PAPER • **OPEN ACCESS**

Large Time Step Electromagnetic Transient Simulation of Large Scale Power System Based on Time Domain Transformation Method

To cite this article: Ye Zhang *et al* 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **223** 012022

Large Time Step Electromagnetic Transient Simulation of Large Scale Power System Based on Time Domain Transformation Method

Ye Zhang[1], Liang Tu[1],Yongjie Leng[2,*], Qinghua Zhang[2], Luyin Zhang[2] and Dongyuan Zhang[2]

[1]Systems Research Institute China South Power Grid International Co., Ltd., Guangzhou, China
[2]Power grid automation dept. Integrated Electronic Systems Lab Co., Ltd., Jinan, China

[*]E-mail: lengyongjie@ieslab.cn; Tel.18663774570

Abstract. Electromagnetic Transients (EMT) simulation is an effective approach to study the dynamic behavior of complex AC/DC power grids. However, with increasing applications of the electronic equipment and the expansion of power grid, conventional EMT simulation tools are facing significant challenges with regard to simulation speed and scale. In order to improve the performance of EMT simulation, some approaches have been proposed. A time domain transformation methodology [1] has recently been proposed. In this paper, based on the large time step EMT algorithm, an electromagnetic transient simulation program has been developed and is used to study large scale power system dynamic behaviors. The result shows that the new EMT algorithm can not only guarantee the simulation accuracy, but also effectively improve the speed of full electromagnetic transient simulation of large scale complex power grids.

1. Introduction

Electromagnetic Transients (EMT) simulation is an effective tool to study the dynamic behavior of complex AC/DC power grids. However, with the electronic equipment increase and power grid expansion, conventional EMT tools are facing significant challenges with regard to simulation speed and scale. In order to improve the EMT's performance, several computing technologies have been adopted, which can be divided into four categories.

1.1. System Equivalent

The AC power grid is divided into the internal system and the external system. The internal system is the one with great interests, and the detailed EMT modeling is used for this part. The remaining system is the external system which is reduced to an equivalent system. In order to precisely reflect the wide band frequency dynamic characteristics of the external system, the frequency dependent network equivalent is proposed to represent the high frequency behavior of the external system. But, besides the possible passivity problem, the system equivalent method should have limitations when the external systems contain nonlinear components [2-6].

1.2. Hybrid Simulation

The hybrid simulation divides the system into two parts: the large system, which uses electromechanical transient models as well as the other part which is of more interests and represented with electromagnetic transient simulation model. The electromechanical transient is based on fundamental frequency, single-phase and phasor-type data, while the electromagnetic transient is based on three-phase instantaneous waveform data, which includes wide-band frequency elements. The difference of modeling in TS-EMT hybrid simulation presents many difficult problems, which need further investigation [7-12].

1.3. Parallel Computing and Multi-rate simulation technique

The parallel implicit multi-rate simulation algorithm, builds the basic modeling, and then, the parallel algorithm via the transmission line equation. The result shows that the multi-rate electromagnetic transient simulation algorithm based on transmission lines has higher parallelized levels and efficiency than the existing one. Simulation study shows that the parallel implicit multi-rate electromagnetic transient simulation based on the transmission lines might be unstable [13-16].

1.4. Frequency-adaptive Simulation of Transients

In power system, the AC frequency is typically 50 or 60 Hz, and perturbations usually cause low frequency deviations, resulting in narrow bandwidth waveforms. In order to use large time step, the original system needs to be transformed into a shifted-frequency system where the frequency around the fundamental frequency becomes the frequency around dc (0 Hz). Using of large time step can improve the simulation efficiency and expand the scale [17-20].

In this paper, a new frequency adaptive algorithm is adopted, which uses a time domain transformation technology. The component model is obtained through discretization at the branch level. With this method, the time step can be increased by tens or hundreds of times, without losing accuracy, which greatly improves the simulation speed.

2. Time Domain Transformation Theory

The amplitude and phase of voltages and currents in AC system are actually a low-frequency signals. These signals produce slowly varying waveform superimposed on the fundamental frequency, as follows:

$$x(t) = A(t)\cos[\omega_0 t + \phi(t)] \tag{1}$$

Suppose that $x(t)$ is the solution of the following ordinary differential equation (ODE):

$$x' = f(t,x) \tag{2}$$

Upon defining

$$y = \frac{x'}{\omega_s} \tag{3}$$

ω_s is a newly introduced simulation parameter, which usually set as the fundamental frequency.

$$\omega_s = \omega_0 \tag{4}$$

We can construct two new variables with the following transformation:

$$\begin{bmatrix} u(t) \\ v(t) \end{bmatrix} = T(t) \begin{bmatrix} x(t) \\ y(t) \end{bmatrix} \tag{5}$$

Where the transformation matrix is defined as

$$T(t) = \begin{bmatrix} \cos(\omega_s t) & -\sin(\omega_s t) \\ -\sin(\omega_s t) & -\cos(\omega_s t) \end{bmatrix} \tag{6}$$

The amplitude $A(t)$ and the phase angle $\phi(t)$, are slowly varying signals, then we have

$$u(t) \approx A(t)\cos[\phi(t)] \tag{7}$$

$$v(t) \approx A(t)\sin[\phi(t)] \tag{8}$$

which implies that $u(t)$ and $v(t)$ are signals varying more slowly than the original signal $x(t)$ and $y(t)$.

