MODELING of POWER SYSTEM ELEMENTS by WAVELETS and TLM
A Case Study-Transformer Internal Fault Study

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ABSTRACT

In this paper wavelet based transient simulation and transmission line method (TLM) are proposed for modeling and solving power networks. The wavelet domain equivalents of electrical circuit components are defined for solving the network to find currents and voltages of the nodes. During the computer simulations, a number of simulations are performed to get the best level of wavelet decomposition. The modeling algorithm is then compared to another method so called TLM to see the ability of solving integro-differential equations. MATLAB ™ is used for modeling and required computer calculations.

I. INTRODUCTION

Computer aided simulation for solving power electronic circuits takes a very important role and helps the user to get the best performance from the circuit. There are a lot of methods for analyzing those circuits. Some of them can be listed such as Laplace Transform Approximation [1], Fourier Series Approximation [2], State Variable Analysis [3], Analysis by Neglecting Harmonics [4], Analysis using Boolean Algebra [5], Averaging Approximation [6], Complex Variable Analysis [7], Parc vector analysis [8], Switching Function Analysis [9].

Wavelet based simulation, using steady state equations, was developed by Gandelli [10] and Lui [11]. On the other hand, Liu [12] and Zheng [13] had remarkable contributions at power system transient analysis. All these methods have been approved in the solution of power electronics circuits since for a long time.

However, the known methods summarized above use steady state equations of the circuit and hence, numerical solution of integral and derivative equations takes time for the convergence.

It is possible that a coefficient matrix can be used in wavelet domain instead of numerical integral and derivative processes. As it is proposed in this work, circuit equations are turned to their basic algebraic forms by replacing integral and derivative matrices.

The transform coefficient matrices and circuit component models have got sparse matrix characteristic. Therefore, the proposed algorithm is as fast as the conventional methods. Haar wavelets are used for wavelet based modeling and computer simulation since they have orthogonal property and their inverse transform matrices can easily be obtained.

The TLM method was first developed in early 1970s for modeling two-dimensional field problems. Since then it has been extended to cover three dimensional problems and circuit simulations. For circuit simulation, the TLM method can be used to develop a discrete circuit model directly from the system without setting up any integro-differential equations. The TLM model algorithm is discrete in nature and ideally suited for implementation on computers [14], [15].

In this paper, the two proposed algorithms are compared according to their computational efficiency. It is seen that both techniques are similar to each other by defining circuit components according to based on modeling aspect.

II. MODELING TECHNIQUES

2.1 Wavelet Based Linear Resistor Model

The V-I characteristic of a resistor, R, is described as $v(t) = R * i(t)$ in continuous time domain. Let WVand WI be the DWT coefficient vectors of the voltage V and the current I, set the coarsest resolution level as zero, it has

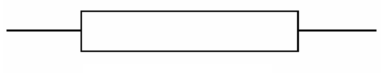
$$\begin{aligned} WV &= DWT * V = [cv..WV_s^T]^T \\ WI &= DWT * I = [ci..WI_s^T]^T \end{aligned} \qquad (1)$$

and WV is calculated by using Eq. (2).

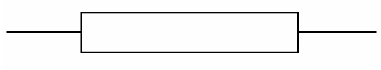
$$WV = R * U * WI \qquad (2)$$

Where **U** is an identity matrix **ci** and **cv** are the DC components of voltage and current waveforms, $\mathbf{WI_s}$ and

WV_s represent the wavelets coefficients. The equivalent circuit of resistor in wavelet domain is shown in Fig. 1.



$$v(t) = R * i(t)$$



$$WV = R * U * WI$$

Figure 1. Resistor model in wavelet domain [12], [13]

Resistor, R, is modeled as constant variable in TLM and its value is added into the system impedance such as $Z_{system} = (R + ZL_{sw} + ZL + Zc)$.

