TELKOMNIKA, Vol. 11, No. 9, September 2013, pp. 5097~5104
ISSN: 2302-4046

A Novel Traveling Wave based Differential Protection for Distributed Parameter Line

Baina He[1], Yunwei Zhao*[2], Hengxu Ha[1]
[1]College of Electrical and Electronics Engineering, Shandong University of Technology, ZiBo, China, 255049. Tel: 13685331324
[2]Department of Electric Engineering, Shandong Industry Polytechnic College, ZiBo, China, 256414.
*Corresponding author, e-mail: zhaoyun2090@sina.com

Abstract

Traditional current differential protection is based on Kirchhoff's Law, certainly is severely influenced by the distributed capacitance current. A new traveling wave based differential protective principle is proposed by employing the characteristics of current traveling waves for the distributed parameter line model. There are fixed propagation relations between traveling waves of terminals as the line is healthy or the fault is external, however, the relationship is broken for the internal faults. The protective criterion and scheme are established by this character. The key technique is to quickly calculate the propagating traveling waves from the other terminal on line. The coefficients of propagation function from one terminal to another are obtained by using orthogonal projection methods. The principle and algorithm need not high sampling frequency, are adaptive for not only fundamental component but the transient components, as well as is not sensitive to setting parameters. The large amounts of ATP simulation tests show that the protective scheme and algorithm is simple with high reliability, security, speedy and sensitivity.

Keywords: *traveling wave, differential protection, distributed parameter line model, orthogonal projection*

1. Introduction

Transmission lines play an important role in power transmission system. However, traditional transmission line protections, such as directional pilot protection, distance pilot protection, differential pilot protection, etc, are all employing the steady state power frequency component, based on the simple RL line model. For Extra High Voltage (EHV) or Ultra High Voltage (UHV) transmission lines, due to the distributed capacitances, the capacitive current increases significantly. These results in the amplitude and phase angle shift of the currents at the terminals of transmission line [1, 2]. Therefore, the capacitive currents caused by distributed parameters should be taken into account in the traditional current differential protective relays.

On the other hand, the fault transients in long EHV/UHV lines, due to the distributed parameters and the non-linear boundary conditions, have not only long decaying period, but also significant amplitude, which will lead to the mal-operation of differential protective system that based on steady state power frequency components [3, 4].

In order to match the capacitive currents for the differential protection in EHV/UHV long distance transmission lines, some capacitive current compensation schemes for current differential protection have been proposed, which can be classified into three categories: half-compensation, full-compensation and mixing compensation. However, the compensating errors are great if we use bus voltage to calculate capacitive current compensation, in additional, the fault transients are not considered yet. Therefore, it will reduce the sensitivity and security of differential protection with the distributed capacitance compensation [5-7].

The traveling wave based differential protection based on distributed parameter line model is proposed by document [8] and [9], however, they are all based on the non-distortion or

Received February 15, 2013; Revised June 4, 2013; Accepted June 17, 2013

nonlossy line model. Moreover, the principle and algorithms they proposed need higher sampling frequency and complex computation, therefore are not adaptive for realization.

This paper presents a novel scheme and algorithm of differential protection based on distributed parameter line model, which the fault transients and the distributed capacitive current are all taken into account completely. By fault analysis of transmission line, one can find that there are fixed propagation relations between traveling waves of terminals as the line is healthy or the fault is external, however, the relationship is broken for the internal faults. The protective criterion and scheme are established comparing an operating current traveling wave and restraint current traveling wave. The operating current traveling wave is defined as the difference of that between the two terminals, as well as the restraint current traveling is defined as the sum of the two terminals. The key technique is to quickly calculate the propagating traveling waves from one terminal to the other terminal on line. The coefficients of propagation function from one terminal to another are obtained by using orthogonal projection methods [10]. The principle and algorithm need not high sampling frequency, match for not only fundamental component but the transient components, as well as is not sensitive to setting parameters. The large amounts of ATP simulation tests show that the protective scheme and algorithm is simple with high reliability, security, speedy and sensitivity.