3. Numerical Solutions Based on Time Domain Transformation

Suppose the TR method is used to solve the ODEs about $u(t)$ and $v(t)$, then we have

$$\begin{bmatrix} u_n \\ v_n \end{bmatrix} = \begin{bmatrix} u_{n-1} \\ v_{n-1} \end{bmatrix} + \frac{h}{2}\left\{ \begin{bmatrix} u'_{n-1} \\ v'_{n-1} \end{bmatrix} + \begin{bmatrix} u'_n \\ v'_n \end{bmatrix} \right\} \tag{9}$$

Where h is the time step. We obtain the following discretization formula:

$$T(t_n)\begin{bmatrix} x_n \\ y_n \end{bmatrix} = T(t_{n-1})\begin{bmatrix} x_{n-1} \\ y_{n-1} \end{bmatrix} + \frac{h}{2}\left\{ \omega_s T(t_{n-1} + \frac{\pi}{2\omega_s})\begin{bmatrix} x_{n-1} \\ y_{n-1} \end{bmatrix} + T(t_{n-1} + \frac{\pi}{2\omega_s})\begin{bmatrix} f_{n-1} \\ g_{n-1} \end{bmatrix} \right\}$$
$$+\frac{h}{2}\left\{ \omega_s T(t_n + \frac{\pi}{2\omega_s})\begin{bmatrix} x_n \\ y_n \end{bmatrix} + T(t_n + \frac{\pi}{2\omega_s})\begin{bmatrix} f_n \\ g_n \end{bmatrix} \right\} \tag{10}$$

$$R(t) = \begin{bmatrix} \cos(\omega_s t) & \sin(\omega_s t) \\ -\sin(\omega_s t) & -\cos(\omega_s t) \end{bmatrix} \tag{11}$$

Applying the properties of $R(t)$ and $T(t)$, we can derive

$$\begin{bmatrix} x_n \\ y_n \end{bmatrix} = R(h)\begin{bmatrix} x_{n-1} \\ y_{n-1} \end{bmatrix} + \frac{h}{2}\left\{ \omega_s R(h - \frac{\pi}{2\omega_s})\begin{bmatrix} x_{n-1} \\ y_{n-1} \end{bmatrix} + R(h)\begin{bmatrix} f_{n-1} \\ g_{n-1} \end{bmatrix} \right\} + \frac{h}{2}\left\{ \omega_s R(-\frac{\pi}{2\omega_s})\begin{bmatrix} x_n \\ y_n \end{bmatrix} + \begin{bmatrix} f_n \\ g_n \end{bmatrix} \right\} \tag{12}$$

4. Component Models Based on Time Domain Transformation

Models for different network components can be obtained at the branch level based on (12), which provides an algebraic equation relating branch voltages and currents at any given instant of time to their past values. Prior to this, the concepts of "differential network" and "differentially extended network" of the original network are firstly introduced. The "differential network" is the network which gives the differential solutions of the original network. The "differentially extended network" is obtained through combining the "differential network" and the original network.

The "differentially extended network" of one network shown in Figure 1. is used to illustrate the concepts. The left part of Figure 1. is same as the original network. The right part is the corresponding "differential network", where the resistance of R_d , the inductance of, L_d and the capacitance of C_d equal to the resistance of R, the inductance of L, and the capacitance of C , respectively.

Applying (12) to the "differentially extended network" gives the equivalent circuit for the time domain simulation which is shown in Figure 2, where

$$G^L = \frac{h}{2L}K^{-1}\left[E - \frac{\omega_s h}{2}R(-\frac{\pi}{2\omega_s}) \right]^{-1} K \tag{13}$$

$$G^C = \frac{2C}{h}K^{-1}\left[E - \frac{\omega_s h}{2}R(-\frac{\pi}{2\omega_s}) \right] K \tag{14}$$

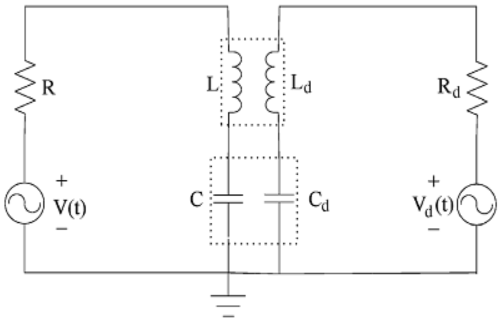

Figure 1. Differential expansion network

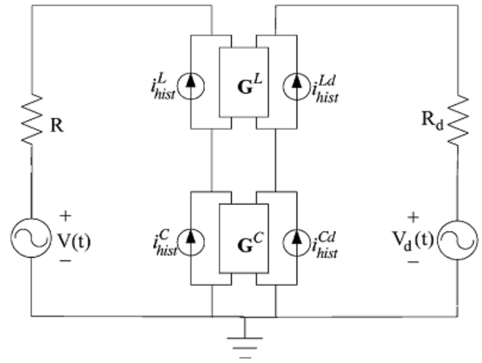

Figure 2. Equivalent circuit of original network in time domain simulation

The history current of L and L_d is

$$\begin{bmatrix} i_{hist}^{L} \\ i_{hist}^{L_d} \end{bmatrix} = K^{-1}\left[E - \frac{\omega_s h}{2}R(-\frac{\pi}{2\omega_s})\right]^{-1} \times R(h) \times \left\{ \frac{h}{2L}K\begin{bmatrix} u_{n-1}^{L} \\ u_{n-1}^{L_d} \end{bmatrix} + \left[E + \frac{\omega_s h}{2}R(-\frac{\pi}{2\omega_s})K\begin{bmatrix} i_{n-1}^{L} \\ i_{n-1}^{L_d} \end{bmatrix}\right]\right\} \tag{15}$$