2.2 Wavelet Based Linear Inductor Model

The V-I characteristic of an inductor, L, is described in continuous time domain is $v_L(t) = L\frac{di}{dt}$. Let us suppose that the minimum time interval in the finest resolution level is the sampling cycle, ΔT. For the transient study in the discrete time interval (0 - ?T), the following equation (3) is written.

$$v_L = L * D_T * I - L * i(0) * v_{L0} \quad (3)$$

Where i(0) is the initial value of the circuit current, and

$$v_{L0} = \frac{1}{\Delta t}[1\,0\,0 \ldots.\,0]^T \quad (4)$$

$$D_T = \frac{1}{\Delta T}\begin{bmatrix} 1 & & & \\ -1 & 1 & & \\ & \cdot & \cdot & \\ & & \cdot & \cdot \\ & & -1 & 1 \end{bmatrix} \quad (5)$$

Let WV_{L0} be the DWT coefficients vector of v_{L0}, then in wavelet domain following equation is obtained.

$$WV = L * WD_T * WI - L * i(0) * WV_{L0} \quad (6)$$

where WD_T is called the transient differential operator. $L*WD_T$ represents the wavelet domain impedance of an inductor.

$$v(t) = L(di/dt)$$

$$L * WD_T * WI \qquad L * i(0) * WV_{L0}$$

$$WV = L * WD_T * WI - L * i(0) * WV_{L0}$$

Figure 2. Transient model of inductor in wavelet domain [12], [13]

Equivalent circuit of inductor in wavelet domain is shown in Fig. 2. As it is shown in Fig. 2, equivalent circuit is formed by a wavelet domain impedance and a voltage source which is determined by the initial value of current through the inductor.

TLM based modeling is similar to the wavelet based one summarized above. The basic TLM technique models linear reactive components as transmission line segments (called stubs). The stub model representing the inductor is terminated by a short circuit because, to emphasize inductive behavior, current and, hence, storage in the magnetic field must be maximized. The TLM model for a capacitor is a stub with its far end and open circuit. It emphasizes voltage differences, storage in the electric field and, hence, mainly capacitive behavior.

To model an inductor using a transmission line stub is given in Fig. 3. The stub model representing the inductor is terminated by a short circuit to emphasize inductive behavior and current. The variables *i* and *t* are treated as inductor current and time. Ldi/dt is then equal to the voltage V_L across the inductor.

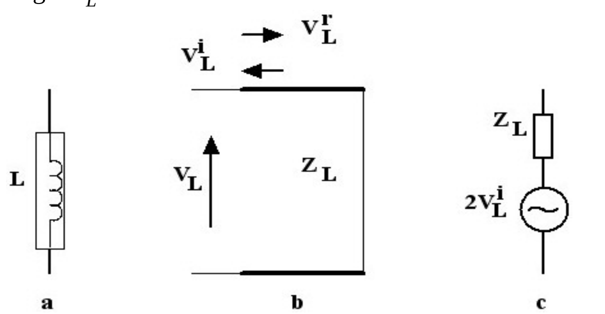


Figure 3. a) inductance, b) stub model of inductance, c) TLM equivalent circuit

Any differential terms in the form of Ldi/dt can be replaced by the discrete transform $Z_L i + 2.V_L^i$, where $Z_L = \frac{2.L}{\Delta t}$, Δt is the time step and V_L^i is the incident pulse. It is assumed that it takes one time step Δt for the pulse to make a round-trip to travel to one end and be reflected back as the incident pulse in the next time step. In summary,

$$V_L(t) = L.\frac{di}{dt} \quad (7)$$

According to the TLM theory, the voltage across the port of the transmission is also equal to the sum of the incident pulse V^i and reflected pulse V^r. Thus, at any time step,

$$_nV_L = Z_L._n i + 2._n V_L^i \quad (8a)$$
$$= {}_nV_L^i + {}_nV_L^r \quad (8b)$$

where the subscript n donates the n^{th} time step.

