Simulation of UHF signal propagation in transformer and a novel algorithm for partial discharge localization

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Abstract: Detection of partial discharges (PDs) in high voltage equipment can be viewed as a way of anticipating the forthcoming failure of equipment and thus saving it through planned maintenance. There are various methods for detection of partial discharge. Among them UHF signals can be used for monitoring and finding the location of PD. The first stage of this method is modelling and simulating of UHF propagation of partial discharge in transformer. The modelling and simulation of UHF propagation can be done by CST software environment. Due to the processing limitation of the mentioned software, in this work, simulations have been executed using the numerical method of finite difference time domain (FDTD) by coding in both MATLAB and C++ environments. For a typical specimen, we have shown that there is a good agreement between software and code results. This simulation can be used in verification of localization algorithms. Here, localization of an artificially produced partial discharge signals have been conducted by merging particle swarm optimization (PSO) and FDTD. The obtained results show that this method can be utilized in PD localization in transformer.

1 INTRODUCTION

Power transformers are strategically important components used in the power transmission network. Their failure due to insulation breakdown can lead to serious consequences. PD is a pre-cursor to arcing or final transformer failure. Its detection is an effective means of verifying the insulation performance of power transformers [1, 4].

There are Different methods for detection of partial discharge. These methods are classified two categories of electrical and non-electrical methods. Non-electrical detection methods include acoustic signal detection, dissolved gas analysis and light detection. Dissolved gas analysis (DGA) is routinely employed to detect internal electrical discharging in power transformers. DGA can provide some information about the nature and severity of the PD [2]. However, knowledge of the PD location (which cannot be obtained from DGA) would be a great help to the specialists who must make decisions about remedial action [2].

Electrical methods include the use of capacitive sensors, inductive sensors and detection of UHF signals. UHF PD detection has been continuously applied in GIS monitoring but recently some researches have been made to apply this method for PD detection of power transformer [1]. This technique can be expected to realize wide range and high sensitive measurement of PD with less influence from external noise [1]. The following issues have been investigated by research in this area:

1) Simulating propagation of UHF signal [1-3-4, 5].
2) Locating of PD using UHF method [4-6].
3) Different antennas designed with various bandwidths at UHF frequency range [7-8].
4) Evaluation of the measurements sensitivity performed using UHF method [9].

The modelling and simulation of UHF propagation can be done by CST software environment. Due to the processing limitation of the mentioned software such as long run-time of program, impossibility of merging with locating algorithm and ..., in this work, simulations have been executed using the numerical method of FDTD by coding in both MATLAB and C++ environments. For a typical specimen, we have shown that there is a good agreement between software and code results. This written code can be utilized in investigation of impact of different factors on received signal via sensors. Moreover, there is an opportunity to use this utility in studying the possibility of happening PD in different insulating parts of a transformer. Also this simulation can be used in verification of localization algorithms. Here, localization of an artificially produced partial discharge signals have been conducted by merging PSO and FDTD. The obtained results show that this method can be utilized in PD localization in transformer.

2 FDTD METHOD

FDTD is an effective transient EM wave simulation method with extensive applicability and easy to realize [3]. In 1966 Yee proposed a technique to solve Maxwell's curl equations using FDTD technique. Yee's method has been used to solve numerous scattering problems on microwave circuits, dielectrics, and etc. Initially there was little interest in the FDTD method, probably due to a lack of sufficient computing resources. However, with the advent of low cost, powerful computers and advances to the method itself, the FDTD technique has become a popular method for solving electromagnetic problems [1].