The history current of C and C_d is

$$\begin{bmatrix} i_{hist}^{C} \\ i_{hist}^{C_d} \end{bmatrix} = -K^{-1} \times R(h) \times \left\{ \frac{2C}{h}\left[E + \frac{\omega_s h}{2}R(-\frac{\pi}{2\omega_s})\right]K\begin{bmatrix} u_{n-1}^{C} \\ u_{n-1}^{C_d} \end{bmatrix} + K\begin{bmatrix} i_{n-1}^{C} \\ i_{n-1}^{C_d} \end{bmatrix}\right\} \tag{16}$$

Where $K = \begin{bmatrix} 1 & 0 \\ 0 & 1/\omega_s \end{bmatrix}$

E is the 2-order identity matrix. Equations (13)–(16) give the component models of inductors and capacitors based on the discretization formula (12). The branch level models of other network components can be similarly obtained.

5. Steady State Study of Large Scale Power System

In order to investigate effect of the large time step EMT algorithm in large scale power system application scenarios, a steady power flow based on a real power system (large scale power system I) is studied. This system includes 3147 three-phase nodes, 3431 transmission lines, 122 generators, 879 transformers. The computer used for simulation is installed with a Core i7-5960X CPU (3.0-GHz octa-core processor) and 4 channel DDR4 2133 memory (4X4GB). To verify the accuracy, the obtained results are compared with the results of PSD-BPA's power flow program. And different time step is also used to test the accelerated ratio.

5.1. The Large Time Step EMT in 1us

The large time step EMT calculates the power flow in 1us time step. The Table 1 shows the results comparing with PSD-BPA. Table 1 only gives the bus voltages with top 5 largest errors.

Table 1. Comparing steady state voltage

Node	RMS Voltage PSD-BPA(kV)	RMS Voltage Large Time Step(kV)	Error(kV)
Node1	228.4112412	228.4195998	-0.008358603
Node2	228.4021348	228.4104823	-0.008347455
Node3	228.5585101	228.5668526	-0.00834245
Node4	228.8753206	228.8832036	-0.007883063
Node5	228.8757874	228.8836587	-0.00787134

5.2. The Time Consumption of Different time Step

The large time step EMT simulation used different time steps (10us, 50us,150us,500us) for 10s steady state simulation. Regarding to different time step, we can measure the voltage on the same node and compare them with the result in 1us time step. Table 2 shows the comparisons and Table 3 lists the time consumption.

As shown in Table 2, with the time step increasing, the node voltage still remains good accuracy. And the Table 3 indicates the obvious acceleration with larger time step.

Table 2. Comparing the voltage of different time step

Time step(μs)	Node voltage (kV)	Voltage error(kV) (based on 1μs step)
1	510.4869121	--
10	510.4869717	0.0000596
50	510.4884144	0.0015024
150	510.5004392	0.01352715
500	510.5335448	0.0466327

Table 3. Comparing time consumption of different time step

Time Step(μs)	Calculating Time Consumption(s)
1	557.99
10	43.86
50	23.36
150	19.71
500	9.35

5.3. The Time Consumption With Multi Threading

The large time step EMT can be combined with parallel computation technology. The time consumption with different threads are given in Table 4. The simulation duration is 10s.

Table 4. Comparing the calculating time consumption of different threads

Threads	Time Step/Simulation Duration (50us/10s)	Time Step/Simulation Duration (500us/50s)
1	106.16	109.322
2	58.2474	61.9543
3	42.5405	43.3763
4	35.8628	36.2689
5	28.8461	29.3556
6	24.6741	26.2666
7	20.7669	21.6865
8	18.7007	19.548

As shown in Table 4, with the number of thread increasing, obvious acceleration can be observed. Beyond 4 threads, acceleration is gradually slowed down.

6. Transient Study of Large scale Power System

To test the performance of the large time step EMT simulation, different faults are applied to the large scale power system as in section 5 is used. The results are compared with the PSD-BPA's transient stability program.

6.1. Three-phase faults

Fault setting is shown as in Table 5.The curve comparisons are shown in Figure 3, Figure 4, Figure 5.