For a short-circuited transmission line, the pulse is reflected and inverted when it encounters the short-circuited end. Therefore, the reflection coefficient is -1 as the reflected pulse becomes the incident pulse in the next time step, from Eq. (8b)

$$\begin{aligned} {}_{n+1}V_L^i &= -{}_nV_L^r \\ &= {}_nV_L^i - {}_nV_L^r \end{aligned} \quad (9)$$

It is clearly seen from Eq. (6) and Eq. (8a and 8b) that the component of $L*WD_T*WI$ in wavelet domain is similar to $i*Z_L = i*\frac{2.L}{\Delta t}$ in TLM domain while the component of $L*i(0)*WV_{L0}$ is similar to ${}_nV_L^i = {}_nV_L - {}_nV_L^r$, successively.

2.3 Wavelet Based Capacitor Model

The V-I characteristic of a capacitor, C, in continuous time domain is represented by the following equation.

$$v(t) = v(0) + \int_0^t \frac{i(t)}{C} dt \quad (10)$$

For a finite length signal, it yields to Eq. (11)

$$V = v(0)*VC0 + \frac{1}{C} IN_T * I \quad (11)$$

where VC0=[1……..1]^T.

$$IN_T = \Delta T \begin{bmatrix} 1 & & & & & \\ 1 & 1 & & & & \\ . & . & . & & & \\ . & & . & . & & \\ . & & & . & . & \\ 1 & . & . & . & 1 & 1 \end{bmatrix} \quad (12)$$

IN_T is called the transient differential operator. Thus, in wavelet domain Eq. (11) is expressed as,

$$WV = v(0)*WVC0 + \frac{1}{C} WIN_T * WI \quad (13)$$

where WIN_T is wavelet domain representation of IN_T, and

$$WV_{C0} = [k_j \quad 0 \quad 0 \quad 0 \ldots 0]^T \quad (14)$$

$k_j=2^{-j/2}$ is a constant that is determined by the finest resolution level J. Moreover, WIN_T/C forms the transient impedance of capacitor in wavelet domain.

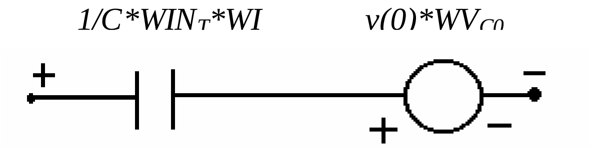


Figure 4. Transient model of a capacitance in wavelet domain [12], [13].

Fig. 4 shows the equivalent circuit of a capacitor in wavelet domain. In transient analysis, the capacitor is modeled as transient impedance and a voltage source that is calculated from the initial value of the capacitor voltage.

In a similar manner capacitance can be simulated in TLM. Fig. 5 shows a capacitance in time domain, its TLM representation, and also its Thevenin equivalent.

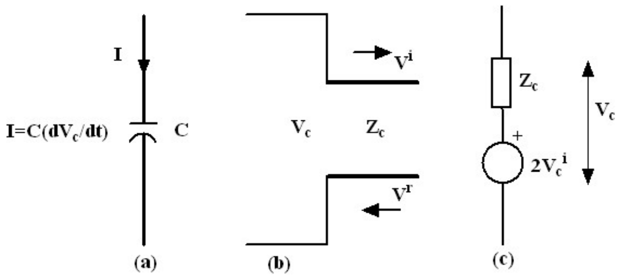


Figure 5. A capacitance, a) in time domain, b) its TLM representation, and c) its Thevenin equivalent.

The characteristic impedance, Z_C, is calculated as $Z_c = \frac{\Delta t}{2C}$ where Δt is the sampling interval.

Capacitor voltage is then calculated as

$$_kV_C = 2_k V_C^i + {}_kI.Z_C \quad (15)$$

This also equals to the sum of incident and reflected voltages, ${}_kV_C = {}_kV_C^i + {}_kV_C^r$, by definition. At the next simulation time step, incident voltage is updated by using Eq. (16).