2. Transient Differential Protection Principle

Consider a single phase transmission line, shown in Figure 1. Suppose that there is a fault at location F, where is x kilometers far from terminal M, the line length is l. Based on the traveling wave theories, one can get the relationship of Forward Current Traveling Wave (FCTW) and Backward Current Traveling Wave (BCTW) between the two terminals M and N in frequency domain.

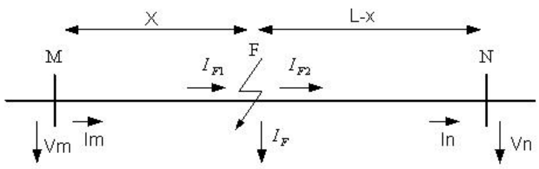

Figure 1. Typical Single Phase Line

At the case of no fault or external faults, there are fixed propagation relations between the two terminals:

$$\begin{cases} F_N(s) = F_M(s)A_L(s) \\ B_M(s) = B_N(s)A_L(s) \end{cases} \tag{1}$$

Where, $F = I + V / Z_c$ means Forward Current Traveling Wave, $B = I - V / Z_c$ means BCTW, $A_L(s) = \exp[-\gamma(s)L]$ means propagating function, $\gamma(s) = \sqrt{Z(s)Y(s)}$ means the propagation coefficient, Z and Y are respectively the per-length series impedance and shunt admittance of transmission line.

However, at the case of internal fault, see Figure 1, the relations of the traveling waves are shown in the follows:

$$\begin{cases} F_N(s) = F_M(s)A_L(s) - I_F \exp[\gamma(L-x)] \\ B_M(s) = B_N(s)A_L(s) - I_F \exp[\gamma(L-x)] \end{cases} \tag{2}$$

Where, I_F is the fault current of the branch of fault point to ground.

The novel transient differential protection principle will be detailedly explained utilizing the single-phase transmission network shown as Figure 2.

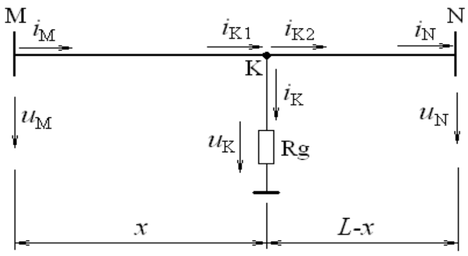

Figure 2. Single Phase Fault Line Model

2.1. Propagation Relationship

When the line is healthy or the exterior fault occurs, the propagation relation at two teminal (M,N) of line is written as:

$$\begin{cases} B_M(z) = A_L(z)B_N(z) \\ F_N(z) = A_L(z)F_M(z) \end{cases} \quad (3)$$

Where, $Z_C = \sqrt{Z(z)/Y(z)}$ is surge impedance, $B = U - Z_{cI}$ and $F = U + Z_{cI}$ are respectively the backward and forward voltage traveling wave, $A_L(Z) = \exp(-\sqrt{Z(z)Y(z)}L)$ is propagation function. Supposed that, at terminal M and terminal N:

$$\begin{cases} B_{op}(z) = A_L(z)B_N(z) \\ F_{op}(z) = A_L(z)F_M(z) \end{cases} \quad (4)$$

Hence, the longitudinal differential protection discriminant at the two terminal will be constructed as followed.

$$\begin{cases} \Delta B_M = \left\| B_{op}(z) - B_M(z) \right\| \\ \Delta F_N = \left\| F_{op}(z) - F_N(z) \right\| \end{cases} \quad (5)$$

Where, $\|\ \|$ stands for 2-norm, that is to say, virtual value.

