A Wide Band Multi Port Equivalencing Method for Real Time Digital Simulators

Xi Lin, A. M. Gole, Ming Yu

Abstract-- This paper proposes a wideband multi-port equivalent for real time digital simulators, which permits the simulation of a large power system in real time with reduced hardware cost. The proposed equivalent includes a Frequency Dependent Network Equivalent (FDNE) for the high frequency electromagnetic transients and a Transient Stability Analysis (TSA) type solution block for the electromechanical transients. The FDNE equivalent is obtained using Vector Fitting techniques. A method for approximating the frequency dependent characteristics of large power networks is also presented. The conventional TSA algorithm is shown to be unsuitable for real-time application; and a modification suitable for implementation on real-time platforms is proposed. The validity and efficiency of the proposed equivalencing method are demonstrated using examples that include: i) a large ac network and ii) a multi-infeed HVDC system based network.

Keywords: Power System Simulation, Real Time Digital Simulator, Dynamic Equivalent, Frequency Dependent Network Equivalent, Electromagnetic Transient, Transient Stability.

I. Introduction

ELECTROMAGNETIC Transient (EMT) type digital time domain simulators are extensively used in power system studies. In EMT type tools, a power network is represented in very high detail making it possible to accurately model phenomena such as switching transients which cover the frequency spectrum from dc to tens of kilohertz. However with non-real time programs, the computational burden due to the high level of detail limits the size of the system that can be modeled and also usually restricts the study interval to a few seconds.

The Real Time Digital Simulator (RTDS) is a real-time application of EMT type simulation on a parallel computation platform. Using this tool, a wide-band EMT model of a power system with up to several hundred buses can be simulated in real time [1]. Because the simulation can be kept running continuously (over hours or days) in real time, it becomes possible to use the same tool for the study of very low and high frequency system behaviours.

However the size of the RTDS hardware (counted in terms of processor racks) and subsequently its monetary cost is proportional to the size of the modeled system. Hence it makes economic sense to model in full non-linear detail only that part of the network which is of great interest (referred to as the internal system), and formulate the remainder (external system) of the network into an appropriately accurate equivalent. It should be noted that the equivalent must be able to properly represent the high frequency electromagnetic as well as the low frequency electromechanical transient behaviour.

The fast transient response of the external system can be well preserved by a linear frequency dependent network equivalent (FDNE) model under most practical conditions. The FDNE can be obtained by fitting to the frequency response characteristic of the original network with an admittance characteristic which can be represented by a rational function in the s-domain. [2][3]

The slow transient response of the external system is dominated by the electromechanical oscillations of the generators which can be accurately simulated using a Transient Stability Analysis (TSA) algorithm. TSA programs are widely used to study the electromechanical transients in very large electrical networks, but are restricted in their dynamic representation to low frequency phenomena (0-5 Hz). In these programs, the electromagnetic transients in the transmission network are ignored as the network is represented in fundamental frequency steady-state phasor form.

Combining EMT and TSA algorithms for investigating different aspects of the same problem is referred to as 'hybrid simulation' [4-8]. In some previous approaches, a TSA program is interfaced to an EMT program through a fundamental frequency Thevenin (or Norton) equivalent. This approach neglects the high frequency behaviour of the external system [4-6]. In some other approaches [7][8], a single port FDNE equivalent, is used instead of the fundamental frequency equivalent.

This paper extends previous work by proposing a wideband equivalent for real-time simulation that has the following features:

- A combined (TSA+FDNE) multi-port equivalent
- Adaptation of TSA to run on a real-time platform

The validity and efficiency of the proposed method are demonstrated using examples that include: i) a multi-infeed HVDC system based network and ii) a large ac network.

II. Structure of The Proposed Equivalent

The structure of the proposed equivalent is shown in Fig. 1, with the fast, linear, passive and frequency dependent characteristics represented by a FDNE, which is embedded into the EMT solution as a multi-port admittance and becomes

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part of the main EMT solution; and the slow, nonlinear, fundamental frequency dynamic characteristics achieved by means of the TSA solution block, which is interfaced to the EMT solution through a controlled current source. The details of implementation of these two parts are presented in the following sections.