$${}_{k+1}V_C^i = {}_kV_C^r = {}_kV_C - {}_kV_C^i \quad (16)$$

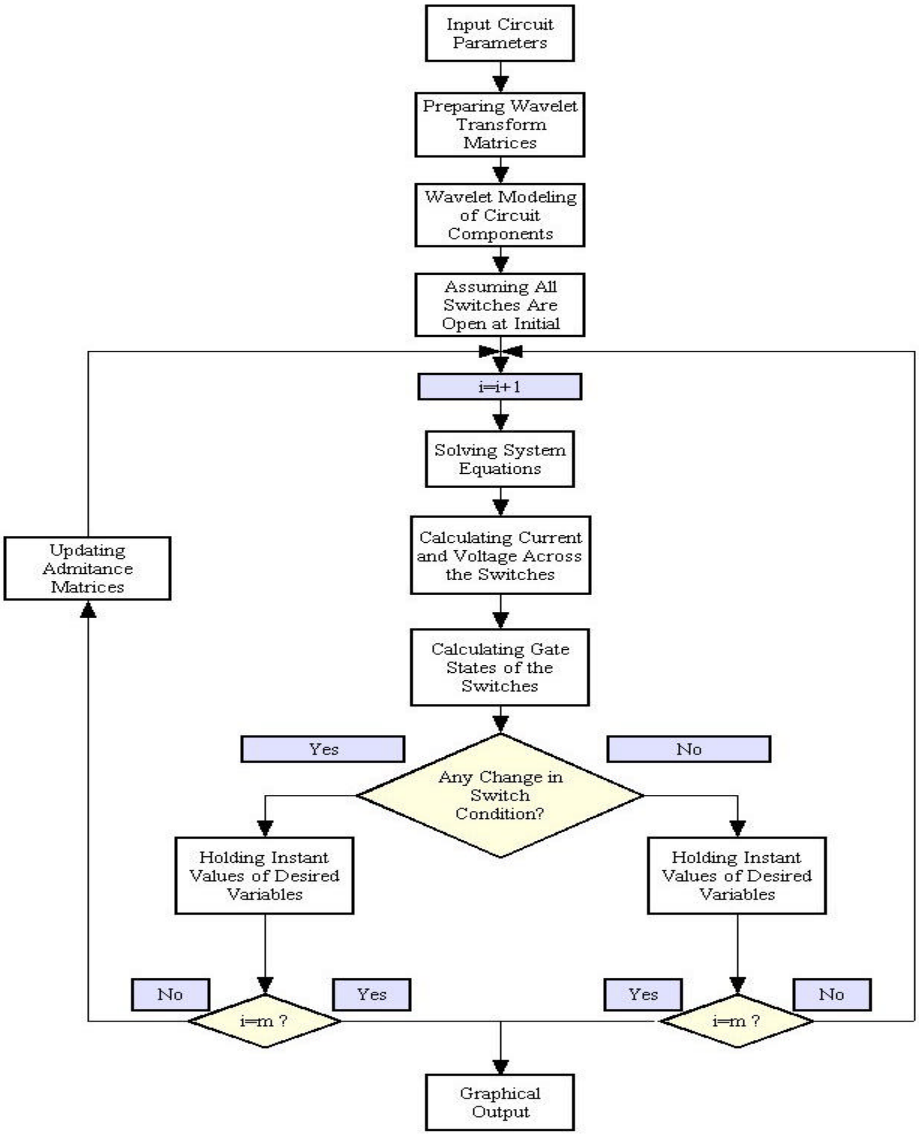


Figure 6. The proposed simulation algorithm

It is clearly seen from Eq. (13) and Eq. (15 and 16) that the component of $\frac{1}{C*WIN_T*WI}$ in wavelet domain is similar to $i*Z_C = i*\frac{\Delta t}{2C}$ in TLM domain while the component of $v(0)*WV_{C0}$ is similar to ${}_{k+1}V_C^i = {}_kV_C^r = {}_kV_C - {}_kV_C^i$, successively.

The proposed computer simulation algorithm is described as follows.

1. The netlist is composed according to node numbers of the model circuit.

2. Wavelet transform matrix is built (no required for TLM).

3. Circuit component model in wavelet domain is formed (system matrix calculated for TLM).

4. The circuit is solved. Since the circuit components are modeled in the form of impedance or admittance, the circuit can be solved by impedance or admittance matrix method (TLM currents and voltages calculated).

