Symbolic Simulation By Mesh Method Of Complementary Circuitry

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Abstract

Transient simulation of electric network with non – zero initial values could be quite challenging even in frequency domain, especially when transient equation formulation involves vectorial sense establishment of the initialization effect of the storage elements. In this paper, we derived a robust laplace frequency transient mesh equation which takes care of the vectorial sense of these initialization effects by mere algebraic formulation. The result of the new derived transient mesh equation showed promising conformity with the existing simpowersystem simulation tool with just knowledge of the steady state current and not the state variables.

Keyword: transient simulation, mesh equation, state variables, and non – zero initialization.

1 INTRODUCTION

A single run of a conventional simulation provide limited information about the behaviour of electrical circuit. It determines only how the circuit would behave for a single initial, input sequence and set of circuit parameter characterizing condition. Many cad tasks require more extensive information than can be obtained by a single simulation run. For example the formal verification of a design requires showing that the circuit will behave properly for all possible initial start sequences that will detect a given set of faults, clearly conventional simulation is of little use for such task [1].

Some of these tasks that cannot be solved effectively by conventional simulation have become tractable by extending the simulation to operate a symbolic domain. Symbolic simulation involves introducing an expanded set of signal values and redefining the basic simulation functions to operate over this expanded set. This enables the simulator evaluate a range of operating conditions in a single run. By linearizing the circuits with lumped parameters at particular operating points and attempting only frequency domain analysis, the program can represent signal values as rational functions in the s (continuous time) or z (discrete time) domain and are generated as sums of the products of symbols which specify the parameters of circuits elements [2 – 4]. Symbolic formulation grows exponentially with circuit size and it limits the maximum analyzable circuit size and also makes more difficult, formula interpretation and its use in design automation application [5 – 10]. This is usually improved by using semisymbolic formulation which is symbolic formulation with numerical equivalent of symbolic coefficient. Other methods of simplification include simplification before generation (SBG), simplification during generation SDG, and simplification after generation (SAG) [11 – 16].

Symbolic response formulation of electrical circuit can classified broadly as modified nodal analysis (MNA) [17], sparse tableau formulation and state variable formulations. The state variable method were developed before the modified nodal analysis, it involves intensive mathematical process and has major limitation in the formulation of circuit equations. Some of the limitations arise because the state variables are capacitor voltages and inductor currents [18]. The tableau formulation has a problem that the resulting matrices are always quite large and the sparse matrix solver is needed. Unfortunately, the structure of the matrix is such that coding these routine are complicated. MNA despite the fact that its formulated network equation is smaller than tableau method, it still has a problem of formulating matrices that are larger than that which would have been obtained by pure nodal formulation [19].

In this paper a new mesh analytical method is introduced which may be used on linear or linearized RLC circuit and can be computer applicable and user friendly. The simplicity of the new transient mesh formulation lies in the fact that minimal mesh index is enough to formulate transient equation and also standard method of building steady state mesh impedance bus is just needed to build the two formulated impedance buses that are required to formulate the new transient mesh equation. Simplicity, compactness and economy are the advantages of the newly formulated transient mesh equation.

2 New Transient Mesh Equation.

Mesh analysis may not be as powerful as the nodal analysis in power system because of a little bit of application complication in circuits with multiple branches in between two nodes, when power system is characterized with short line model, mesh analysis become a faster option especially when using laplace transient analysis. The new mesh method sees a linear RLC transient network in frequency domain as one that sets up complementary circuit by the initial dc quantities at transient inception. With this mesh method, the complimentary circuit sets its resultant residual quantities (voltage drop) which complement the mesh transient voltage source.