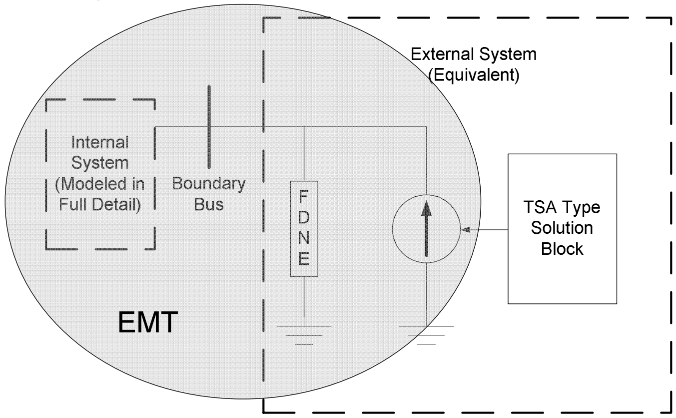

Fig.1 Wide Band Two Part Equivalents

III. Frequency Dependent Network Equivalent

This section discusses the implementation of the FDNE part of the proposed equivalent which is used for representing the fast electromagnetic behaviour of the external system.

A. Implementation of Frequency Dependent Admittance in EMT Simulation

The process of finding an equivalent model for the high-frequency behaviour of the external network starts with the knowledge of the frequency dependent admittance(s) (FDA) as seen from the boundary. Fig. 2 shows a typical frequency dependent admittance with its magnitude and phase plotted as functions of frequency.

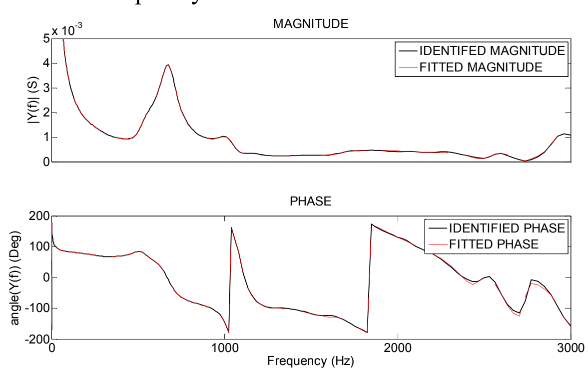

Fig. 2 FDNE Example

The procedure used to implement the FDA in the EMT algorithm, is to fit the FDA with a rational function in the s-domain. The s-domain transfer function can be implemented in the standard current source-conductance form used in the EMT algorithm [9]. Here, the fitting process is achieved using the procedure of 'Vector Fitting' [3], which has been shown to be successful in fitting complicated frequency domain responses. A typical example of the fitting is shown in Fig. 2, in which the frequency variation of one of the off-diagonal elements of the admittance matrix of the external system to be considered later in the first example case in Section V is shown. In Fig. 2, the solid and dashed lines show the plots for the actual admittance and the fitted admittance respectively.

B. Deriving the frequency response from power flow data

The approach described in the previous subsection in the above section provides highly accurate FDNE implementations. However it does require knowledge of the frequency domain characteristics of the real network, which are often not readily available. Such a characteristic can be accurately obtained by calculation if detailed parameters of the interconnecting power apparatus (such as the tower and cable geometries, conductor and earth resitivities and frequency dependence of loads) are accurately known [10]. Such information is often very difficult to obtain, and for such cases, this paper introduces a method for estimating the FDNE characteristic from more commonly available data as discussed below.

The commonly available data for system analysis is the power flow data, for example, data stored in PSS/E raw format [11]. It only contains the fundamental frequency parameters of the power system. With some assumptions, the frequency domain characteristics of common power system components such as transmission lines, cables and transformers can be approximated from their fundamental frequency parameters.

As an example, consider a long transmission line or cable, which has frequency dependent admittance and propagation characteristics which cannot be accurately represented by simple lumped pi-section models. A commonly used distributed parameter model for transmission lines in EMT simulations is the Bergeron model [9][12], which is exactly accurate if the conductor and ground are ideal conductors. In such a model, the incremental inductance and capacitance per unit length are independent of frequency and can be directly calculated from their fundamental frequency values. The resistance of the line can be approximated by inserting suitable lumped resistances at the middle and ends of the line [12]. The frequency dependent response of the line can then be easily acquired [10]. By following a similar procedure with the other network elements, and the FDA matrix can be readily assembled using a nodal analysis formulation [12].

The advantages of the above proposed method are:

- The FDA can be easily and rapidly obtained by processing of the standard power flow data file.
- If more detailed geometrical and physical data is available for some of the components, their representations can be accurately calculated and the FDA matrix can be reconstructed using these values.
- The method provides an opportunity to be selective. Some components have such frequency dependent characteristics that are not linear (for example, synchronous generators). Such characteristics can be intentionally simplified to linear form in order to avoid numerical difficulties in the curve fitting process.