5. The desired outcomes are obtained.

The proposed procedure is shown in Fig. 6.

III. APPLICATION

At this case a turn to turn fault is modeled by TLM. Let us suppose that 1/10 portion of the primary winding (of a single phase transformer) has a turn to turn fault. The Thevenin equivalent of the TLM system is shown in Fig. 7. Resistance of primary winding is the summation of $R_{11} + R_{22} + R_{33}$ and inductance of the primary winding is the summation of $L_{11} + L_{22} + L_{33}$. As in section C, before the fault, the system equation is as the same with (8a, in matrix form) but the only difference is that load is modeled as a series R and L circuit. However during the fault, the following equations are derived and modeled.

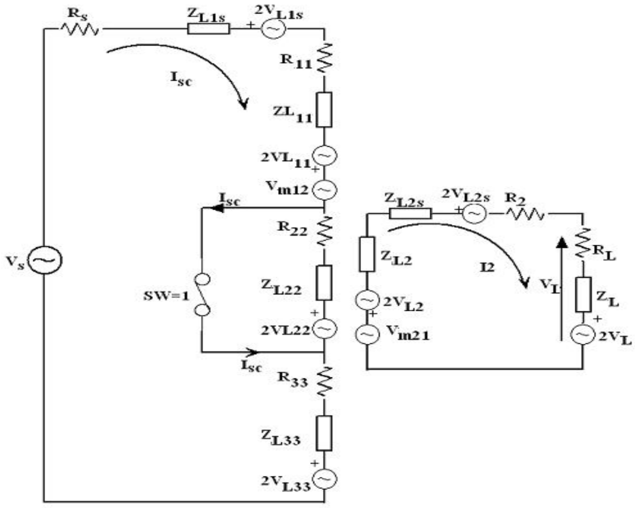


Figure 7. A Turn to turn fault at primary side (a TLM example).

Fig. 8 shows primary current of the transformer in wavelet based solution whereas Fig. 9 shows the current in TLM based solution.

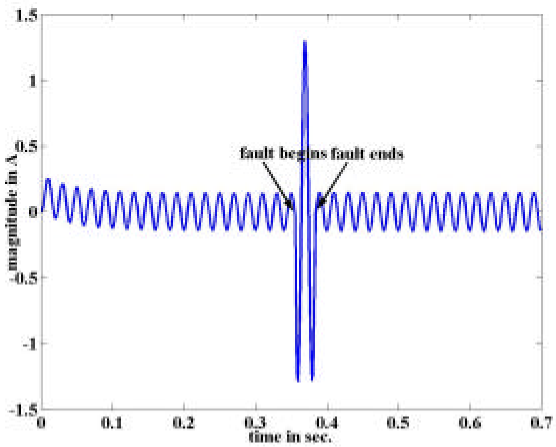


Figure 8. Primary current of the transformer during internal short circuit in wavelet based modeling

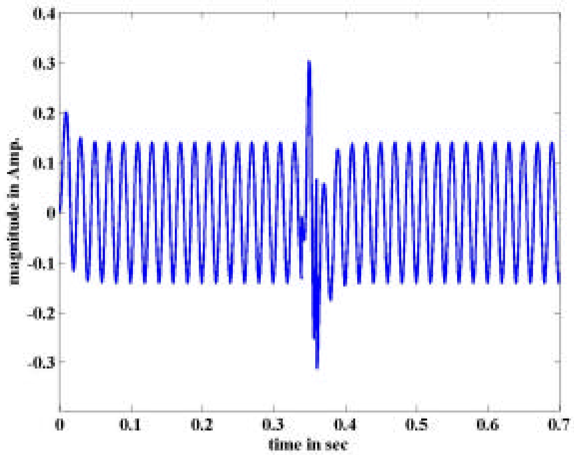


Figure 9. Primary current of the transformer during internal short circuit in TLM based modeling

IV CONCLUSION

In this study, the use of wavelets for the transient analysis of power electronic circuits and similarities with the TLM method are presented. First, circuit models are extracted by using Haar wavelet function at the desired order.