The constitutional effect of the initial quantities at the transient inception combine with the voltage sources on the RLC linear circuits (1) is setting up of two identifiable impedance diagrams. One impedance diagram is the normal laplace transformed impedance diagram of the original circuit elements, in this paper it is called the auxiliary transient Impedance diagram. The other impedance diagram is due to non zero transient initialization effect of the storage elements and it is called the complementary transient impedance diagram in this paper.

$$Z(s)I(s) - E(s) = Z_c(s)I_c(s) \qquad (1)$$

Where Z(s) is the Auxiliary impedance bus, s – domain equivalent of steady state mesh impedance matrix, $Z_c(s)$ is the s – domain complementary impedance bus, it is the storage element driving point impedance bus due to transient inception effect, I(s) is the laplace mesh current vector and $I_c(s)$ is the initial dc mesh current vector, equivalent to the steady state mesh current vector at the transient inception.

2.1 Derivation

The newly transient mesh equation may be derived by considering a simple three node, three mesh linearized RLC circuit, fig. 1, if Kirchhoff's voltage law is applied on the various meshes then,

From mesh 1

$$E_1(t) - \{R_1[I_1(t) - I_2(t)] + L_1\frac{d}{dt}[I_1(t) - I_2(t)] + \frac{1}{C_1}\int[I_1(t) - I_2(t)]dt + E_5(t) - \{R_5[I_1(t) - I_3(t)] + L_5\frac{d}{dt}[I_1(t) - I_3(t)] + \frac{1}{C_5}\int[I_1(t) - I_3(t)]dt - E_3(t) - \{R_3I_1(t) + L_3\frac{d}{dt}I_1(t) + \frac{1}{C_3}\int I_1(t)dt = 0 \qquad (2)$$

taking the laplace transform of equation (2) to get,

$$E_1(s) - E_3(s) + E_5(s) - [I_1(s) - I_2(s)][R_1 + sL_1 + \frac{1}{C_1}] - I_1(s)[R_1 + sL_1 + \frac{1}{C_1}] - [I_1(s) - I_3(s)][R_5 + sL_5 + \frac{1}{C_5}] + [I_1(0) - I_2(0)]L_1 + [I_1(0) - I_3(0)]L_5 + I_1(0)L_3 - \frac{V_{c1}(0)}{s} - \frac{V_{c3}(0)}{s} - \frac{V_{c5}(0)}{s} = 0 \qquad (3)$$

but

$$V_{ck}(0) = i_k(0)\frac{1}{s_1C_k} \qquad (4)$$

Where i_k (0) is the initial branch current and s_1 is the steady state frequency.

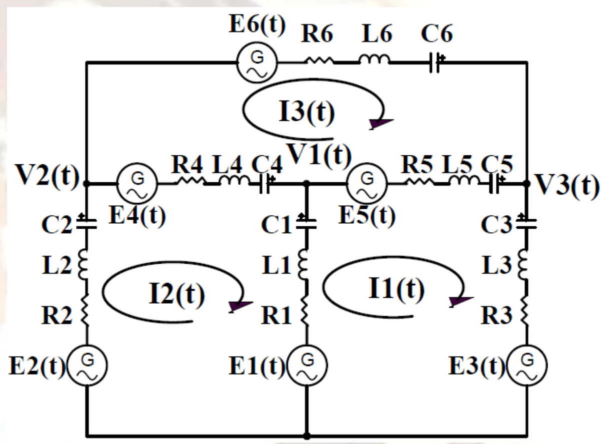

Figure 1: Three node, three mesh linear transient electric circuit.

substituting branch current in (4) with appropriate mesh currents to get branch capacitor voltage drops in terms of mesh currents,

$$V_{c1}(0) = [I_1(0) - I_2(0)]\frac{1}{s_1C_1}$$
$$V_{c5}(0) = [I_1(0) - I_3(0)]\frac{1}{s_1C_5} \qquad (5)$$
$$V_{c3}(0) = I_1(0)\frac{1}{s_1C_3}$$

