Comparisons of Impact on the Modeling Detail on Real Time Simulation of Large Power Systems with HVDC

Yuefeng Liang, Xi Lin, A.M. Gole, Ming Yu, Yi Zhang, Boming Zhang

Abstract— **Electromagnetic Transient (EMT) and Transient Stability Analysis (TSA) are two major types of digital time domain simulation tools for power system studies. The EMT has the most accurate models, but its significant computational requirement makes it unsuitable for modeling very large systems. Conversely, the TSA models are simpler; hence it is faster and is more suitable for very large systems. However, with the TSA's simpler models, higher frequency phenomena such as switching and fault transients, power electronic switching, etc. cannot be represented. A compromise approach is to judiciously partition the system into 'internal' parts which are of more interest and contain detailed EMT models of the components and an 'external' part of lesser interest, which is represented by a comprehensive wideband equivalent. This wide band equivalent combines a frequency dependent network equivalent (FDNE) to represent the high frequency behavior, together with a TSA solution to represent the electromechanical low frequency behavior. This paper investigates the impact on simulation accuracy of large networks with embedded HVDC links, based on the various approaches (EMT, TSA and the wide-band equivalent). The test systems include a modified version of the New England 39 Bus Test System that incorporates a HVDC infeed and a large 2300 bus 139 generator systems with a HVDC infeed. The results show that from the point of view of the internal system, both high and low frequency behaviors are accurately modeled using the proposed wide-band equivalent technique.**

Index Terms: **Electromagnetic Transient (EMT), Transient Stability Analysis (TSA), Wide-band Equivalent, Large Power System, HVDC, Real-Time Digital Simulator (RTDS)**

I. INTRODUCTION

THE large scale and complexity of modern power systems require sophisticated analysis tools such as electro-magnetic transient (EMT) programs and transient stability analysis (TSA) programs. EMT models are the most detailed with all transmission as well electromechanical components modeled using detailed differential equations. EMT modeling allows very accurate representation of the network, but is computationally very expensive [1]. The bulk of power system studies consider rotor angle for which transient stability analysis (TSA) programs are adequate. In such programs the bulk of the electrical transmission network is considered to be in a quasi-steady state and is represented as algebraic "phasor models", with the dynamic modeling (differential equations) being confined to rotating machines, exciters, governors and turbines and a few other elements. The computational effort with TSA models is significantly smaller, thereby allowing the modeling of very large systems (excess of 50,000 busses) [2][3], even on single processors. Also, high frequency dynamics are ignored, a larger integration step (typically half a cycle) is used.

When power electronics based equipment is included in the power system, such as HVDC and FACTS, the TSA model is sometimes not sufficiently accurate to represent the power system. The EMT, with the most accurate model, can represent power system with such kind of equipment properly. Especially the implementation of EMT algorithms on real-time simulators can make the power system to be studied just like in a real physical world [4] . However, conducting a full scale EMT simulation, especially in real time, can be computationally very expensive. One of the pioneering works is a hybrid approach [5] which uses instantaneous analysis for detailed part and phasor analysis for the rest of the system. This approach is able to simulate large-scale power systems in real-time. However, the phasor analysis only considers the fundamental frequency behaviors. Recently a wide-band equivalent technique [6][7] has been introduced, which enables very large power systems to be modeled on real time electro-magnetic transients (EMT) digital simulators with greatly reduced computation cost and wide-band frequency response. This paper compares the impact on the modeling detail on simulating of large power system with HVDC using these three approaches. Such a comprehensive comparison was not included in earlier works.

II. THE REAL TIME IMPLEMENTATION OF EMT SIMULATION

The Real Time Digital Simulator (RTDS) is a real time implementation of an EMT simulation. The power system to be simulated is divided into parts by utilizing the traveling wave characteristic of transmission lines. A specially designed

Paper submitted to the International Conference on Power Systems Transients (IPST2011) at the Delft University of Technology.