These models have two common types, transient and steady state. One of the main advantages of the proposed techniques, wavelets and TLM, is discrete in nature and can be adopted in nonlinear components easily. Results are compared with the MATLAB solutions and observed that the outcomes are consistent with each other at the level of 5 or above. Higher level analysis takes long time to converge. In this study, optimum decomposition level is set 9. It has been observed that TLM based solution of modeling is faster than wavelet based modeling due to requiring less computational manipulation.

For a future work, a hysteresis model of transformer can be used to get more accurate simulations both in TLM and wavelet based modeling. Besides different mother wavelet families can be tried for computer simulations.

REFERENCES

1. Takeuchi, T. J. (1968), Theory of SCR Circuit and Application to Motor Control, Tokyo Electrical Engineering College Press, Tokyo

2. Linos Jacovides, Analysis of Induction Motor Drives with a Non-sinusoidal Supply Voltage Using Fourier Analysis, IEEE Trans. On Ind. App., A-9, No. 6,741-7(1973)

3. P. H. Nayak and R.G. Hoft, Computer-Aided Steady-state Analysis of Thyristor DC Drives on Weak Power Systems, IEEE Con. Rec. 1976 11th Annu. Meet. Ind. App. Soc.,835-47.

4. P. C. Krause and T.A. Lipo, Analysis and Simplified Representations of a Rectifier-Inverter Induction Motor Drive, IEEE Trans. on Power App. And Sys., PAS-88, No.5,588-595(1969)

5. M. Rammorty and b. Hango, Application of State-Space Techniques to Steady-State Analysis of Tyristor

Controlled Single-Phase Induction Motors, Int. J. Control, 16, No.2, 353-368 (1972)
6. G. W. Wester and R.D. Middlebrook, Low-Frequency Characterization of Switched DC-DC Converters, IEEE Trans. On Aero. And Elec. Sys., AES-9, No.3, 376-85 (1973).
7. R.D. Middlebrook and S.Cuk, A General Unified Approach to Modelling Switching-Converter Power Stages, Conf. Rec. 1976 IEEE Power Electronics Specialists Conference, 18-34
8. D. W. Novotny, Steady-State Performance of Inverter Fed Induction Machines by Means of Time Domain Complex Variables, IEEE Trans. On Power App. and Sys., PAS-95, No.3, 927-35 (1976)
9. K. R. Jardan, S. B. Devan, G.R. Slemon, General Analysis of Three-Phase Inverters, IEEE Trans. On Ind. And Gen. App., IGA-5, No. 6, 672-9 (19689)
10. A. Gandelli, A. Monti, F. Ponci, State Equations In Haar Domain, Dipartimento di Elettotecnica-Politecnica di Milano Italy IEEE 0-7803-5491-5, 1999
11. Ming Liu1, Chi K. Tse1 and Jie Wu2., A Wavelet Approach to Fast Approximation of Steady-State Waveforms of Power Electronics Circuits, Int. J. Circuit Theory and Application 2003
12. T. Zeng, E. B. Markam, A. A. Girgis, Power System Transient and Harmonic Studies Using Wavelet Transform, IEEE Transactions on Power Delivery, Vol. 14, No. 4, October 1999.
13. J. Liu, Wavelet Modeling of Power Transients, Ph.D Dissertation, Clemson University, 2000.
14. Hui, S.Y.R., C. Christopolus, Non-linear Transmission Line Modelling Technique for Modelling Power Electronic Circuits, European Power Electronics Conference, Florence. Proceedings Vol. 1, 80-84, 1991.
15. O. Ozgonenel, D.W.P. Thomas, C. Christopoulos, Modeling and Identifying of Transformer Faults, IEEE Power Engineering Society, PowerTech 2005, 27-30 June 2005, St. Petersburg, Russia. ISBN:5-93208-034-0.