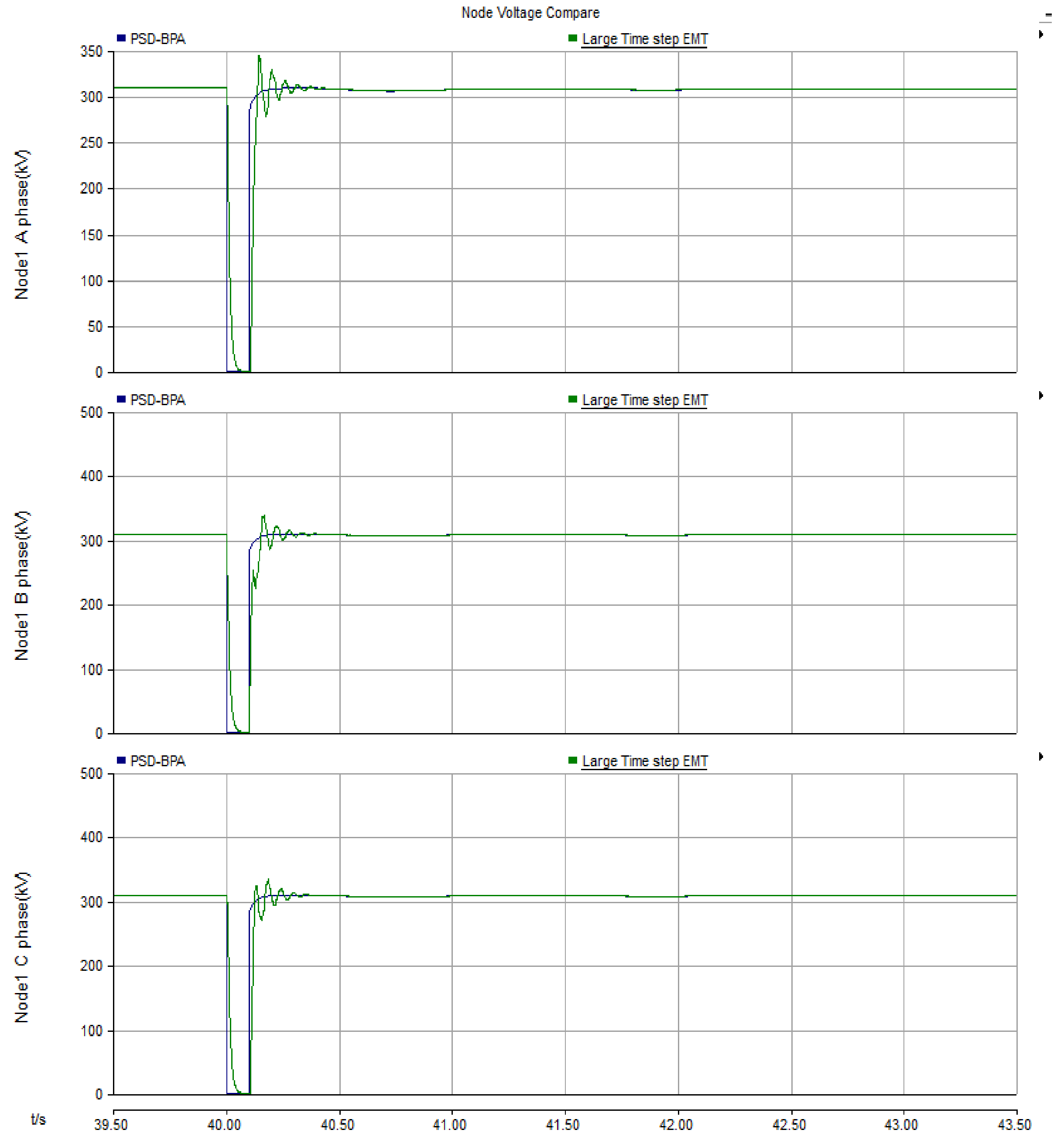

Figure 3. Node voltage curve

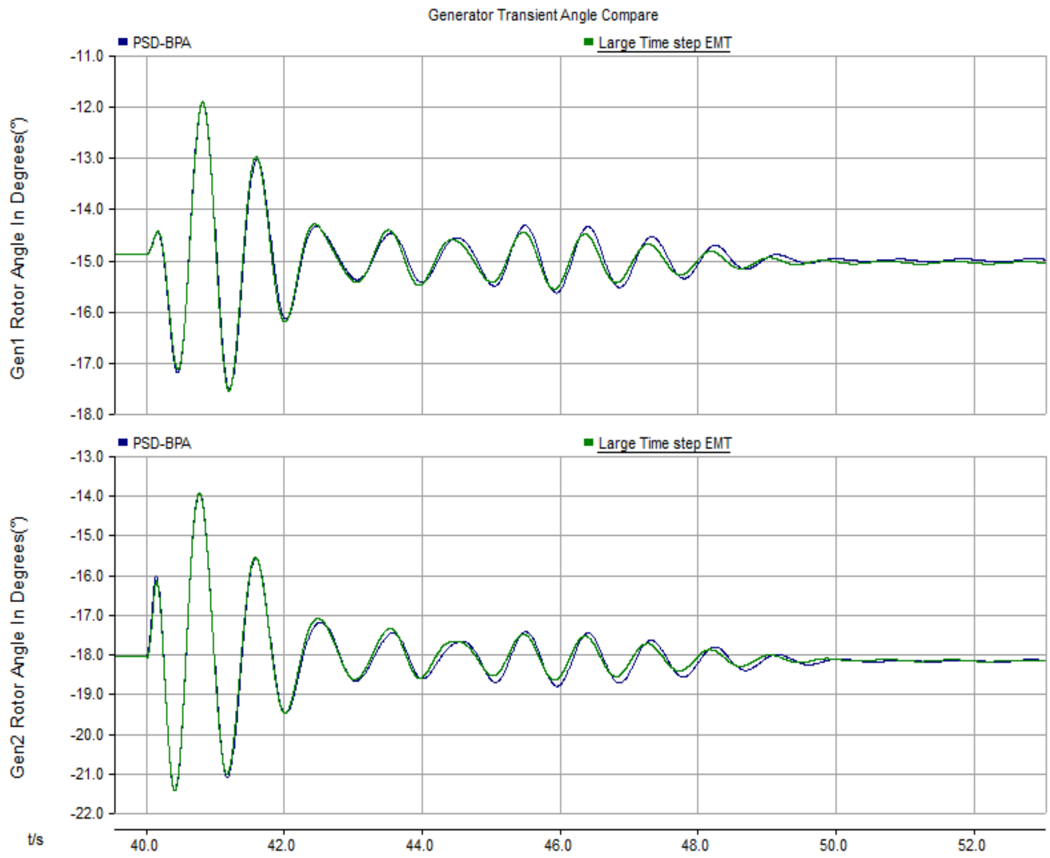

Figure 4. Generator transient angle curve

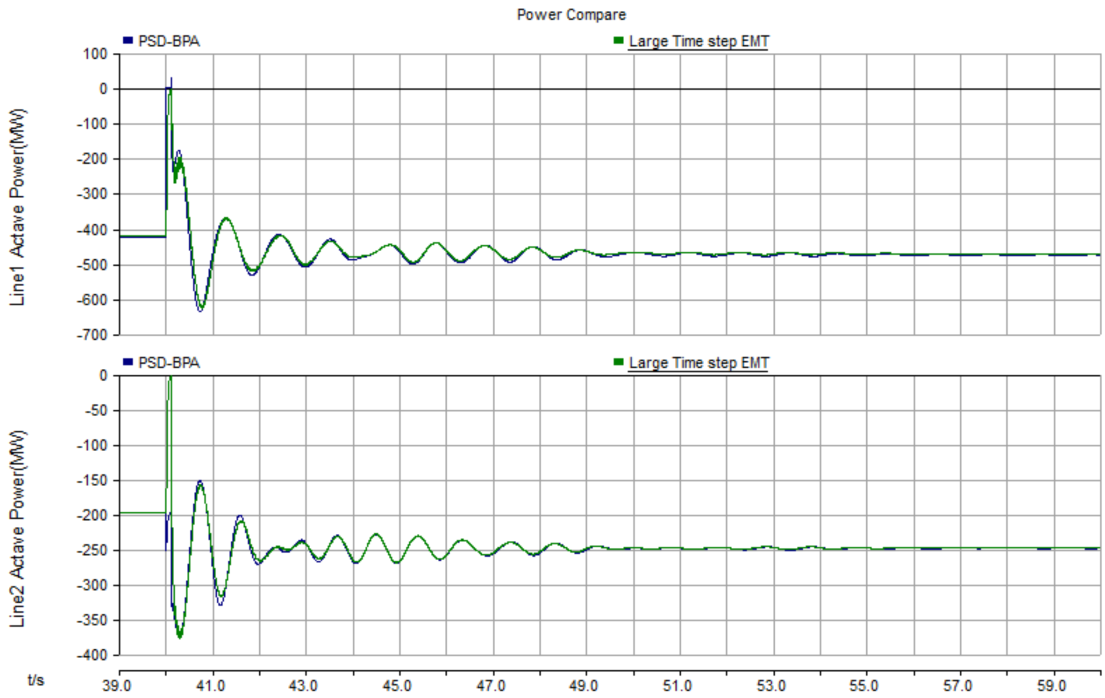

Figure 5. Power curve

Table 5. Fault setting

Fault Point	Simulation Time(s)	Fault Time (s)	Fault Duration (ms)	Time Step(us)	Time Consumption (s)
Node1 bus side	60	40	100	500	119.663

6.2. Two Faults Between Two Lines

Fault setting is shown as in Table 6. The curve comparisons are shown in Figure 6, Figure 7, Figure 8.