Yuefeng Liang, Xi Lin and A.M.Gole are with the University of Manitoba, Winnipeg, MB, R3T 5V6 Canada.
E-mail(phone/fax):yuefeng@ee.umanitoba.ca(1-204-9495742/1-204-4524303) , Xi.Lin@powertechlabs.com and gole@umanitoba.ca (1-204-474-9959 /1-204-474-7522).
Ming Yu is with the RTDS Technologies Inc., Winnipeg, MB, R3T 6B6 Canada; e-mail: myu@rtds.com
Yi Zhang and Boming Zhang are with Tsinghua University, Beijing,China.
E-mail: veriasea@gmail.com and Zhangbm@tsinghua.edu.cn

powerful parallel computation platform is used to solve the nonlinear differential equations. In this way, the size of the system to be simulated is not limited by one processor or one computer. Using highly parallel, ultra-fast computer architectures, these simulators are able to model electrical networks in real-time. To simulate the power system in real time is not just to save computation time; more importantly, actual protective relays and control equipments can be connected to the RTDS in a close of loop and be tested as if they are in a real power system [4] .

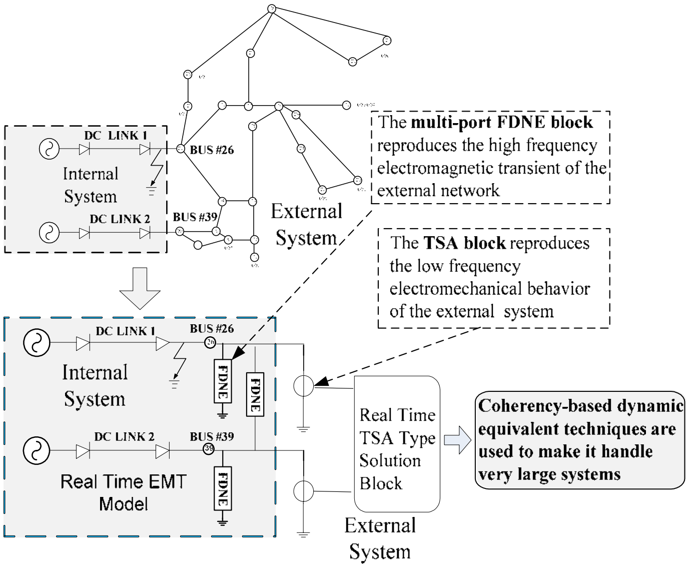
The non-real time EMT simulation is usually not designed to run for a long time. For a short study interval the low frequency electromechanical dynamics might not be properly captured. The real time EMT simulation has to be finished within the real transient time. It can run continuously, without any specified termination time, and is able to replicate real physical world phenomena accurately. Hence the RTDS is capable of modeling the fast high frequency events which are the traditional domain of EMT programs, but can also be used to study lower frequency electromechanical oscillations. In this paper the RTDS is employed as the real time EMT simulation in the comparison.

III. WIDE-BAND EQUIVALENT TECHNIQUE

The real time digital simulator (RTDS) has the ability to handle large systems [1]. But its capability for accurately reproducing dynamic and transient behavior of large systems is often limited by the cost of additional hardware requirements. For a non-real time EMT program, there is a possibility for a large power system to be modeled if the computation time is not an issue to be concerned with. However, just as mentioned in previous section a non-real time EMT program usually is not designed to study a large system and run for a long period of time. Hence for both real time and non-real time EMT simulation, modeling a very large system with full detail would still be unpractical or uneconomical.

In practice what we are interested in is a partition of the full system. Hence the system is often divided into internal and external systems depending on which portion of the system need to be studied in detail. The components in internal systems, such as generators, controls, HVDC devices etc, are modeled in full EMT detail. Faults or other disturbances are applied within internal systems. External systems are those which we have less interest in and are thus modelled in a simplified equivalent. The challenge is that this equivalent should replicate the responses of the external system to disturbances in the internal system with reasonable accuracy, but with much reduced computation resources.

The wide-band equivalent technique [6][7] has been proposed to address this challenge. As shown in Fig. 1 the high frequency behavior of the external network was represented by a terminating frequency dependent network equivalent (FDNE), and the low frequency electromechanical behavior was modeled using a full [6] or reduced [7] Transient Stability Analysis (TSA) program. The FDNE is implemented as a multi-port admittance matrix with rational polynomial elements (in the Laplace or s-domain)[8] embedded into the EMT solution. The frequency response characteristic of this admittance closely matches the frequency response behavior of the entire external network (ignoring non-linearities) over the selected frequency range (typically from a few Hz to several kHz). As the elements are rational polynomial functions, they can be readily converted to time-domain differential equations and included in the EMT simulation [9].