Obviously, when the line is healthy or the exterior fault occurs, we can easily concluded that:

$$\begin{cases} \Delta B_M = 0 \\ \Delta F_N = 0 \end{cases} \quad (6)$$

However, internal fault occurs at location K, where the distance to terminal M is x. Equation (22) will be rewritten as,

$$\begin{cases} \Delta B_M = \left\| \exp(-\gamma x) Z_c I_K \right\| \\ \Delta F_N = \left\| \exp(-\gamma (L - x) Z_c I_K \right\| \end{cases} \quad (7)$$

Where, I_K is the short circuit current at location K.

Therefore, the protection criterion is:

$$\begin{cases} \Delta B_M > B_{set} \\ \Delta F_N > F_{set} \end{cases} \tag{8}$$

Where, Bset and Fset are respectively the threshold values of differential discriminat at both terminals.

2.2. Criterion Realization

The voltage $u_M(k)$ and current $i_M(k)$ at both terminal M, N can be obtained from communication equipments on the busbar. The backward traveling wave at both terminal will be:

$$\begin{cases} b_M(k) = u_M(k) - Z_c i_M(k) \\ b_N(k) = u_N(k) - Z_c i_N(k) \end{cases} \tag{9}$$

Where, $Z_C = \sqrt{X_1 / B_1}$, X_1, B_1 are respectively the reactance and susceptance per kilometer at power frequency, which will bring error to the algorithm. Then, parameter estimation method will be adopted to make up the error in the propagation function and the transformer.

In the discrete z domain, combined with (4), that is,

$$b_{op}(k) = \sum_{l=0}^{m} \alpha_l b_N(k - N_{\min} - l) - \sum_{l=1}^{n} \beta_l b_{op}(k - l) \tag{10}$$

Then, the real-time backward traveling wave criterion will be got utilizing time window W.

$$\Delta b_M(k) = \frac{1}{W}\sqrt{\sum_{l=k-W}^{k} \left| b_{op}(l) - b_M(l) \right|^2} \tag{11}$$

Similarly, the real-time forward traveling wave criterion at terminal N can be obtained.

2.3. Propagation Function Fitting Online

Whether the propagation funcion is accurate will affect the dependability of protection. Although parameter $\{\alpha_0, \cdots, \alpha_m, \beta_1, \cdots, \beta_n\}$ can be fitting according to transmission distribute parameter, due to the accuracy of distribute parameter and frequency characteristic of transformer, the propagation relation of actual traveling wave at both terminal still disagrees with that of line primary side. Meanwhile, the above analysis is carried on at power frequency, which also brings on error in calculation. Hence, the best solution to reduce the error lies in fitting online and real-time, according to the actual datum at both terminal when the line is healthy.

When the line is healthy, the backward traveling wave at M terminal is:

$$b_M(k) = \sum_{l=0}^{m} \alpha_l b_N(k - N_{\min} - l) - \sum_{l=1}^{n} \beta_l b_M(k - l) \tag{12}$$

The matrix equation will be constructed of sample values during time k to time k-p-Nmin-m.

$$\begin{bmatrix} b_M(k-p) \\ \cdots \\ b_M(k) \end{bmatrix} = \begin{bmatrix} b_N(k-p-N_{\min}) & \cdots & b_N(k-p-N_{\min}-m) & b_M(k-p-1) & \cdots & b_M(k-p-n) \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ b_N(k-N_{\min}) & \cdots & b_N(k-N_{\min}-m) & b_M(k-1) & \cdots & b_M(k-n) \end{bmatrix} \begin{bmatrix} \alpha_0 \\ \cdots \\ \alpha_m \\ \beta_1 \\ \cdots \\ \beta_n \end{bmatrix} \tag{13}$$