In this paper the method which is used is Yee method. In this method the simulation environment is divided into small Yee cells and the dimension of the cell is $\Delta x = \Delta y = \Delta z = \delta$. In Figure 1 the structure of this method is shown. In such way the number of divisions of simulated area in x, y and z direction are N_x , N_y and N_z respectively. In this structure each point is located in:

$$(i, j, k) = (i\Delta x, j\Delta y, k\Delta z) \quad (1)$$

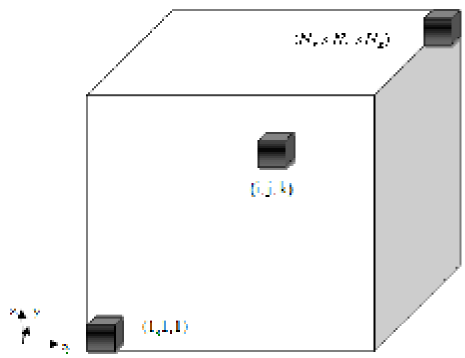

Figure 1: Yee cell which is used in the simulation

The electric and magnetic fields are calculated from Maxwell's equations. For example the magnetic field in the x direction (H_x) is calculated from equation (2). The other electric and magnetic fields are obtained from the same way [11].

$$\begin{aligned} H_x^{n+\frac{1}{2}}(i,j,k) &= \frac{2\mu_x(i,j,k) - \Delta t \sigma_x^m(i,j,k)}{2\mu_x(i,j,k) + \Delta t \sigma_x^m(i,j,k)} H_x^{n-\frac{1}{2}}(i,j,k) \\ &+ \frac{2\Delta t}{(2\mu_x(i,j,k) + \Delta t \sigma_x^m(i,j,k))\Delta z} (E_y^n(i,j,k+1) - E_y^n(i,j,k)) \\ &- \frac{2\Delta t}{(2\mu_x(i,j,k) + \Delta t \sigma_x^m(i,j,k))\Delta y} (E_z^n(i,j+1,k) - E_z^n(i,j,k)) \end{aligned} \quad (2)$$

In these equations, Δt is time step, n is time index, H is magnetic field, E is electric field, ε is permittivity, μ is permeability, σ is conductivity. To yield accurate results, the grid spacing δ in the finite difference simulation must be less than the wavelength, usually less than $\lambda / 10$. The stability condition relating the spatial and time step size is:

$$V_{max} \Delta t \leq \frac{1}{\sqrt{\frac{1}{(\Delta x)^2} + \frac{1}{(\Delta y)^2} + \frac{1}{(\Delta z)^2}}} \quad (3)$$

Where V_{max} is the maximum velocity of the wave. Having derived the FDTD updating equations, a time marching algorithm can be constructed as illustrated in Figure 2[11].

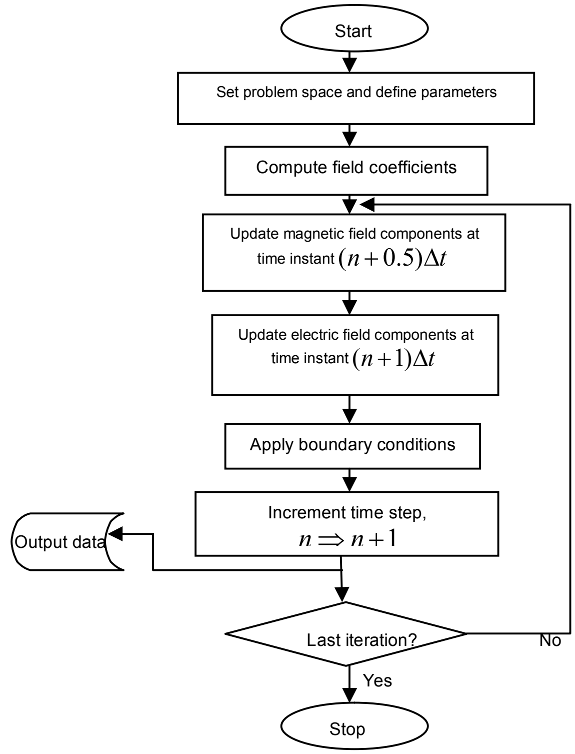

Figure 2: Explicit FDTD procedure [11].