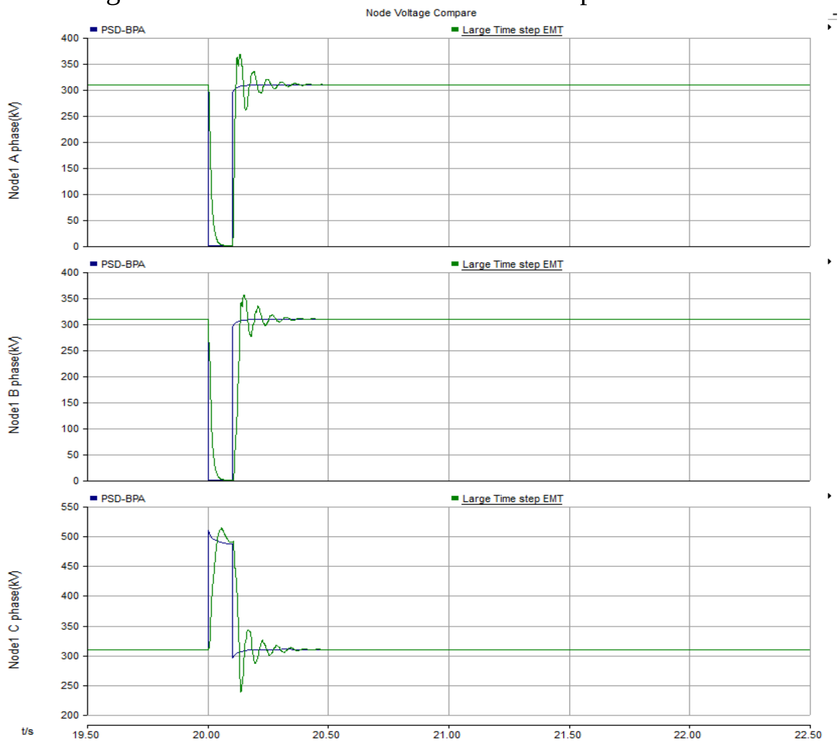

Figure 6. Node voltage curve

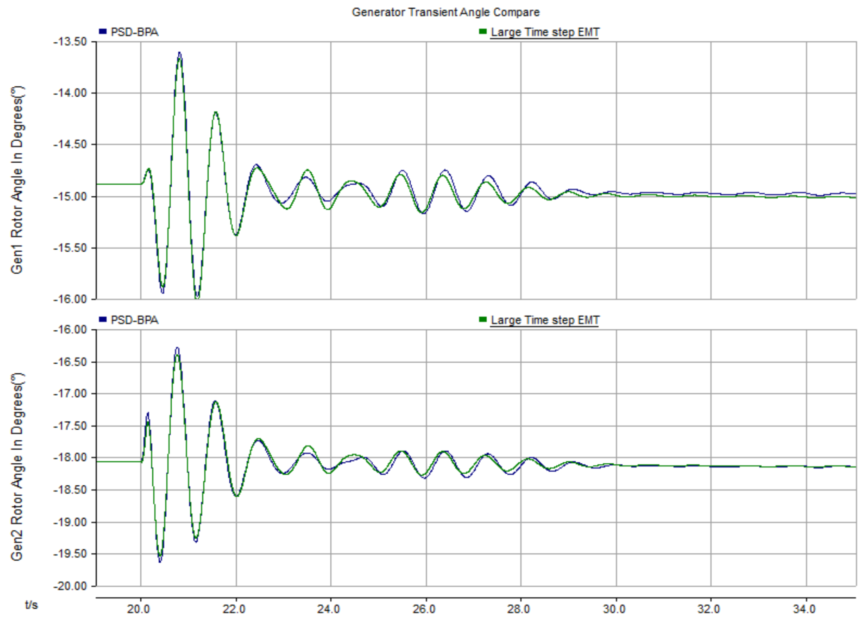

Figure 7. Generator rotor angle curve.

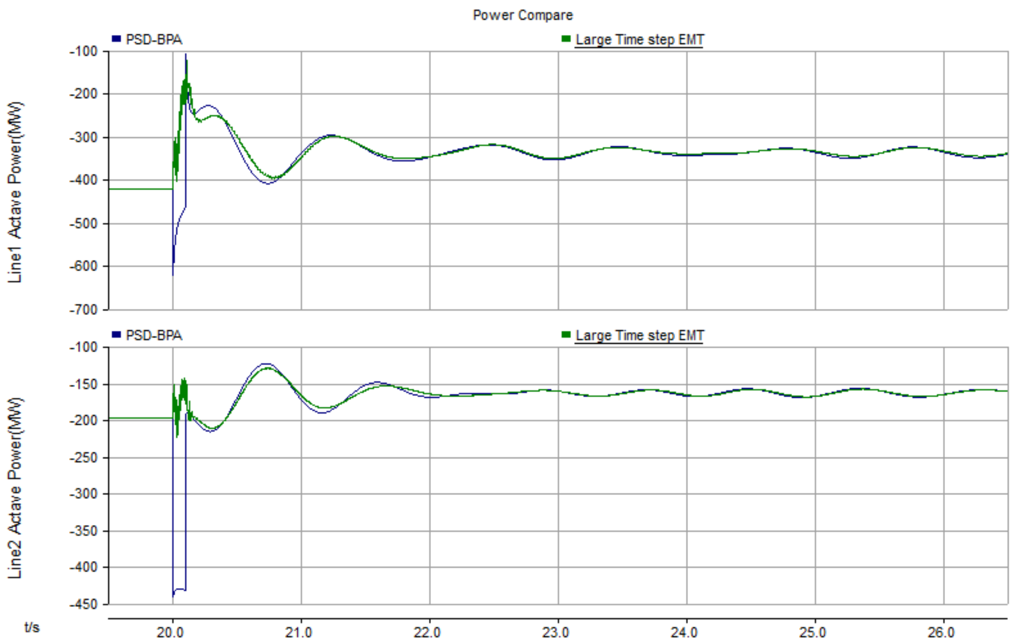

Figure 8. Power curve.

Table 6. Fault setting

Fault point	Simulation Time(s)	Fault Time (s)	Fault Duration(ms)	Time Step (us)	Time Consumption(s)
Line 1 A phase Line 2 B phase	40	20	100	500	109.681

Through the fault transient result comparison, we can see the large time step EMT have good accuracy and exhibits more details during fault process.

7. Transient Studies of Larger-scale power system II with Large Time Step EMT, PSD-BPA and PSCAD/EMTDC

In this paper, another large scale power system (power system II) is further used to study the obtained transient response through comparing with PSCAD/EMTDC and PSD-BPA.

The power system II includes 291 three-phase nodes, 360 transmission lines, 29 generators, 40 three-phase loads.

The same computer as in section 5 is used. Large time step EMT uses a time step 500us, simulation duration is 20s. The system fault is applied at 15s.

7.1. Fault 1

Fault setting is shown in Table 7. The consumed time of the large time step EMT simulation is 2.36s. The comparison of obtained results is shown as in Figure 9.

Table 7. Fault setting

Fault Point	Fault Description	Output Variable
500kV Line1: Node1-node2 N-1	Node2 side three-phase fault and the fault line is removed after 0.1s.	voltage of the node1 rotor angle of generator 1 in power plant 1 Power in 500kV line2 node1-node3

7.2. Fault 2

Fault setting is shown in Table 8. The consumed time of the large time step EMT simulation is 2.1s. The simulation results are shown as in Figure 10.