Equation (13) can be simpledly written as:

$$\mathbf{B}_0=\mathbf{B}_1\mathbf{C} \tag{14}$$

Where, $\mathbf{B}_0=[b_M(k-p),\cdots,b_M(k)]^{\mathrm{T}}$, whose dimension is p×1;

$$\mathbf{B}_1=\begin{bmatrix} b_N(k-p-N_{\min}) & \cdots & b_N(k-p-N_{\min}-m) & b_M(k-p-1) & \cdots & b_M(k-p-n) \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ b_N(k-N_{\min}) & \cdots & b_N(k-N_{\min}-m) & b_M(k-1) & \cdots & b_M(k-n) \end{bmatrix},$$

Whose dimension is p×(m+n); $\mathbf{C}=[\alpha_0,\cdots,\alpha_m,\beta_1,\cdots,\beta_n]^{\mathrm{T}}$, whose dimension is (m+n)×1. By means of Least Square Method, C can be estimated as:

$$\mathbf{C}=(\mathbf{B}_1^{\mathrm{T}}\mathbf{B}_1)^{-1}\mathbf{B}_1^{\mathrm{T}}\mathbf{B}_0 \tag{15}$$

2.4. Threshold Value Setting

Based on Equation (24), when interior fault occurs, △bM≈‖ZcIK‖. The criterion of threshold setting is shown as followed.Threshold value should be smaller than differential quantity, when the slightest fault occurs at the end of potective areas.

Threshold value should also be bigger than differential quantity caused by actual and computation error, when the worse fault occurs at the side of exterior areas, e.g. three-phase short circuit.

Obviously, single-phase to earth fault through transition resister is slight fault, meanwhile, protection threshold seletion is relevant to the transition resister. Supposed that the biggest transition resister that protection can immune is Rmax. Then the differential quantity is:

$$\Delta b_{AG} \approx \frac{Z_c}{1.732R_{\max}}U_N \tag{16}$$

Considered that transition resister and surge impedance protection can immune are respectively 500 and 300, besides, the maximum calculation error and imbalance factors account for about 20%. The threshold will be set:

$$B_{set}=0.2\sim 0.4U_N \tag{17}$$

3. Simulation Tests

The ATPDraw simulation tests concerns a typical double source 500kV transmission system, as shown in Figure 3. The system included two generators. Em=408∠-40°kV, Z_m=1+j50Ohm/km; En=408∠-60°kV, Z_n=5+j100Ohm/km.

The sampling period is 1.0×10^{-3}s, that is, 20 samples per cycle. The protected transmission line length is 280km. The distributed parameters are shown as follows.

Zero-mode parameters:

R_0=1.03625×10-1Ω/km, Z_{c0}=8.95272×102Ω, v_0=2.52210×105km/s.

Positive and negative mode parameters:

R_1=1.93967×10-2Ω/km,Z_{c1}=3.45328×102Ω, v_1=2.94788×105km/s;

R_2=1.96010×10-2Ω/km,Z_{c2}=3.87593×102Ω, v_2=2.95260×105km/s.

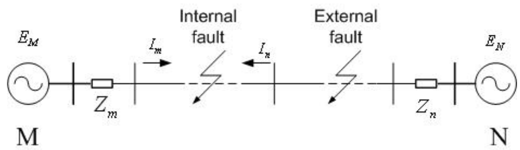

Figure 3. Simulation Model

3.1. Propagation Function Parameter Estimation

When the line is healthy, the coefficient of propagation function will adopt two points α_1 and α_2 with time window is 10 samples. Figure 4 is the curve of parameter vary with time. Based on traveling wave at terminal M, traveling wave fop at terminal N will be calculated employing fitted propagation function. The comparison result between fop and the actual traveling wave fn is shown in Figure 5(A) and error in Figure 5(B).