The **multi-port FDNE block** reproduces the high frequency electromagnetic transient of the external network

The **TSA block** reproduces the low frequency electromechanical behavior of the external system

Coherency-based dynamic equivalent techniques are used to make it handle very large systems

Fig. 1 An Improved Wide Band Two Parts Equivalent

An example of the fitting is shown in Fig. 2, where the solid and dashed line respectively are plots of the original and fitted frequency response of the magnitude and phase of a typical matrix element of the admittance matrix $\left[Y_{4,6}(j\omega)\right]$ of the 39 bus New England system shown in Fig. 3. As can be seen, an accurate fit can be achieved.

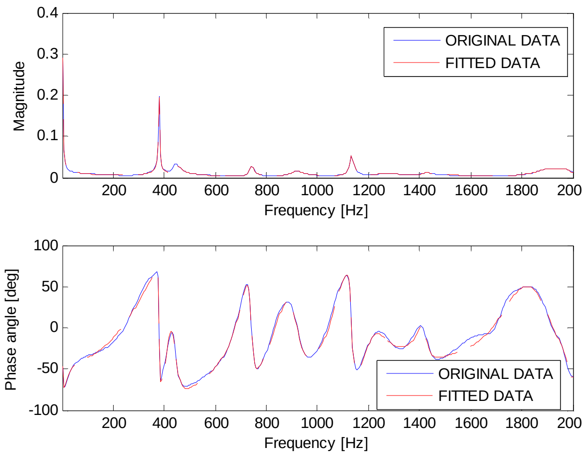


Fig. 2 FDNE Fitting Example

IV. SIMULATION CASES

As mentioned in section 1, this paper compares the impact on the modeling detail on power system which includes HVDC with different simulation techniques. The RTDS is employed here as a real time implementation of EMT simulation. The EMT simulation result, whenever available, should be used as the benchmark of the system behaviors since it has the most accurate model than the other two simulation techniques. A commercial TSA simulation software is used for the comparison.

In order to compare the closeness of the two curves the error index E_IDX is defined as (1). A perfect fit would produce an error index of zero.

$$E\_IDX = \frac{\sqrt{\sum_{i=1}^{m} error_i^2}}{\sqrt{\sum_{i=1}^{m} amplitude_i^2}} \cdot 100\% \qquad (1)$$

$error_i$: The difference between the curve and the benchmark at point i .

$amplitude_i$: The amplitude of the benchmark curve at point i

m : The number of test points

Two different test systems with various fault locations are used for comparisons. These included i) a modified 39 bus system with an HVDC infeed; ii) a 2,300 bus AC/DC system. The first system could be modelled entirely on the real time digital simulator (RTDS). The simulation result is regarded as the benchmark in the comparison. The second system was represented using the developed wide band equivalent technique and a TSA program, as it is too large to be modeled in full EMT detail at a reasonable cost.

A. Simulation of a 39-Bus AC System Using Two Port Equivalent

This test system is derived from the well-know New England Test System [10] and shown in Fig. 3. The internal system (i.e. the system of more interest) is taken to be the union of internal systems 1 and 2. The equivalent of the remainder external system is thus a two port equivalent (with each port being a three phase connection) as it interfaces to two separated internal systems. The internal system includes 5 generators, 13 buses, 6 transformers, 7 transmission lines and one back to back DC link. This full system could be run in the RTDS and its simulation result (referred as RTDS FULL MODEL in the plot) is regarded as the benchmark in the comparison. Then the full system is modeled using a TSA simulation program and its simulation result is referred as TSA FULL MODEL in the plot. When the proposed equivalent technique is applied to the system the two internal systems are modelled in full EMT detail on the RTDS. The external system is replaced with the wide-band equivalent [6] which also runs on the RTDS. The detail internal system and equivalent external system represent the full system and the legend RTDS+FDNE+TSA is used in the plot.