Substituting equation (5) in (3) and simplifying to get,

$$I_1(s)[Z_1(s) + Z_3(s) + Z_5(s)] - I_2(s)Z_1(s) - I_3(s)Z_5(s) - [E_1(s) - E_3(s) + E_5(s)] = I_1(0)\{[L_1 - \frac{1}{ss_1C_1}] + [L_3 - \frac{1}{ss_1C_3}] + [L_5 - \frac{1}{ss_1C_5}]\} - I_2(0)[L_1 - \frac{1}{ss_1C_1}] - I_3(0)[L_5 - \frac{1}{ss_1C_5}] \qquad (6)$$

then,

$$I_1(s)[Z_1(s)+Z_3(s)+Z_5(s)]-I_2(s)Z_1(s) \\ -I_3(s)Z_5(s)-[E_1(s)-E_3(s)+E_5(s)] \\ =I_1(0)[Z_{(C)1}(s)+Z_{(C)3}(s)+Z_{(C)5}(s)] \\ -I_2(0)Z_{(C)1}(s)-I_3(0)Z_{(C)5}(s) \quad (7)$$

where

$$Z_{(c)k}=[L_k-\frac{1}{ss_1C_k}] \quad (8)$$

$Z_{(c)k}(s)$ is the dc transient driving point impedance, L_k and C_k are the k – th branch inductance and capacitance respectively.

For mesh 2

Similarly, Kirchhoff's voltage law may be applied in mesh 2 and simplified as in mesh 1 to get ,

$$I_2(s)[Z_1(s)+Z_2(s)+Z_4(s)]-I_1(s)Z_1(s) \\ -I_3(s)Z_4(s)-[-E_1(s)+E_2(s)+E_4(s)] \\ =I_1(0)[Z_{(C)1}(s)+Z_{(C)2}(s)+Z_{(C)4}(s)] \\ -I_1(0)Z_{(C)1}(s)-I_3(0)Z_{(C)4}(s) \quad (9)$$

For mesh 3

Similarly, Kirchhoff's voltage law may be applied in mesh 3 and simplified as in mesh 1 to get

$$I_3(s)[Z_4(s)+Z_5(s)+Z_6(s)]-I_2(s)Z_4(s) \\ -I_1(s)Z_5(s)-[-E_4(s)-E_5(s)+E_6(s)] \\ =I_3(0)[Z_{(C)4}(s)+Z_{(C)5}(s)+Z_{(C)6}(s)] \\ -I_2(0)Z_{(C)4}(s)-I_1(0)Z_{(C)5}(s) \quad (10)$$

Equations (6), (8) and (8) may be combined to form s – domain mesh matrix equation as follows,

$$\begin{pmatrix} Z_{11}(s) & Z_{12}(s) & Z_{13}(s) \\ Z_{21}(s) & Z_{22}(s) & Z_{23}(s) \\ Z_{31}(s) & Z_{32}(s) & Z_{33}(s) \end{pmatrix} \begin{pmatrix} I_1(s) \\ I_2(s) \\ I_3(s) \end{pmatrix} - \begin{pmatrix} E_{(m)1}(s) \\ E_{(m)2}(s) \\ E_{(m)3}(s) \end{pmatrix} \\ = \\ \begin{pmatrix} Z_{(c)11}(s) & Z_{(c)12}(s) & Z_{(c)13}(s) \\ Z_{(c)21}(s) & Z_{(c)22}(s) & Z_{(c)23}(s) \\ Z_{(c)31}(s) & Z_{(c)32}(s) & Z_{(c)33}(s) \end{pmatrix} \begin{pmatrix} I_1(0) \\ I_2(0) \\ I_3(0) \end{pmatrix} \quad (11)$$

where

$$Z_{11}(s)=Z_1(s)+Z_3(s)+Z_5(s) \\ Z_{22}(s)=Z_1(s)+Z_2(s)+Z_4(s) \\ Z_{33}(s)=Z_4(s)+Z_5(s)+Z_6(s) \\ Z_{12}(s)=Z_{21}(s)=-Z_1(s) \\ Z_{13}(s)=Z_{31}(s)=-Z_5(s) \\ Z_{23}(s)=Z_{32}(s)=-Z_4(s) \quad (12)$$