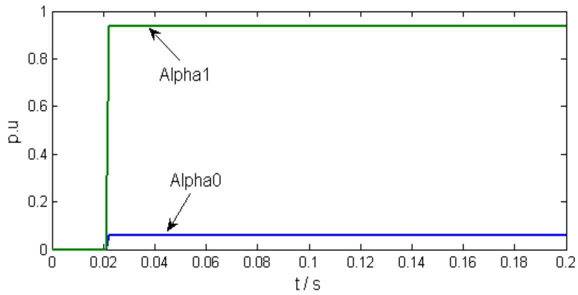

Figure 4. Parameter Fitting Result

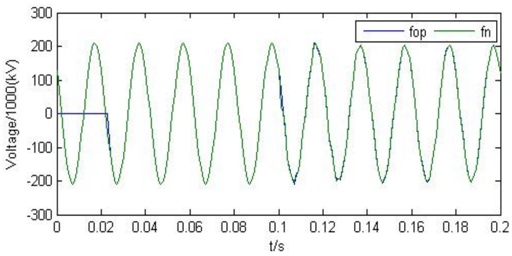

Figure 5(A). Comparison Result

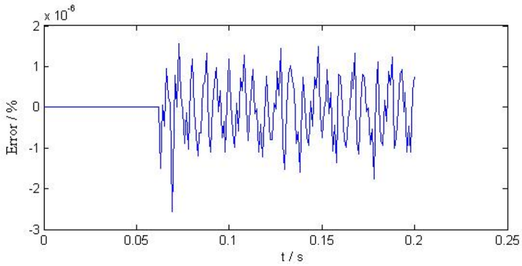

Figure 5(B). Fitting Error

Under assumption that the whole line is healthy, the only two propagation function coefficient α_1 and α_2 can be estimated, $\alpha_1 = 0.0567$, $\alpha_2 = 0.9376$. Known from Figure 5(A), the calculated and actual forward traveling wave at terminal N are similar, which provide that novel principle in this paper is available. Whilst, the error in Figure 5(B) is smaller than 2×10^{-6}, which would not affect the algorithm result with the coefficient ranks increasing.

3.2. Protection Criterion Validation

The operating results of the new differential protection for three-phase short circuit fault are respectively shown in Figure 6-8.

The comparison result between calculated traveling wave fop and actual traveling wave f_n is displayed in Figure 6(A). Figure 6(B) shows the error, which is defined as the formula given below. The error is no more than 40% when internal fault occurs.

$$error\% = \frac{f_{op} - f_n}{|f_n|} \times 100 \tag{18}$$

The operating and restraint value curves are respectively shown in Figure 7(C). It is known that the operating values are much larger than the restraint value when the internal fault occurs, due to the operating voltage approximately equals the ZcIF, where IF is fault current. The ratio of operating and restraint value is larger than 1, seen from Figure 7(D), which proves that the protection is reliable.

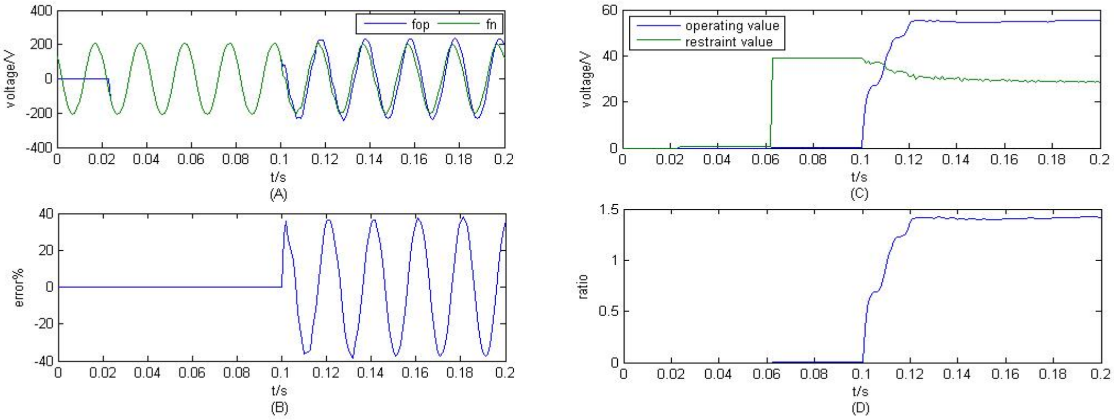

Figure 6. Simulation Results of Internal Short Circuit Fault

The simulation results of external fault, where the faults are located at the Bus N and Bus M, are respectively shown in Figure 7 and Figure 8. It can be seen that for external faults, the operating voltages are much less than restraint voltages at both terminal of the transmission line. For external fault at terminal N and M, the ratio of operating and restraint values are respectively about 0.08 and 0.3, much less than 1, which proves that the protection is security and dependability