A three phase ground fault of 12 cycles (200 ms) duration on boundary bus 16 is simulated. The small fault resistance to the ground and long duration fault time (12 cycles) can cause the commutation failure (CF) which is the failure to transfer current from a conducting valve to the next valve in the conduction cycle. Although in the TSA program the DC link is modeled in a certain detail the commutation failure and its affection still can not be properly captured. The simulation results are shown in Fig. 4 - Fig. 6 .

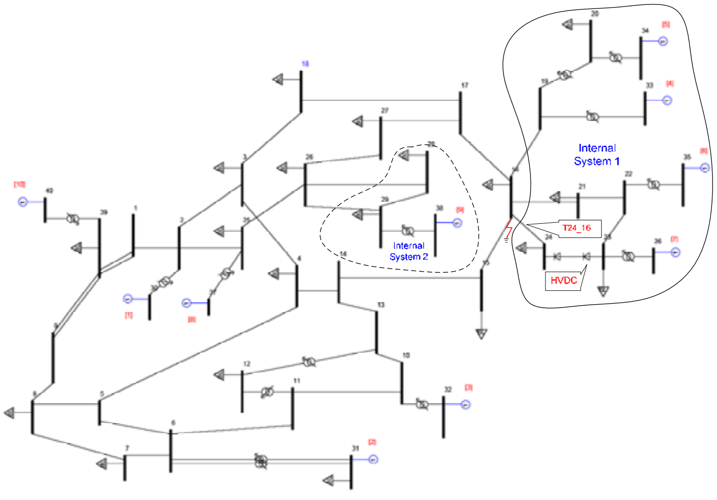


Fig. 3 New England 39 Bus System

The DC link inverter side voltage is shown in Fig. 4. The first is a full detail EMT implementation simulation (RTDS FULL MODEL), the next is the proposed equivalent representation of the system (RTDS+FDNE+ TSA), and the third one (TSA FULL MODEL) models the full system using a TSA program. The error index $IDX1$ between the EMT full model and the equivalent model is 0.99496% which shows the equivalent model is quite close to the full EMT model. The error index $IDX2$ refers to the difference between the EMT and TSA full model, which is 16.87593% and shows a bigger difference from the benchmark than the error index $IDX1$.

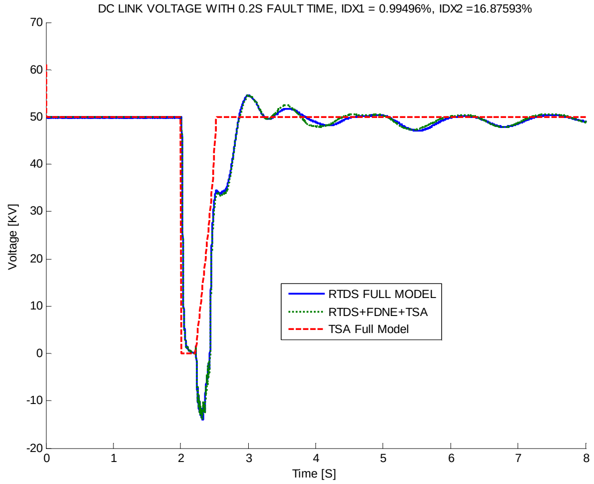


Fig. 4 DC link voltage

The reason is that a commutation failure happened during recovery which is clearly captured by the full model in EMT detail (RTDS FULL MOEL) and the equivalent technique (RTDS+FDNE+TSA), but is not able to be accurately simulated on the purely phasor based TSA representation (TSA FULL MODEL) used in the comparison. It can be concluded that if the equivalent is a correct representation of the external system the dynamic behavior of the boundary transmission line T24_16 for both full and reduced model should be close when the fault is in the internal system 1. The active and reactive power of the boundary transmission line T24_16 are shown in Fig. 5.