IV. The Implementation of TSA Type Solution on RTDS

This section discusses the implementation of the TSA part of the proposed equivalent which is used for representing the slow non-linear electromechanical behaviour of the external system.

A. Difficulties in implementation of conventional TSA algorithms in real time

Because TSA programs ignore the detailed electromagnetic transients, they can potentially run much faster than EMT programs. Indeed, today a TSA program can even appear to run in real time when simulating a power system with several thousand buses. However, this appearance of "real time" is only in an average sense, which means that some time-steps take much longer to simulate than other time-steps. This is because conventional TSA simulations typically use time-steps ranging from 2ms–10ms. For such relatively large time-steps, a suitable iterative calculation method is usually applied for solving the nonlinear network equations [13]. As the number of iterations in any given time-step is not known a-priori, this results in an unpredictable amount of processing time for each time-step.

In contrast to the above approach which is suitable for off-line simulation, a true real-time simulator is required to keep in absolute synchronism with a real world clock. Hence the system solution in *every* simulation time-step $\mathbf{\Delta t}$ must be completed in an equivalent amount of *real world time* $\mathbf{\Delta t}$.

The above discussion reveals the difficulty of interfacing a conventional TSA algorithm to a true real-time simulator platform. An alternate workaround solution is discussed in the following section.

B. The Proposed Scheme

The proposed approach uses a modified approach to implement the TSA type algorithm for real-time platforms.

- The TSA simulation time-step is reduced so that the predictor-corrector iteration is no longer needed. This ensures a constant solution time per simulation time-step which is within the real-time requirement.
- A simple conversion method is developed to convert between the instantaneous values of the EMT solution and the phasor values of the TSA solution.

The general structure of the proposed scheme is shown in Fig. 3. Block 'a' measures the interface currents in the detailed RTDS model (internal system) to be injected into the external system, and converts them from three phase instantaneous values to fundamental frequency positive sequence phasor values. Block 'b' represents the external network using a fundamental frequency phasor formulation. Connected to block 'b' are blocks 'c' which represent dynamic equipment such as generators, motors etc. This equipment is represented by its own differential equations. Block 'd' is used to calculate the TSA injected current into the EMT solution. The blocks in Fig.3 are individually constructed as user defined control (UDC) models in RTDS [14].

C. Nature of the Network Solution

In the proposed scheme the TSA solution is conducted with a sufficiently small time-step so that the network voltages in any time-step are close to the voltages in the previous time-step. This permits the network equations to be solved using a linear formulation that does not require predictor-corrector type iteration, permitting the use of a single solution in each time-step. For example, a constant power load in the conventional TSA solution can now be modeled as a current source the value of which is:

$$\vec{I}(t) = \frac{(P + jQ)}{\vec{V}(t-\Delta t)^*} \tag{1}$$

Thus the processing time of each time-step is constant.

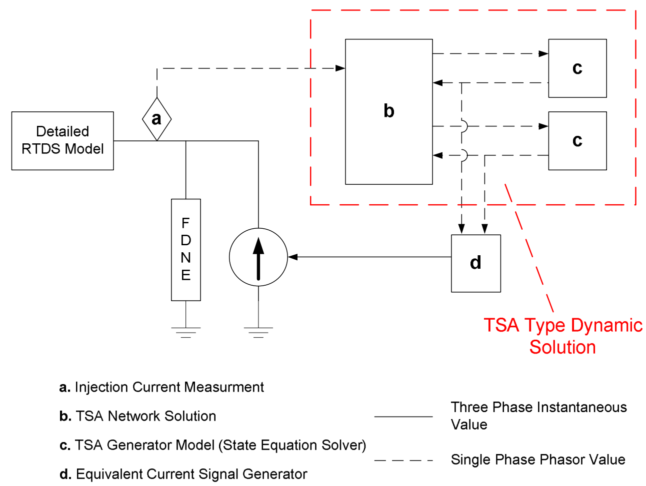

Fig. 3 General Structure of the Proposed TSA Solution Scheme

D. Boundary Data Conversion

In the EMT solution, the voltages and currents are calculated as three phase instantaneous values. In the TSA solution, only fundamental frequency positive sequence phasor values are calculated [13].

To interface the EMT solution to the TSA solution, the three phase instantaneous values of voltage and current on the boundary bus need to be converted to positive sequence phasor values. In other research papers, this has been done by calculating the RMS value of the voltage [4], a Fast Fourier Transformation (FFT) [6] or a consecutive curve fitting technique [5][7][8].