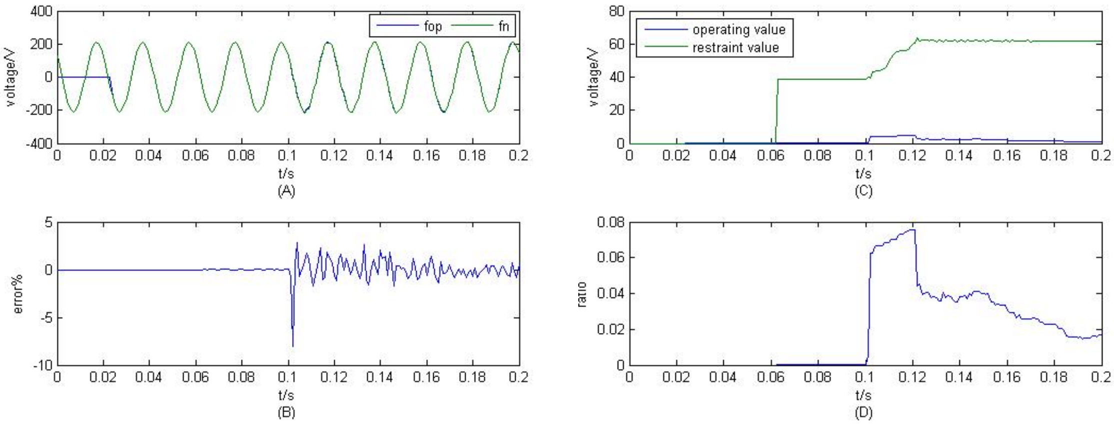

Figure 7. Simulation Results of External Short Circuit Fault at Terminal N

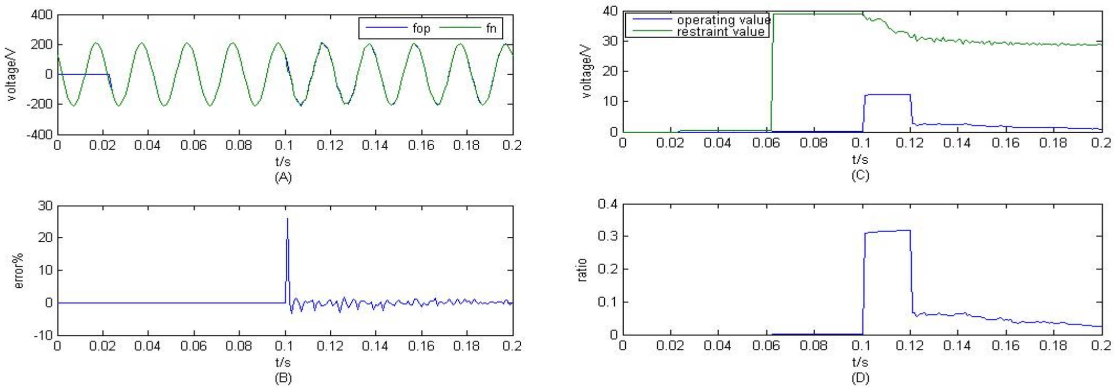

Figure 8. Simulation Results of External Short Circuit Fault at Terminal M

4. Conclusion

A novel transient differential protection is proposed, breaking through the traditional techniques, by means of projection operators and z transform for the distributed parameter lines. The benefit of this new method lies in that calculations are simplified and in particular, the precision of algorithm has greatly improved. Time-domain simulations based on the new model show the good agreement with those calculated by ATPDraw. The new differential principle is capable of instantaneously identifying internal and external faults. At the same time the criterion has higher reliability and security. Additionally, the trip order can be sent within 10ms. This new method is primarily intended for the transient analysis.