$$Z_{(c)11}(s)=Z_{(c)1}(s)+Z_{(c)3}(s)+Z_{(c)5}(s) \\ Z_{(c)22}(s)=Z_{(c)1}(s)+Z_{(c)2}(s)+Z_{(c)4}(s) \\ Z_{(c)33}(s)=Z_{(c)4}(s)+Z_{(c)5}(s)+Z_{(c)6}(s) \\ Z_{(c)12}(s)=Z_{(c)21}(s)=-Z_{(c)1}(s) \\ Z_{(c)13}(s)=Z_{(c)31}(s)=-Z_{(c)5}(s) \\ Z_{(c)23}(s)=Z_{(c)32}(s)=-Z_{(c)4}(s) \quad (13)$$

$$E_{(M)1}(s)=E_1(s)-E_3(s)+E_5(s) \\ E_{(M)2}(s)=-E_1(s)+E_2(s)+E_4(s) \\ E_{(M)3}(s)=-E_4(s)-E_5(s)+E_6(s) \quad (14)$$

$\Rightarrow$

$$E_{(M)m}(s)=\sum_{k=1}^{K}E_k(s) \quad (15)$$

where m = 1,2 – – – M–th mesh and also k = 1,2 – – – K–th branch incident on the m–th mesh.

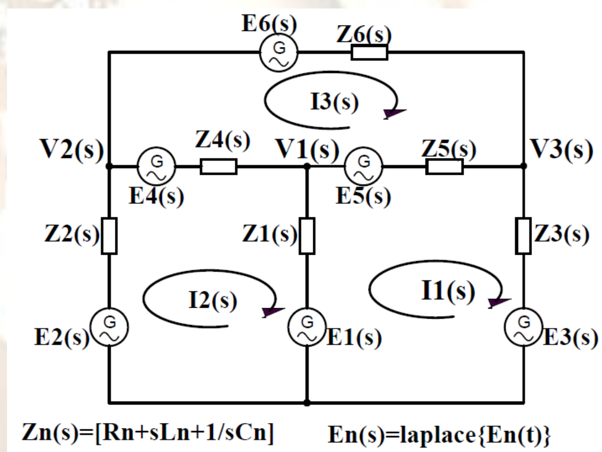

Figure 2: s – domain auxiliary circuit diagram for transient nodal analysis.

2.2 Generalized Matrix Form for Transient Nodal Equation

Equation (11) may be used to generalize an equation in the matrix form for transient mesh analysis of M th mesh electrical circuit, thus

$$\begin{pmatrix} Z_{11}(s) & Z_{12}(s) & \cdots & Z_{1m}(s) \\ Z_{21}(s) & Z_{22}(s) & \cdots & Z_{2m}(s) \\ \vdots & \vdots & & \vdots \\ Z_{m1}(s) & Z_{m2}(s) & \cdots & Z_{mm}(s) \end{pmatrix} \begin{pmatrix} I_1(s) \\ I_2(s) \\ \vdots \\ I_m(s) \end{pmatrix} - \begin{pmatrix} E_1(s) \\ E_2(s) \\ \vdots \\ E_m(s) \end{pmatrix} \\ =$$

$$\begin{pmatrix} Z_{(C)11}(s) & Z_{(C)12}(s) & \cdots & Z_{(C)1m}(s) \\ Z_{(C)21}(s) & Z_{(C)22}(s) & \cdots & Z_{(C)2m}(s) \\ \vdots & \vdots & & \vdots \\ Z_{(C)m1}(s) & Z_{(C)m2}(s) & \cdots & Z_{(C)mm}(s) \end{pmatrix}\begin{pmatrix} I_1(0) \\ I_2(0) \\ \vdots \\ I_m(0) \end{pmatrix} \quad (16)$$

The variables of equation (16) are defined in the compact equation of section 2.