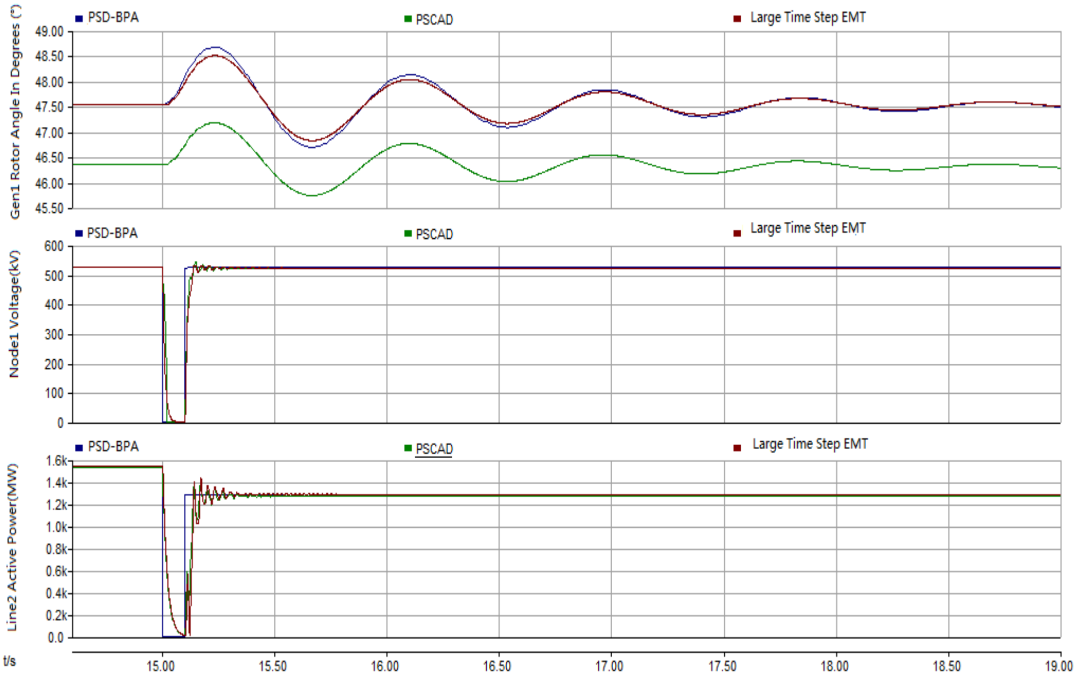

Figure 9. Node1-node2 line n-1 fault.

Table 8. Fault setting

Fault Point	Fault Description	Output Variable
500kV Line1: Node1-node2 N-2	Node2 side three-phase fault and the fault line is removed after 0.1s. 0.3s later generator 2 in power plant 1 is removed.	voltage of the node1 Generator 1 rotor angle in power plant 1 Power in 500kV line2 node1-node3

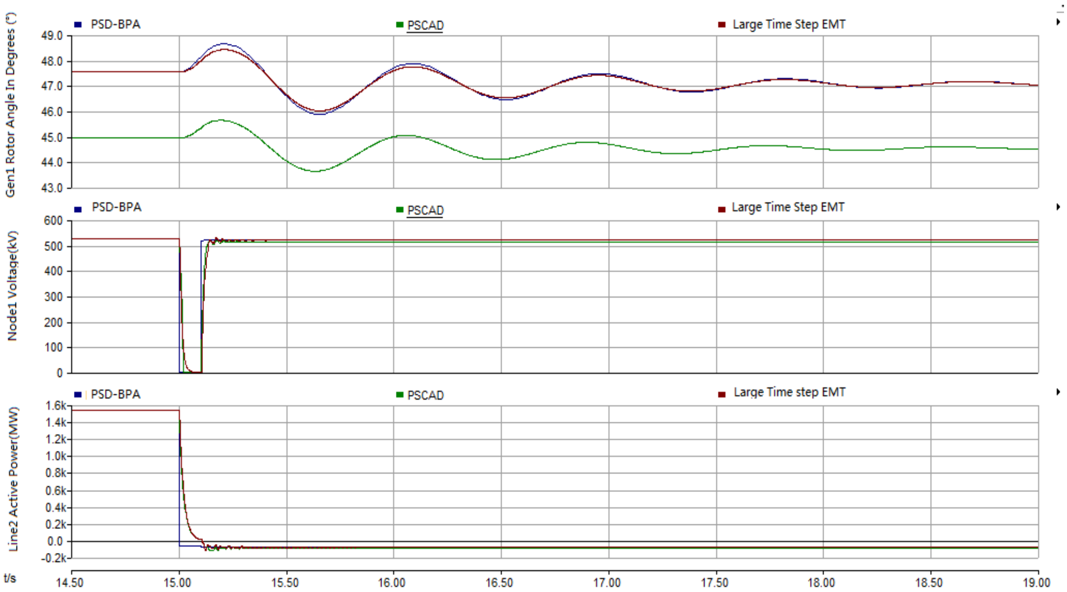

Figure 10. Node1-node2 line n-2 fault.

Because of the minor deviation in initial state and load condition, the generator rotor angles of PSCAD/EMTDC have certain error. But the overall trend is consistent. The large time step EMT can directly obtain initial conditions from PSD-BPA with a developed translation tool, the obtained results are more accurate. The comparison of results also indicates that, under the same grid structure and initial condition the electromechanical transient and electromagnetic transient simulation can acquire similar results.

8. Conclusion

This paper introduces a large time step EMT modeling and simulation method using time domain transformation methodology. This method can effectively improve the speed of EMT simulation, and also guarantee high accuracy. It is a useful tool for the study of complex dynamic behaviors of large scale complex AC/DC power grids. Using different simulation software, this paper compares the results during the steady state and transient conditions with large scale power grid. And the results demonstrate the high accuracy as well as efficiency of the large time step EMT simulation method.