3 VERIFICATION OF FDTD SIMULATION ENVIRONMENT BY USING CST SOFTWARE

According to the algorithm that presented in the previous section, the program for UHF signal propagation simulation was written in C++ environment. In this simulation dipole antenna is used for PD modelling. The theory analysis and practical measurement show that PD signals have a very steep wave front of 1~10 ns. So a typical pulse for exciting the antenna can be simulated by Gauss function as following [12]:

$$i(t) = I_0 \exp[-(t-t_0)^2 / (2\sigma^2)] \quad (4)$$

Where I_0 is amplitude, t_0 is the initial time, σ is characteristic waveform parameter which describing the pulse width at half maximum value (PWHM), the PWHM of PD pulse is equal to 2.36σ . It has been proved that this parameter is closely correlated to the geometric shape and insulation intensity of PD gap. Generally, smaller defect geometry dimension, causes steeper PD pulse wave front. Accordingly, PD current waveform parameter σ would be smaller too. Hence, the characteristic parameter σ of PD pulse current can help us to understand the PD state [12].

To evaluate the proposed method, a distribution transformer is considered. The dimensions of this transformer extracted from [13] are shown in Table 1. Figure 3 shows a cross view of this transformer.

Table 1: Transformer data which is used in simulation

Phase number	3
Core material	Steel
Core diameter	135 mm
Internal height of window (H_w)	300 mm
Internal width of window (W_w)	120 mm
External height of window (H)	536 mm
External width of window (W)	624 mm
Yoke diameter	118 mm
Tank height	950 mm
Tank width	840 mm
Tank length	350 mm
Dielectric constant of oil	2.2

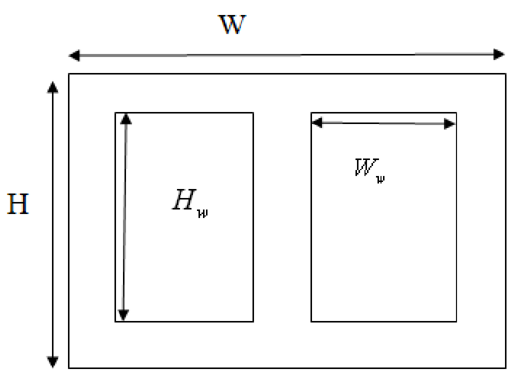

Figure 3: Core dimensions

For simplicity of comparison between two simulation environments, only one core is considered in center of transformer tank. The space step in FDTD method is chosen to be $\Delta x = \Delta y = \Delta z = 5\,mm$ and the time step according to equation (3) is set to $\Delta t = 9.6292 \times 10^{-12}$. The setting in CST was so applied that the number of its meshes to be equal with that in proposed simulation environment. The radiating source point is set at the point (85, 415, 225) in space coordination. Figure 4 shows the simulating environment in CST. The radiating source is energized by a current wave form shown in Figure 5. Figure 6 shows the electric field in two simulation environments. It is clear from this figure that the results have good accordance with each other.

The created simulation environment with FDTD method can be used for simulation of transformer with full components. For achieving this goal some cylinders were used to simulate the limbs and yokes of transformer core in FDTD environment. Figure 7a and 7b show the cross view of simulated transformer. Tangential electrical fields and vertical magnetic fields in FDTD environment were set to be zero in the boundaries of the core. Same considerations were applied to simulate windings. Different dielectric constants in different space positions were considered to simulate various insulating materials inside transformer tank. This simulation environment can be used for investigation of impact of different factors on received signal via sensors. Moreover, there is an opportunity to use this utility in studying the possibility of happening PD in different insulating parts of a transformer.