The method proposed in this paper is based on the fact that the generator electromechanical swings represented in the TSA are primarily affected by the real power supplied to the external network at the boundary bus. Hence a highly accurate data conversion procedure can be developed which is much simpler to implement than the FFT and curve fitting approaches stated above. Thus instead of attempting to extract the fundamental frequency positive sequence components of the voltage and current at the boundary, the method attempts to specify three phase balanced phasor voltages on the boundary in the TSA solution, which can push the same amount of real power into the external system model as calculated by the independent and accurate EMT solution of the internal system model. Based on this, a simple conversion method, as demonstrated in Fig. 4 is used.

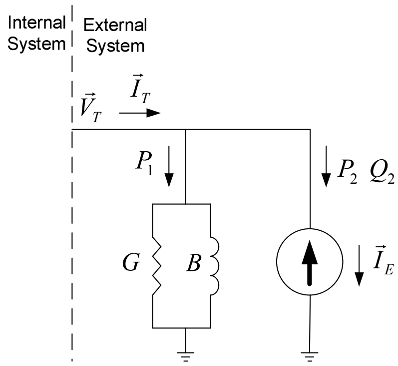

Fig. 4 Instantaneous Value to Phasor Value Conversion

Fig. 4 shows the two part equivalent as seen at the fundamental frequency and positive sequence (say as seen from the TSA solution point of view). The objective is to determine the positive sequence phasor values $\vec{V}_T$ and $\vec{I}_T$ at the boundary bus for use in the TSA solution. The positive sequence values $G + jB$ of the admittance of the FDNE at fundamental frequency are known. The phasor value $\vec{I}_E$ of the controlled three phase current source is calculated in the TSA program. The instantaneous values of the corresponding three phase currents $iEa(t)$, $iEb(t)$ and $iEc(t)$ are thus also readily calculated by expressing the above phasor in time domain form. P_1 is the real power flows through the FDNE ($G + jB$) and is calculated in the EMT program.

P_2 is the instantaneous value of real power into the controlled current source. As we know the instantaneous value of $vTa(t)$, $vTb(t)$, $vTc(t)$ as calculated in the EMT program, and the instantaneous values of $iEa(t)$, $iEb(t)$ and $iEc(t)$ are also known as above, P_2 can be readily calculated

The magnitude of $\vec{V}_T$ for use in the TSA can be derived from P_1 as:

$$\left|\vec{V}_T\right| = \sqrt{\left|P_1 / G\right|} \tag{2}$$

Since $\vec{I}_E$ is known as shown above, the relative angle between $\vec{V}_T$ and $\vec{I}_E$ can be derived from P_2,

$$\left|\angle\vec{V}_T - \angle\vec{I}_E\right| = \tan^{-1}\left(\frac{\left|\vec{V}_T\right| \cdot \left|\vec{I}_E\right|}{\left|P_2\right|}\right) \tag{3}$$

Whether $\vec{V}_T$ leads or lags $\vec{I}_E$ can be derived from the knowledge of the sign of the reactive power Q_2 flow into the controlled current source. Unlike the calculation of P_2, the calculation of Q_2 is not absolutely valid during transients. However this is not critical since only the sign of Q_2 is needed for determining the quadrant of $\vec{V}_T$. The injected current $\vec{I}_T$ can be calculated as:

$$\vec{I}_T = (G + jB) \cdot \vec{V}_T + \vec{I}_E \tag{4}$$

This method is very simple and its effectiveness is demonstrated in the example cases shown in the following section.

V. Example Cases

This section validates the above approach by two examples.

A. Simulation of a Multi In-Feed HVDC-AC System Using Two Port Equivalent

The example considers a multi-infeed HVDC system configuration shown in Fig. 5. The ac system has two HVDC inverters as terminating ends of the two HVDC links at boundary buses #3 and #8. The HVDC links form the 'internal' network and is modeled in full EMT detail. The 'external' ac network to the right of the boundary buses contains 33 buses and 9 generators. When modeled as an equivalent, it interfaces as a two port (2×3 phases) network at the two boundary buses.