- For the comparison of the steady power flow, the large time step EMT can achieve fast initialization for the large scale power grid. Although the accuracy of power flow descends with the time step increase, but the deviation is acceptable.
- Through enlarging the time step, the large time step EMT simulation speed-up ratio nearly increased linearly. Especially combined the parallel calculation, the large time step EMT simulation can achieve real time simulation for a system with thousands of buses.
- During the fault transient, the large time step EMT simulation can also maintain high accuracy. In the tested cases, the obtained rotor angles of the synchronous generators are very close to the electromechanical transient results. The largest deviation is under 0.3 degree.
- Before and after the fault transient, the power flow of large time step EMT simulation agree with the electromechanical transient very well. But during the fault transient, besides the fundamental frequency component , the large time step EMT simulation can show more transient details .
- Comparing the results of large time step EMT simulation, PSCAD/EMTDC and PSD-BPA of large scale power grid, they exhibit good agreement in steady state as well as fault transient. It means under the same grid structure and initial condition the electromechanical transient and electromagnetic transient simulation can acquire similar results. And it verifies the effectiveness of large time step EMT simulation method.
- For a 20 seconds simulation, the CPU time of large time step EMT simulation using given hardware is less than 2.4s (for the large scale power system II). The simulation speed is raised by two orders of magnitude than PSCAD/EMTDC. The Large time step EMT could effectively improve the EMT simulation efficiency of large scale AC system.

Acknowledgment

The authors would like to thank Dr. Shengtao Fan for his valuable discussion and advice.

References

[1] Shengtao Fan and Hui Ding J 2012 Time domain transformation method for accelerating EMTP simulation of power system dynamics *IEEE transactions on power systems*, vol 27(4) pp 1778-1787.
[2] Marti L. J 1983 Low-order approximation of transmission line parameters for frequency-dependent models. *IEEE Transactions on Power Apparatus and Systems* vol 102(11) pp 3582-3589
[3] Lin Jikeng, Yan Yipeng, LIU Tao and ZHENG Weihong J 2012 Review on external system equivalent method for electromagnetic transient simulation of power systems *Automation of Electric Power Systems* vol 36(11) pp 108-115.
[4] Gustavsen B and Semlyen A. J 1999 Rational approximation of frequency domain responses by vector fitting *IEEE Transactions on Power Delivery* vol 14(3) pp 1052–1061.

[5] Gustavsen B and Semlyen A. J 2001 Enforcing passivity for admittance matrices approximated by rational functions *IEEE Transactions on Power Systems* vol 16(1) pp 97–104
[6] Gustavsen B J 2008 Fast passivity enforcement for pre-residue models by perturbation of residue matrix eigenvalues *IEEE Transactions on Power Deliver* vol 23(4) pp 2278–2285
[7] Yue Chengyan D 2004 *Study of power system electromagnetic transient and electromechanical transient real—time hybrid simulation* (Bejing: China Electric Power Research Institute)
[8] Liu Yongjun D 2006 *Study on power system electromechanical transient and electromagnetic transient hybrid simulation* (Beijing: Tsinghua university)
[9] Zhang Yi D 2012 *Study on frequency dependent network equivalent based electromagnetic and electromechanical transient hybrid simulation* (Beijing: Tsinghua University)
[10] Liu Wenzhuo, Hou Junxian and Tang Yong J 2010 Electromechanical transient/electromagnetic transient hybrid simulation method onsidering asymmetric faults *Proceedings of the CSEE* vol 30(13) pp 8–15
[11] Zhang Shuqing, Tong Luyuan,Xu Wei and Hong Chao J 2009 Digital computer and RTDS based real-time hybrid simulation *Automation of Electric Power Systems* vol 33(18) pp 61-66
[12] Hu Yizhong, Wu Wenchuan and Zhang Boming J 2014 Development of a frequency dependent network equivalent based RTDS-TSA hybrid transient simulation platform with heterogeneous architecture *Automation of Electric Power Systems* vol 38(16): 88-93
[13] Mu Qing, LI Yalou, Zhou Xiaoxin, Zhao Peng and Zhang Xing J 2014 A parallel multi-rate electromagnetic transient simulation algorithm based on network division through transmission line *Automation of Electric Power Systems* vol 38(7) pp 47-52
[14] Gao Yi, Li Jiping and Wang Chengshan J 2011 Multi-rate method for power system simulation based on self-adaptive variable grouping *Electric Power Automation Equipment* vol 31(2) pp 1-6
[15] GEAR C W and WELLS D R. J 1984 Multi-rate linear multistep methods *BIT Numerical Mathematics* vol 24(4) pp 484-502
[16] GÜNTHER M and KVÆRNØ A and RENTROP P. J 2001 Multi-rate partitioned Runge-Kutta methods *BIT Numerical Mathematics* vol 41(3) pp 504-514
[17] Zhang P and Martf J R. J 2010 Shifted-frequency analysis for EMTP simulation of power. system dynamics *IEEE Transactions on Circuits and Systems* vol 57(9) pp 2564-2574.
[18] Marti J R,Dommel H W and Bonatto B D C 2014 Shifted frequency analysis(SFA)concepts for EMTP modelling and simulation of Dower system dynamics *Power Systems Computation Conference(PSCC) IEEE* pp 1—8
[19] Gao F and Strunz K J 2009 Frequency-adaptive power system modeling for multiscale simulation of transients *IEEE Transactions on Power Systems* vol 24(2) pp 561-571
[20] trunz K, Shintaku R and Gao F. J 2006 Frequency-adaptive network modeling for integrative simulation of natural and envelope waveforms in power systems and circuits *IEEE Transactions on Circuits and Systems* vol 53(12) pp 2788-2803