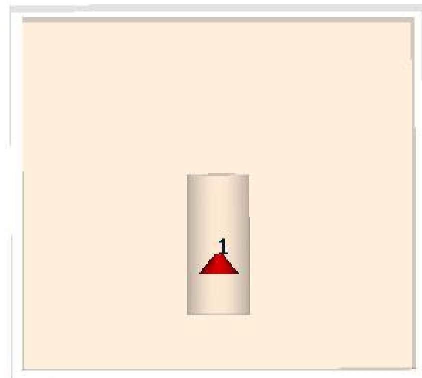

Figure 4: Simulated environment in CST to confirm the FDTD method accuracy

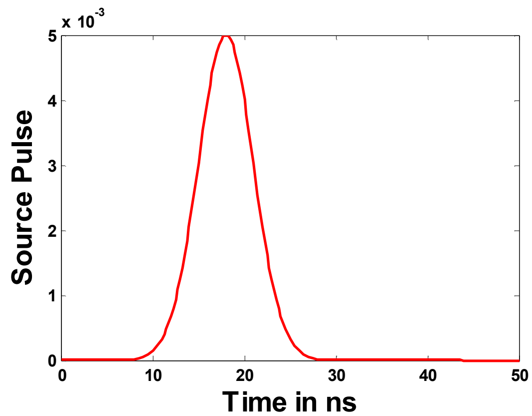

Figure 5: Excitation pulse

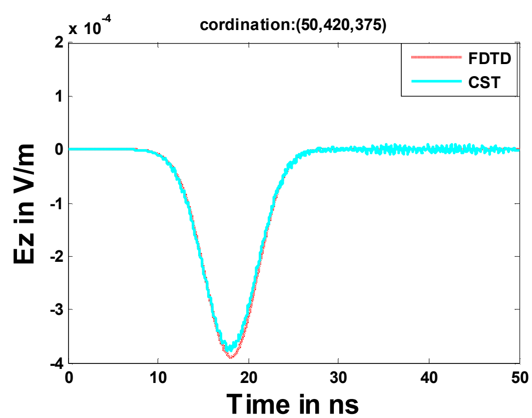

Figure 6: The achieved results for received signal in CST and FDTD method

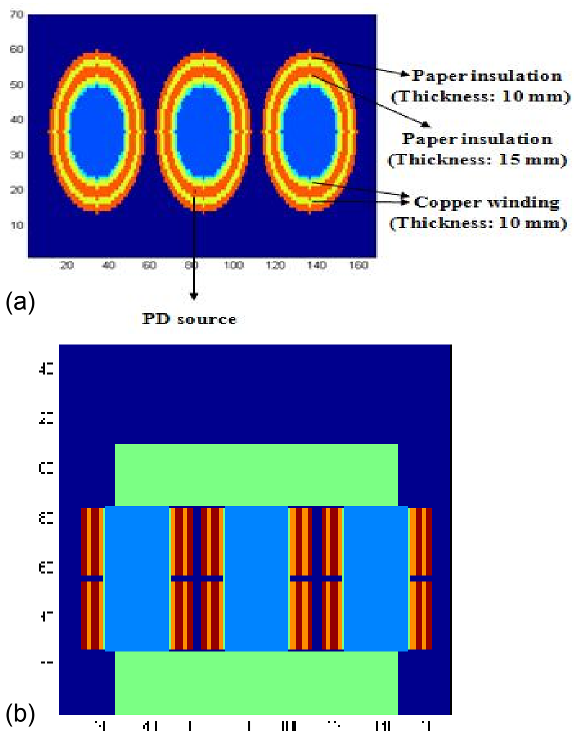

Figure 7: Schema of simulated transformer in different coordinate directions a) z direction b) x direction

4 OFFERING AN ALGORITHM FOR PD LOCALIZATION

In this section, a novel algorithm is suggested for PD localization. This algorithm is obtained with merging of FDTD method and PSO algorithm. At first, a brief explanation is presented about the PSO optimization algorithm and then the localization algorithm is discussed.

4.1 PSO ALGORITHM

PSO is a population based stochastic optimization technique developed by Eberhart and Kennedy in 1995. The PSO algorithm is inspired by social behaviour of bird flocking or fish schooling [14].