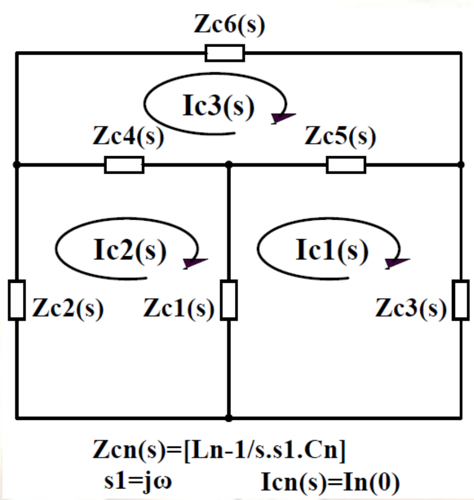

Figure 3: s – domain complementary circuit diagram for mesh analysis.

2.3 Generalized Compact Form For Transient Nodal Equation

The generalized compact form of the equation 16 is thus as follows,

$$Z(s)I(s)-E(s)=Z_{(C)}(s)I_{(C)}(s) \quad (17)$$

$$Z(s)=\begin{pmatrix} Z_{11}(s) & Z_{12}(s) & \cdots & Z_{1m}(s) \\ Z_{21}(s) & Z_{22}(s) & \cdots & Z_{2m}(s) \\ \vdots & \vdots & & \vdots \\ Z_{m1}(s) & Z_{m2}(s) & \cdots & Z_{mm}(s) \end{pmatrix} \quad (18)$$

Z(s) is laplace frequency domain impedance bus, the impedance bus have the same formulation with the common steady state mesh impedance bus only that in this equation, the branch impedances are translated to laplace frequency domain. In this paper it is called the s – domain auxiliary impedance bus.

also

$$Z_c(s)=\begin{pmatrix} Z_{(C)11}(s) & Z_{(C)12}(s) & \cdots & Z_{(C)1m}(s) \\ Z_{(C)21}(s) & Z_{(C)22}(s) & \cdots & Z_{(C)2m}(s) \\ \vdots & \vdots & & \vdots \\ Z_{(C)m1}(s) & Z_{(C)m2}(s) & \cdots & Z_{(C)mm}(s) \end{pmatrix} \quad (19)$$

$Z_{(C)}(s)$ is laplace frequency domain dc driving point impedance bus, the impedance bus could be built from fig 3 using any standard method of building an impedance bus when the branch dc driving point impedance $Z_{(C)k}(s)$ of the circuit is evaluated from equation (8). In this paper it is called the s – domain complementary admittance bus.

$$I(s)=\begin{pmatrix} I_1(s) \\ I_2(s) \\ \vdots \\ I_m(s) \end{pmatrix}, \quad E(s)=\begin{pmatrix} E_1(s) \\ E_2(s) \\ \vdots \\ E_m(s) \end{pmatrix}$$

$$I_c(s)=I(0)=\begin{pmatrix} I_1(0) \\ I_2(0) \\ \vdots \\ I_m(0) \end{pmatrix} \quad (20)$$

I(s) and E(s) are the vector of mesh transient current and mesh voltage source (vectorial sum) in laplace frequency domain respectively, while Ic(s)is equal to I(0) and is the steady state mesh current at the instant of fault inception. Hence Ic(s) is and I(0) will be used interchangeably in this paper.

3 ANALYSIS PROCEDURES

1. Solve for the initial dc mesh current from steady state for example

$$ZI = E \quad (21)$$

where Z is the steady state mesh impedance bus, I is the steady mesh current vector, E is the mesh sum voltage source vector.

2. Transform all the branch voltage sources to laplace equivalent and find the mesh sum (14) and eventually convert to vector form (20).

