a^i = 3.35m
Disk turns	N^i = **A**: 4*13.9 - **B**: 8*12.9 **C**: 4*15.9 - **D$_1$**: 8*12.9 **D$_2$**: 9*19.9 - **C**: 3*15.9
Dielectric coefficient	$\varepsilon_r = 2.5$
Dielectric loss coefficient	$\tan\delta$ = Fix and frequency dependent
Surge velocity	$\upsilon_s = 190\ m/\mu.s$
Conductor conductance	$\sigma = 5 \times 10^7\ S/m$
Permeability	$\mu = \mu_0 = 4\pi \times 10^{-7}\ H/m$
Disks gap	d = 7 mm
Disk to disk capacitance for f < 1 MHz	$C_A^{(i)} = 4470\ p.F$, $C_B^{(i)} = 3050\ p.F$, $C_C^{(i)} = 310\ p.F$, $C_D^{(i)} = 320\ p.F$
Conductor static plate for f < 1 MHz	$C_0^{(1)}$ = 48.285 pF/m $C_1^{(1)}$ = 1.10pF/m
Disk to disk capacitance for 1≤ f ≤ 5 MHz	$C_A^{(i)} = 6000\ p.F$, $C_B^{(i)} = 40000\ p.F$, $C_C^{(i)} = 320\ p.F$, $C_D^{(i)} = 330\ p.F$
Conductor static plate for 1≤ f ≤ 5 MHz	$C_0^{(1)}$ = 62.22 pF/m $C_1^{(1)}$ = 1.12 pF/m
Inter-turn capacitance	$K^{(i)}$ =160 pF/m
Disk to ground capacitance	$C_g^{(i)} = 9\ p.F$

The Figures 7 and 8 show the overvoltages between transformer disks, measured overvoltage and calculated overvoltage respectively. [10], has demonstrated the accuracy of this modeling method.

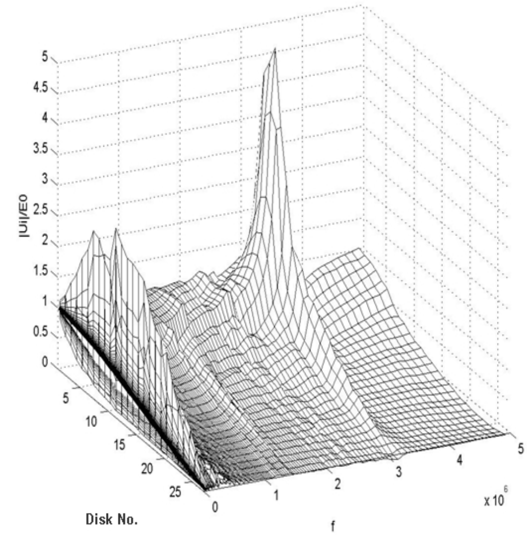

Fig. 7. Proportion of measured voltage between disks to the excitation function in the 10kHz ≤ f ≤ 5 MHz frequency range

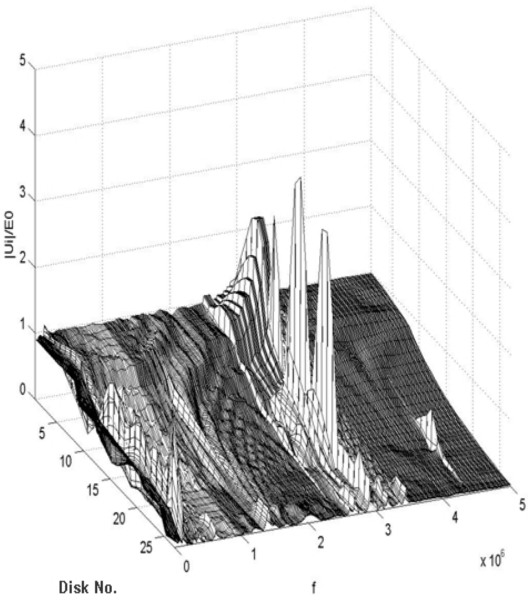

Fig. 8. Proportion of calculated voltage between disks to the excitation function in the 10kHz ≤ f ≤ 5 MHz frequency range

As it shown in the section III-C, the frequency spectrum of I_s/I_N will change when PD location move along the winding length. The frequency spectrum for I_s/I_N depends on the winding parameters and location of PD pulse. By comparing the frequency spectrum of Is/I_N calculated from the recorded signals with the relevant curve determined by simulation, the location of PD can be determined. In this section several examples of those curves, for this transformer, are depicted.

Disks are numbered from top to bottom. As it is shown in figures 9-11, the amplitude of Is/I_N is reduced, as the PD location approaches the end of winding. Realizing the reduction in amplitude and resonance frequencies along the winding, there are specific resonance frequencies in each figure that is not involved in the other figures). Comparing the simulation results with the recorded signals, the location of PD in the winding can be estimated.

V. 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.

Since the recorded PD signals of two type of transformer (one of distribution type and the other one an EHV type) demonstrated a wide range of frequency content in the related PD signals, a MTL model proved to be one of the best models for this purpose.

The winding of a high voltage power transformer, 50MVA, 220/35kV, is simulated by using the MTL model with frequency dependent parameters and then by comparing the result with the measured signals, the accuracy of this simulation is certified.

Then by using this model, the PD propagation in the winding is studied and at the end by a simple method it is shown that by frequency spectrum of I_s/I_N one can find the location of PD pulse in the winding.

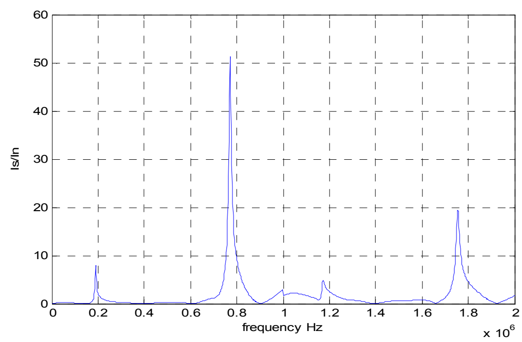

Fig. 9. Frequency spectrum of I_s/I_N when PD occurred in the disk number 1

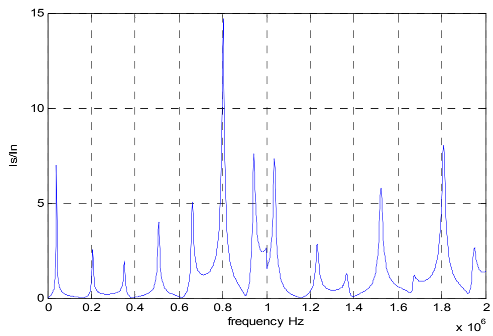

Fig. 10. Frequency spectrum of I_s/I_N when PD occurred in the disk number 7

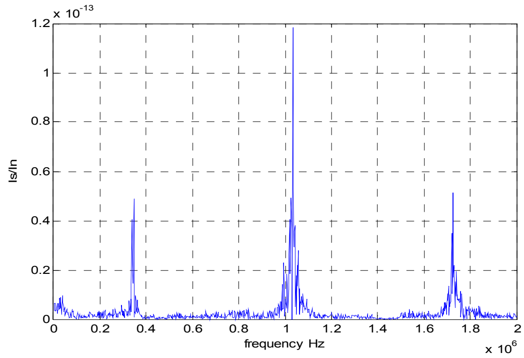

Fig. 11. Frequency spectrum of I_s/I_N when PD occurred in the disk number 11

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