Aknowledgements

The research is supported by Shandong University of Technolgy Science and Technology Funded Project (No.103121 and No.103121), Doctoral Scientific Research Fund (No.411019) and Shandong Province Colleges and Universities Science and Technology Plan Project (J12LN76).

References

[1] Shen Lin, Ernest S Kuh. Transient Simulation of Lossy Interconnections based on the Recursive Convolution Formulation. *IEEE Trans. On Circuits and Systems-I: Fundamental and Applications.* 1992; 39(11): 879-892.
[2] JR Marti. Accurate modeling of frequency dependent transmission lines in electromagetic transient simulation. *IEEE Trans. Power Apparat. Syst.*, 1982; PAS-101: 147-155.
[3] L Marti. Simulation of Transients in Under-ground Cables with Frequency Dependant Modal Transformation Matrix. *IEEE Trans. On Power Delivery*. 1988; 3(3): 1099-1110.
[4] HV Nguyen, HW Dommel, JR Marti. Modelling of Single Phase Non-uniform Transmission Lines in Electro-Magnetic Transient Simulations. *IEEE Trans. On Power Delivery*. 1997; 12(2): 916-921.
[5] He Baina, Zhao Yunwei. The Research of Secondary Arc Spectrum Characteristics on UHV. *TELKOMNIKA Indonesian Journal of Electrical Engineering*. 2012; 10(6): 1465-1469.
[6] SY Lee, A Konrad, R Saldanha. Lossy Transmission Line Transient Analysis by the Finite Element Method. *IEEE Trans. On MAGNETICS*. 1993; 29(2): 1730-1732.
[7] Miranda GCD, Emilio A, Araujo AD, Saldanha RR, Filho JP. Finite Element Method for Transmission Line Corona Effect Simulation Using the EMTP. *Electric Machines and Power Systems.* 1999; 27(7): 781-794.
[8] J Dao, J Jin. A general approach for the stability analysis of the time domain finite element method for electromagnetic simulations. *IEEE Trans. Ant. Prop.*, 2002; 50(11): 1624–1632.
[9] K Amaratunga, J Williams. Wavelet-Galerkin solution for one-dimensional partial differential equations. *Int. Jour. For Num. Meth. In Eng.,* 1994; 32: 2703-2716.
[10] G Pan. Orthogonal wavelets with application in electromagnetism. *IEEE Trans. Mag-32*. 1996; 975-983.
[11] Risnidar C, I Daut, Syafruddin H, Yusniati. Relationships between Harmonic Characteristics and Different Types of Voltage Source. *TELKOMNIKA Indonesian Journal of Electrical Engineering*. 2012; 10(2): 219-228.
[12] Daubechies. The Wavelet Transform, Time-frequency Localization and Signal Analysis. *IEEE Trans. On Information Theory.* 1990; 36(5): 961-1005.
[13] S Mallat, S Zhong. Characterization of Signals from Multi-Scale Edge. *IEEE Trans. on PAMI*. 1992; 14(7): 710-732.
[14] S Mallat. A theory for multiresolution signal decomposition. *IEEE Trans. On Pattern Anal. Machine Intell.,* 1989; 11(7): 674-693.
[15] N Saito, G Beylkin. *Multiresolution representations using the auto-correlation functions of compactly supported wavelets.* Proceedings of ICASSP-92. 1992; (4): 381-384.
[16] Ha Heng Xu, Zhang BaoHui, Lv ZhiLai. A novel Principle of Single-ended Fault Location Technique for EHV Transmission Lines. *IEEE Transactions on Power Delivery.* 2003; 18(4): 1147-1151.