3. Draw the auxiliary laplace impedance diagram as in Fig 2. by converting all the branch elements to laplace equivalent, then build the laplace impedance bus from the impedance diagram by using any of the standard method of building steady state impedance bus.

4. From the branch storage elements formulate the newly derived branch dc transient driving point impedances (8), and then draw the complementary impedance diagram as in fig. 3. from the diagram build the complementary impedance bus (19) with any of the standard method of building steady state impedance bus.

5. Form equation (16) and solve for I(s) using Cramer's rule.

6. Transform I(s) to time domain equivalent using laplace inverse transform. Eg. in Matlab,

$$I(t) = ilap(I(s)) \qquad (22)$$

From this branch currents could easily be obtained at any instant of the transient.

4 TEST CIRCUIT

An earth faulted 100kV - double end fed 70% series compensated 100km single transmission line was used for verification of the formulated s – domain transient mesh equation. In this analysis compensation beyond fault was adopted and fault position was assumed to be 40%.

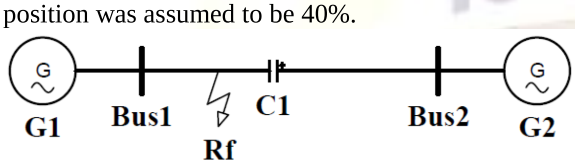

Figure 4: earth faulted single line with compensation beyond fault

Test Circuit Parameter
Generator 1
E1 (t)=10x10^{4}sin(ωt), Z_{G1}=(6+j40)Ω, S=1MVA
Generator 2
E2 (t)=0.8|E1|sin (ωt+45^0), Z_{G2}=(4+j36)Ω, S=1MVA
Line Parameter
Rs=0.075 Ω/km, Ls=0.04875 H/km
Gs=3.75*10^{-8} mho/km, Cs=8.0x10^{-9}F/km
Line length=100 km
Fault position 40% C1=70%compensation.

4.1 Modeling

A lumped parameter was adopted as a model for the test circuit. It was assumed that compensation protection had not acted as such the compensation was of constant capacitance. More so, the model is characterized with constant parameter, shunt capacitance and shunt conductance of transmission line are neglected. The equivalent circuit of the test circuit is below fig 5.

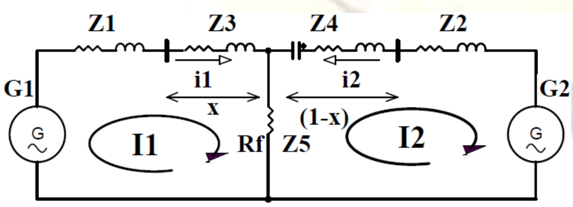

Figure 5: single line with compensation beyond earth fault equivalent circuit (short line model).

5 Transient Simulation

5.1 Symbolic Simulation with Formulated Equation

In this paper the transient mesh currents were simulated by using the described formulation (s – domain mesh equation by method of complementary circuitry). Analysis procedures of section 3 were used to calculate the s – domain rational functions of the mesh currents I(s). The obtained s – domain rational functions were transformed to close form continuous time functions using laplace inverse transformation. Discretization of the close form continuous time functions were done to plot the mesh current response graphs.

5.2 Simpower Simulation of Test Circuit

To validate the formulated transient mesh equation, a simulation of the earth faulted line end series compensated single line transmission was performed using matlab simpowersystem software to obtain the circuit transient mesh current responses. Results were compared with the responses obtained from the simulations using the formulated transient mesh equation.

6 Results

Mesh current response were simulated using the formulated mesh equation and also using simpowersystem package, all simulation were done using Matlab 7.40 mathematical tool. Simulated responses by these methods for the earth faulted double end fed single line transmission were obtained and shown in fig 6 through fig 13. Mesh currents were taken for various simulating conditions. Simulating conditions included; zero initial condition, non – zero initial condition, high resistive (1000Ω) fault but at zero initial condition, and 1 sec. simulation. All simulations were done, except otherwise stated on 100km line at 40% fault position and 5Ω earth resistive fault. Sampling interval for the formulated equation simulation is 0.0005 sec, while that of the simpowersystem simulation is at 0.00005 sec. The overall result showed almost 100% conformity between new mesh symbolic formulation and the simpowersystem simulation.