PSO learned from this bird-flocking scenario, and used it to solve the optimization problems. In PSO, each single solution is a “bird” in the search space. It is called “particle”. All of particles have fitness values which are evaluated by the fitness function (the cost function to be optimized), and have velocities which direct the flying of the particles. The particles fly through the problem space by following the current optimum particles [14].

PSO is initialized with a group of random particles (solutions) and then searches for optima by updating generations. During every iteration, each particle is updated by following two "best" values. The first one is the position vector of the best solution (fitness) this particle has achieved so far. The fitness value is also stored. This position is called Pbest. Another "best" position that is tracked by the particle swarm optimizer is the best position, obtained so far, by any particle in the population. This best position is the current global best and is called Gbest [14].

After finding the two best values, the particle updates its velocity and position according to equations (5) and (6).

$$v_{k+1}^{i} = wv_{k}^{i} + c_1 r_1 (pbest^{i} - x_{k}^{i}) + c_2 r_2 (gbest_{k} - x_{k}^{i}) \quad (5)$$

$$x_{k+1}^{i} = x_{k}^{i} + v_{k+1}^{i} \quad (6)$$

Where v_{k+1}^{i} is the velocity of particle number (i) at the $(k+1)^{th}$ iteration, x_{k+1}^{i} is the current particle (solution or position). r_1 and r_2 are random numbers between 0 and 1. c_1 is the self confidence (cognitive) factor; c_2 is the swarm confidence (social) factor. Usually c_1 and c_2 are in the range from 1.5 to 2.5; w is the inertia factor that takes values downward from 1 to 0 according to the iteration number [14].

The flowchart of PSO algorithm and more explanation about it can be find in [14-15] references.

4.2 MERGING OF FDTD METHOD AND PSO ALGORITHM FOR PD LOCALIZATION

In PD localization method, at first stage the PD source is putted in defined local, then the electric field in z direction (E_z) is saved in three different positions. In fact these fields are “measured fields”. After this stage, is assumed that the PD position is unknown. Some random local is considered as X vector of PSO algorithm. FDTD method is run for these intended positions and obtained electric fields are saved. By using these fields and measured fields, the fitness function of optimization algorithm is calculated from equation (7). Also the velocity vector is calculated from equation (5).

$$fit\text{ - }function = \sum_{i=1}^{N_{max}} ((a)^2 + (b)^2 + (c)^2) \quad (7)$$

$$a = X_{1i}^{m} - X_{1i}^{s}$$
$$b = X_{2i}^{m} - X_{2i}^{s}$$
$$c = X_{3i}^{m} - X_{3i}^{s}$$

Where N_{max}, maximum number of iteration in FDTD method, X_{1i}^{m}, X_{2i}^{m} and X_{3i}^{m} are the measured electric fields in 1, 2 and 3 position and X_{1i}^{s}, X_{2i}^{s}

and X_{3i}^{s} are the simulating fields in 1, 2 and 3 position respectively.

The localization algorithm is run until the value of fitness function reaches zero. When the fitness function value be zero, the algorithm ends and the local of PD be found. In this paper the position of sensors according Figure 8 are considered in the center of transformer tank wall.

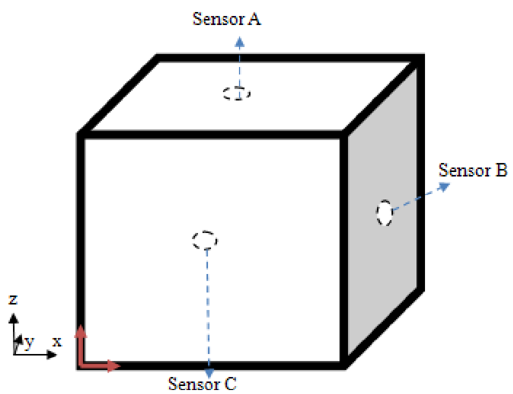

Figure 8: The position of detection sensor

4.3 EXAMPLE FOR PD LOCALIZATION

For this purpose, a $50\times50\times450\,mm^3$ volume is considered to simulate oil filled tank. The PD source is set at the point (25, 25,225) in space coordination. The electric field signal is received at (5, 25,225), (25, 5,225) and (25, 25, 425) in space coordination. In fact these fields are measured fields. The position vector in PSO algorithm (X_k^i) is selected as follows:

$$X= [30\ 40\ 100;\ 25\ 40\ 150;\ 20\ 20\ 145;\ 30\ 30\ 180;25\ 25\ 230;15\ 20\ 250] \quad (8)$$