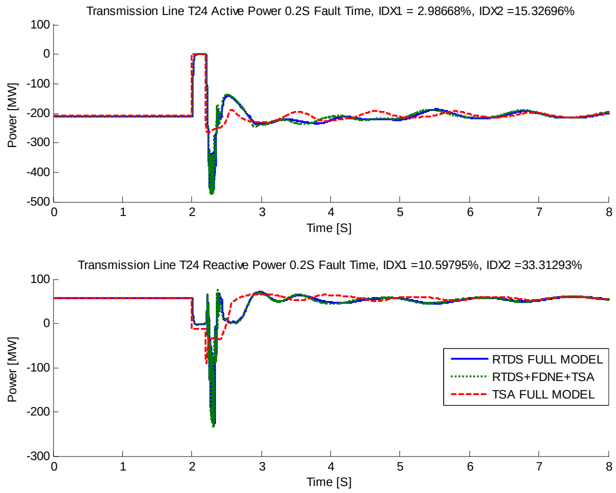


Fig. 5 T Line power

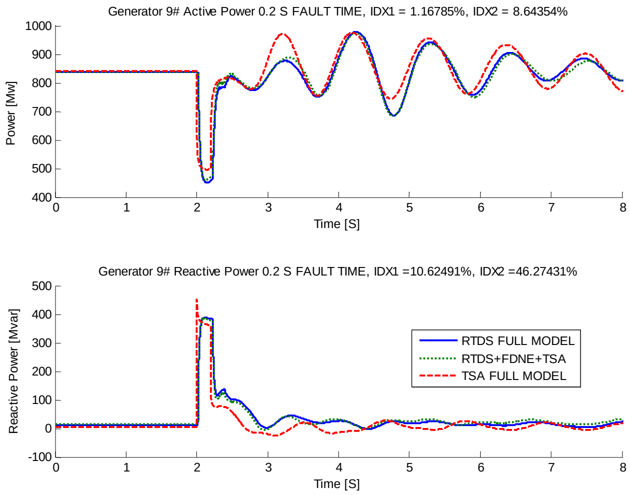


Fig. 6 Generator Power

When the internal system is segmented (such as in the 39-bus case with two internal systems), it is interesting to investigate whether the accuracy in all internal systems is highly accurate. The above results were for internal system 1 in which the fault occurred. Now consider internal system 2. Fig. 6 shows the active and reactive powers of the generator in internal system 2.

There are three curves in each figure of Fig. 5 - Fig. 6 . The error indices $IDX1$ and $IDX2$ are as defined earlier when discussing Fig. 4. It is obvious that the proposed equivalent technique (RTDS+FDNE+TSA) is closer to the full model in EMT detail (RTDS FULL MODEL). This shows that even in the internal system where the fault is not directly applied, the equivalent model is still able to capture the transient behavior with a reasonable accuracy.

In most TSA programs the power electronic devices are modelled, although in much less detail than in EMT programs. Hence to a certain level, the TSA model also can represent the dynamic behaviors of the power system which includes power electronic devices. But if the very fast transient need to be considered the EMT model has to be used. The next test case will illustrate this point.

B. Simulation of a 2300 Bus System Using One Port Equivalent

This test system which is shown in Fig. 7 is a large system from the point view of EMT simulation. It has one internal system which connects to the external system through the boundary transmission line T1473_674. There are two generators (G_21138, G_72266) and a HVDC line (D12473_11473) in the internal system. The external system has 2292 buses, 802 loads, 137 generators which have been aggregated to 30 equivalent generators [7], 142 shunts, 1006 transmission lines and 1338 transformers. The full system is simulated using a commercial TSA program with the time step of 5 ms since the entire system is too large for the RTDS to run the EMT simulation. For the reduced model, the internal system is simulated using a real-time time step of 50 μs. The wide band equivalent which models the external system was run on the RTDS with a time step of 200 μs .The entire system was represented very economically using just 2 RTDS racks. It is estimated that without the equivalent, the simulation would have required more than 100 racks.

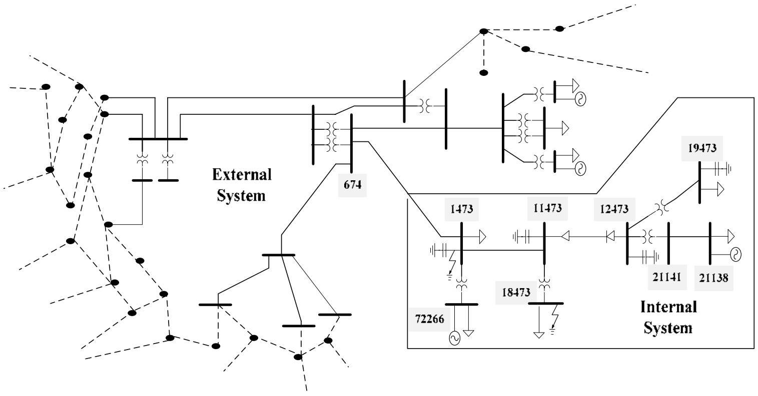


Fig. 7 A 2300 Bus System

A three phase 12 cycles (200 ms) ground fault was applied at bus 1473. In a subsequent simulation, a three phase ground fault with the same duration was applied on bus 18473, which is closer to the HVDC inverter bus.