7 Conclusions

Simulation software has been formulated for transient simulation of RLC circuits initiating from steady state. The simulation software is especially useful for power circuits that are modeled with short line parameter. The result of the simulation of this new symbolic mesh software showed promising conformity with the existing simpowersystem package and has the advantage of being able to simulate complex value initial conditions and also sets the directions and the senses of the state variables automatically.

Test Circuit Simulated Mesh Voltage Response Graphs:

All graph are plotted except otherwise stated, 100 km Line, Compensation 70% Fault Position=40%, And 5Ω Resistive Earth Fault.

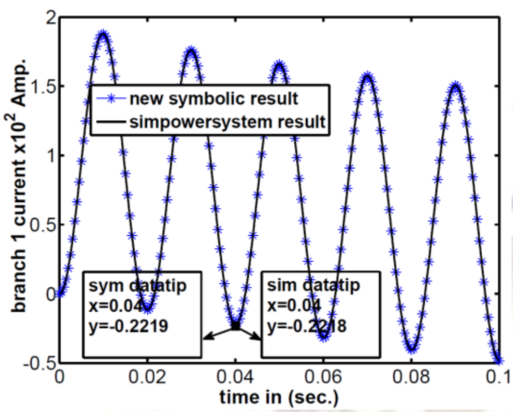

Figure 6: Simulation Of Mesh Current Versus time ; 0% Initial Condition.

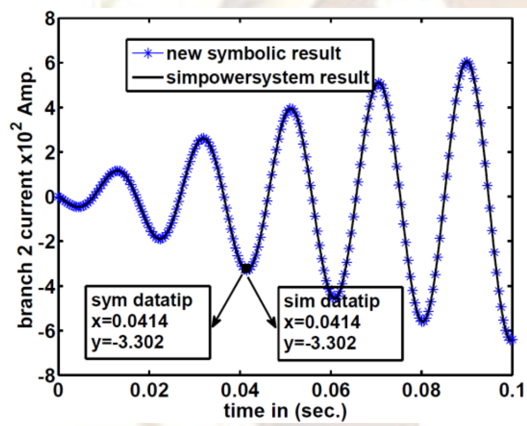

Figure 7: Simulation Of Mesh Current Versus Time ; 0% Initial Condition.

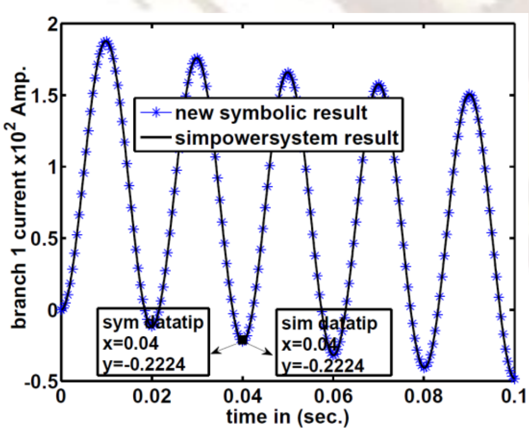

Figure 8: Simulation of Mesh Current versus Time; Initial Conditions, 0.013 Sec of Steady State Run.

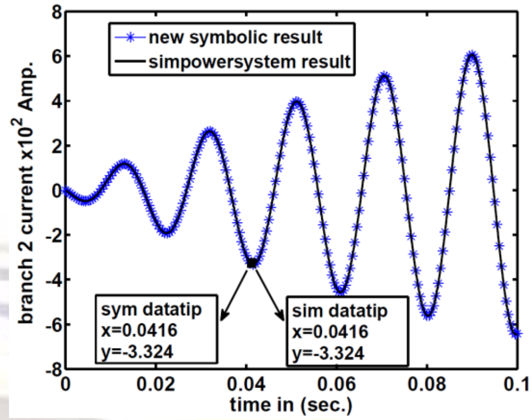

Figure 9: Simulation of Mesh Current versus Time; Initial Conditions, 0.013 Sec of Steady State Run.