This vector has 6 populations. With selection such vector, PD is localized after 36 iterations. Figure 9 shows the fitness function convergence curve.

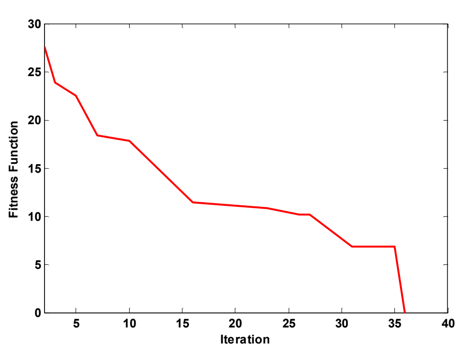

Figure 9: fitness function convergence curve

In other example, PD source is set at (30, 20,125). The electric field signals are received at same position. The position vector in PSO algorithm is selected as follows:

$$X= [40\ 25\ 110;\ 35\ 25\ 145;\ 15\ 40\ 300;30\ 30\ 115;20\ 20\ 175] \quad (9)$$

This vector has 5 populations. With selection such vector, PD is localized after 43 iterations. Figure 10 shows the fitness function convergence curve.

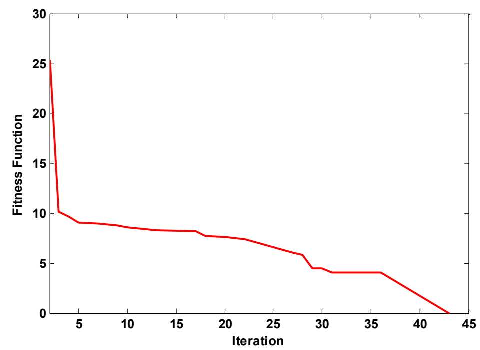

Figure 10: fitness function convergence curve

Finally, PD source is set at (35, 25,90). The electric field signals are received at same position. The position vector in PSO algorithm is selected as follows:

$$X= [20\ 20\ 100;\ 25\ 40\ 150;\ 30\ 15\ 300;\ 30\ 30\ 125;35\ 20\ 275;35\ 35\ 350] \quad (10)$$

This vector has 6 populations. With selection such vector, PD is localized after 12 iterations. Figure 11 shows the fitness function convergence curve.

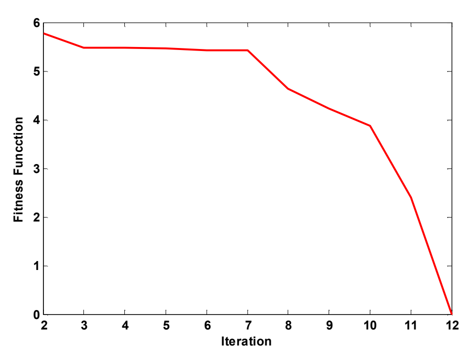

Figure 11: fitness function convergence curve

5 CONCLUSION

In this paper simulation of UHF signal due to release of PD in transformer has done and a new algorithm is presented for it localization. The results show that this new method can be merged with simulation environment that they are used for simulation of PD propagation. If the simulation environment similar to the real transformer, this method can be used for PD localization as efficient method.