The active and reactive power of T1473_674 for the first scenario has been shown in Fig. 8 . From the error index

$IDX1$ it is obvious that the proposed equivalent and the TSA full model are both capable of reproducing the essential dynamic behaviors of the external system. Also, visually, the simulation results are quite close. It is also interesting to note that in the TSA full model the high frequency transient (electromagnetic) has been neglected while in the proposed equivalent this transient during the fault process are still captured.

For the second fault which was closer to the inverter on bus 18473, a significantly larger difference was observed between the proposed equivalent based model and the TSA full model as shown in Fig. 9.

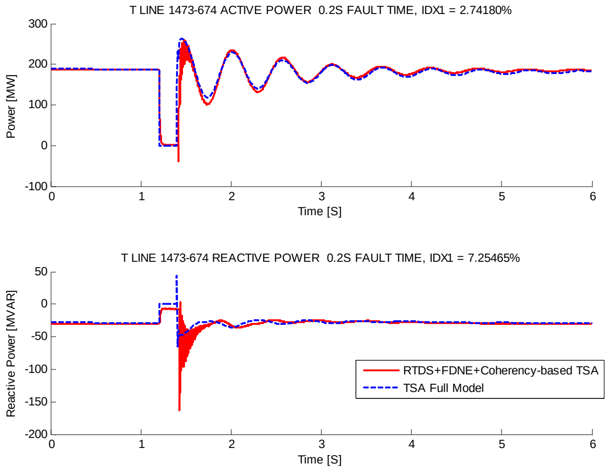


Fig. 8 T Line Power with Fault on Bus 1473

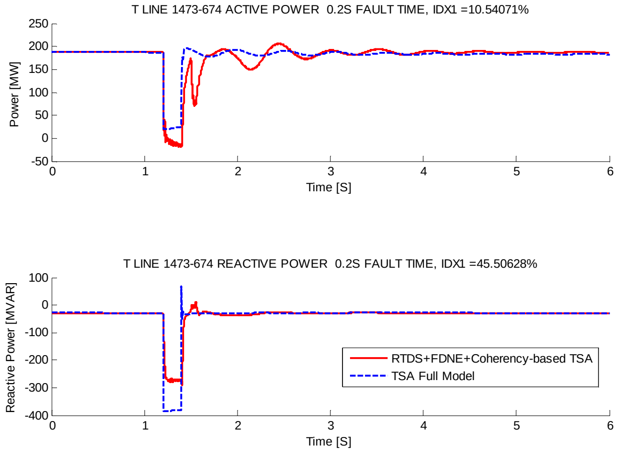


Fig. 9 T Line Power with Fault on Bus 18473

The reason for this is that there is a commutation failure(shown in Fig. 10) during recovery which is clearly captured by the equivalent based model, but is not able to be accurately simulated on the purely phasor based TSA representation used in the comparison. Note that this fault excites low frequency oscillations in the system that is of a larger magnitude than in the TSA solution. This is interesting, because both models ought to have similar accuracy for electromechanical transients, and indeed do show near identical oscillation frequency and damping, as evidenced in Fig. 8 . The results of Fig. 9 indicate that when transient events such as commutation failure are modeled in detail, the disturbance applied to the network is stronger and incites higher amplitude electromechanical oscillations.