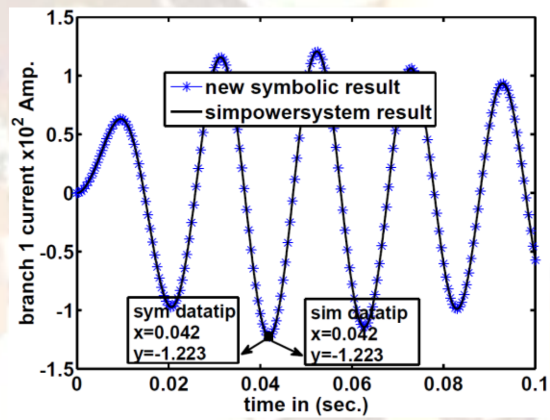

Figure 10: Simulation Of Mesh Current Versus Time; 0% Initial Condition, and 1000Ω Resistive Earth Fault.

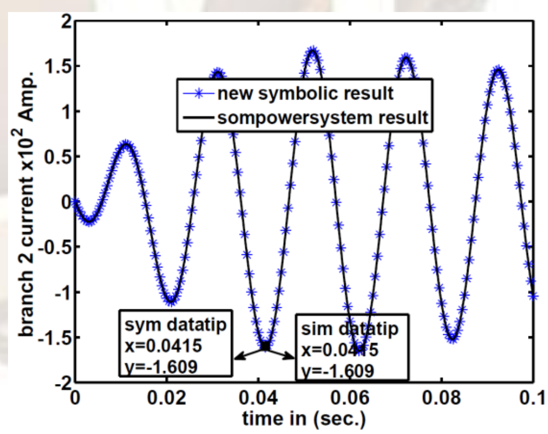

Figure 11: Simulation Of Mesh Current Versus Time; 0% Initial Condition, and 1000Ω Resistive Earth Fault.

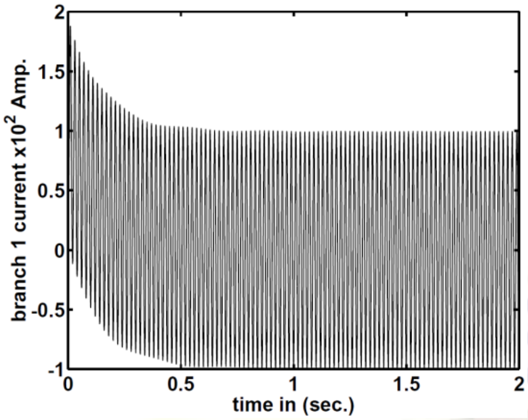

Figure 12: Simulation Of Mesh Current Versus Time ; 0% Initial Condition.

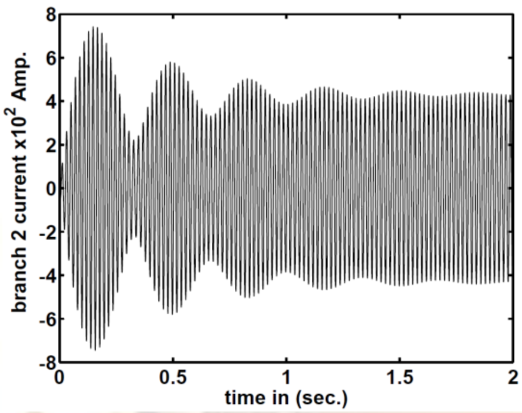

Figure 13: Simulation Of Mesh Current Versus Time ; 0% Initial Condition**.**

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