6 REFERENCES

[1] Xu Bin, Li Junhao, Si Wenrong, and Li Yanming, "Simulating Propagation Characteristic of UHF Signal for PD monitoring in Transformers by FDTD Technique", Power and Energy Engineering Conference, 2009. APPEEC 2009. Asia-Pacific

[2] Martin D. Judd, Li Yang, Ian B. B. Hunter, "Partial Discharge Monitoring for Power Transformers Using UHF Sensors Part 1: Sensors and Signal Interpretation", IEEE Electrical Insulation Magazine, March/April 2005, Vol. 21, No. 2. pp. 5-14.

[3] Zhiguo Tang, Chengrong Li, Wei Wang, Hui Wang1, Li Wang, Yansheng Ding, "The Propagation Characteristics of Electromagnetic Wave Generated from Partial Discharges in Power Transformer by FDTD Simulation" 2007 Annual Report Conference on Electrical Insulation and Dielectric Phenomena, pp.200-203.

[4] L. Yang, M. D. Judd and G. Costa, "Simulating Propagation of UHF Signals for PD Monitoring in Transformers Using the Finite Difference Time Domain Technique" 2004 Annual Report Conference on Electrical Insulation and Dielectric Phenomena, pp.410-413.

[5] Chikku Abraham, S.V. Kulkarni, "FDTD Simulated Propagation of Electromagnetic Pulses due to PD for Transformer Diagnostics", TENCON 2008 - 2008 IEEE Region 10 Conference,pp.1-6.

[6] Z. B. Shen, and E. F. El-Saadany, "Localization of Partial Discharges Using UHF Sensors in Power Transformers" Power Engineering Society General Meeting, 2006. IEEE,pp.1-6.

[7] J. Lopez-Roldan, T. Tang and M. Gaskin, "Optimisation of a Sensor for Onsite Detection of Partial Discharges in Power Transformers by the UHF Method", IEEE Transactions on Dielectrics and Electrical Insulation Vol. 15, No. 6; December 2008, pp.1634-1639.

[8] Zhuorui Jin, Caixin Sun, Changkui Cheng, Jian Li, "Two Types of Compact UHF Antennas for Partial Discharge Measurement", International Conference on High Voltage Engineering and Application, Chongqing, China, November 9-13, 2008. pp.616-620.

[9] S. Coenen, S. Tenbohlen, S. M. Markalous and T. Strehl, "Sensitivity of UHF PD Measurements in Power Transformers" IEEE Transactions on Dielectrics and Electrical Insulation Vol. 15, No. 6; December 2008,pp.1553-1558.

[10] D. Denissov, W. Köhler, S. Tenbohlen1, R. Grund, T. Klein, "OPTIMIZATION OF UHF SENSOR GEOMETRY FOR ON-LINE PARTIAL DISCHARGE DETECTION IN CABLE TERMINATIONS", Proceedings of the 16th International Symposium on High Voltage Engineering, 2009 SAIEE, ISBN 978-0-620-44584-9

[11] Atef Z.Elsherbeni and Veysel Demir, "The Finite Difference Time Domain Method For Electromagnetics With MATLAB Simulations",SCITECH, pp.1-32,2009.

[12] Lixing Zhou, Weiguo Li, Sheng Su, "The Deduction of Partial Discharge Pulse Current from Its Radiating UHF Signal" Power Engineering Conference, 2005. IPEC 2005. The 7th International.

[13] A.k.SAWHNEY, "Principles of Electrical Machines Design" Published by J.C, Fifth Edition in 1984.

[14] M. B. Abdelhalim, A. E. Salama and S. E.-D. Habib," Hardware Software Partitioning using Particle Swarm Optimization Technique" The 6th International Workshop on System on Chip for Real Time Applications, pp.189-194

[15] J. J. Liang, A. K. Qin, Ponnuthurai Nagaratnam Suganthan, and S. Baskar, "Comprehensive Learning Particle Swarm Optimizer for Global Optimization of Multimodal Functions" , IEEE TRANSACTIONS ON EVOLUTIONARY COMPUTATION, VOL. 10, NO. 3, JUNE 2006, pp. 281-295.