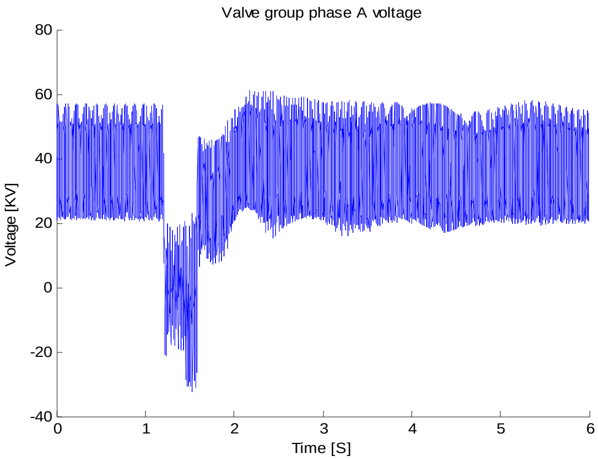


Fig. 10 Valve Group Phase A Voltage

Hence the more detailed representation is seen to affect not only the higher frequency transient behavior, but also the electromechanical behavior.

V. CONCLUSIONS

The EMT program has the most accurate model using detailed differential equations. The disadvantage is the high level cost of the computational resource. In TSA programs, the "phasor models" are used and the dynamic modeling is confined to a certain level. Due to ignoring high frequency dynamics and using a larger integration step (typically half a cycle) it is capable of handling very large power systems. However, the high frequency dynamic behaviors could not be adequately represented. In order to keep both advantages of EMT (most detailed) and TSA (large scale) the wide-band equivalencing technique [6][7] has been developed for system studies. Using this technique, the internal system is modelled in EMT detail and the external systems are modelled with equivalents. The computation resources could be reduced to an affordable level. Comparisons of the modeling accuracy on systems with HVDC using these three approaches have been investigated. A numerical error index is employed to compare the simulation results of these three methods.

From the simulation results it can be concluded that the TSA program can accurately represent the system dynamic behaviour to a certain level, particularly in regions of the network far removed from fault applications. However, for the transients initiated by dc system faults it should be noted that even the electromechanical transients resulting from such faults cannot accurately be captured by the TSA, because the level of excitation of these transients is not accurately represented, even though the oscillation frequency and damping may be. The wide-band equivalent technique models the internal system in a full EMT detail and the external system in a simplified equivalent. The simulation results shows from the point of view of the internal system the wide-band equivalent technique is able to accurately reproduce both high and low frequency behaviors with a remarkable reduced computation cost.

VI. REFERENCES

[1] P.Forsyth, R.Kuffel, R. Wierckx et al, “Comparison of Transient Stability Analysis and Large-Scale Real Time Digital Simulation”, *Power Tech Proceedings, 2001 IEEE Porto*

[2] Transient Security Assessment Tool(TSAT) User Manual, Powertech Labs Inc., Surrey, British Columbia, Canada, April 2007

[3] PSS/E™ 30.2 Manual Set, Power Technologies International, Siemens Power Transmission & Distribution, Inc., November 2005, Schenectady

[4] Kuffel, R. Giesbrecht, J. Maguire, T., Wierckx, R.P., McLaren, P.G.,” A fully digital power system simulator operating in real time”, Electrical and Computer Engineering, 1996. Canadian Conference , Volume 2, 26-29 May 1996 Page(s):733 - 736 vol.2

[5] H. Inabe et al, "Development of an instantaneous and phasor analysis combined type real-time digital power system simulator," Proc. of IPST 2003, Paper No. 13-1, New Orleans, USA, 2003.

[6] Xi Lin; Gole, A.M.; Ming Yu, “A Wide-Band Multi-Port System Equivalent for Real-Time Digital Power System Simulators”, IEEE Transactions on Power Systems, Volume 24, Issue 1, Feb. 2009 Page(s):237 – 249

[7] Yuefeng Liang, Xi Lin, A.M. Gole, Ming Yu “Improved Coherency-Based Wide-Band Equivalents for Real Time Digital Simulators “, IEEE Transactions on Power Systems, Oct. 2010, approved to be published

[8] B.Gustavsen, A.Semlyen, ”Rational Approximation of Frequency Domain Responses by Vector Fitting”, IEEE Trans on Power Delivery, Vol.14,No.3,pp.1052-1061,Jul. 1999

[9] H.W.Dommel, ”Digital Computer Solution of Electromagnetic Transients in Single and Multi-phase Networks”, IEEE Trans on Power Apparatus and Systems, vol.PAS-88,No.4, pp.388-399,Apr.1996.

[10] Coherency Based Dynamic Equivalents for Transient Stability Studies, EPRI 904 Final Report, January 1975