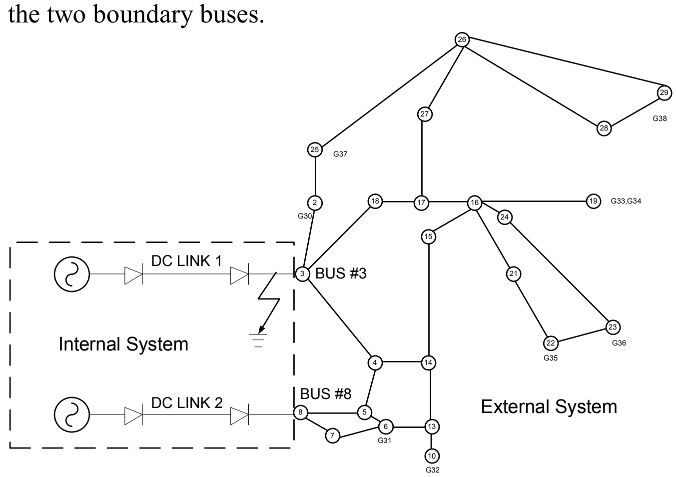

Fig. 5 Multi In-Feeds HVDC/AC Test System

The RTDS full model simulation is run on two RTDS racks, using a 50μs time-step. The RTDS simulation using the equivalent is run on one RTDS rack, with both the detailed 'internal' system and the equivalent 'external' system running with a 50μs time-step.

A single phase to ground fault is applied at Bus #3 for 0.1 second. The inverter side DC voltage of DC Link 2 is shown in Fig. 6.

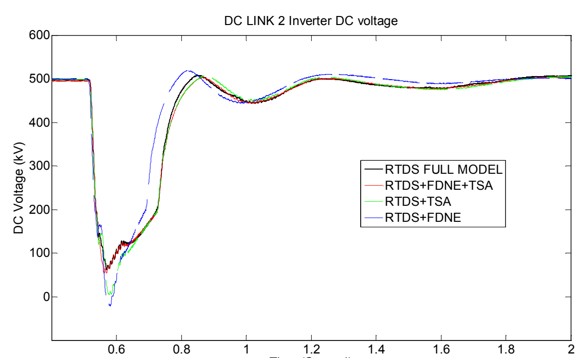

Fig. 6 DC Link 2 Inverter Side DC Voltage Curves with i) Full EMT model in RTDS, ii) with proposed FDNA+TSA equivalent, iii) The equivalent with only TSA representation iv) The equivalent with only FDNE representation

In Fig. 6, four curves are shown. The first is for a detailed

EMT-only implementation (benchmark), the next for the proposed FDNE+TSA equivalent representation of the external system, the third for an equivalent that ignores the FDNE and only considers the TSA solution and the fourth for an equivalent that ignores the TSA and only considers the FDNE. For the case where the FDNE is ignored, it is substituted with a simplified R-L||R equivalent that has the correct fundamental frequency impedance of the external network as seen from the boundary. For the case where the TSA is ignored, fixed sinusoidal sources are used instead of controlled sources.

The bus voltage waveform of Bus #3 is shown in Fig. 7.

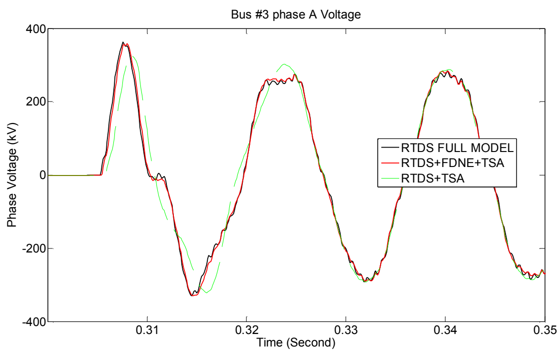

Fig. 7 Bus #3 A Phase Voltage after Fault Clearing

In comparison with the Full RTDS solution (the benchmark for comparison), it is evident that the proposed RTDS+FDNE+TSA model simulates both the AC and DC voltage accurately. This is considered a particularly challenging case to simulate because the interface bus is the critical HVDC converter bus, with no in-between impedance. It can be seen that in this case, both the AC system electromechanical dynamics and electromagnetic transients have significant effects on HVDC system transients and so ignoring either would introduce significant error.

For additional quantitative comparison, several simulations are carried out with varying fault resistance values for a single phase to ground fault applied at Bus #3. Table I tabulates the critical fault resistance values R1 and R2. R1 represents the borderline value that just causes commutation failure (CF) at both the local (DC Link 1) and remote (DC Link 2) converters, whereas R2 is the borderline resistance which just causes CF at DC Link 1 but not at DC Link 2. It can be clearly seen that the only equivalents which accurately match the full model results are those that consider the FDNE representation.

TABLE I
COMMUTATION FAILURE SIMULATION RESULTS

Simulation Setup	R1 (Ohm)	R2 (Ohm)
RTDS FULL MODEL	40.5	72
RTDS+FDNE+TSA	38	72
RTDS+FDNE	38.5	73.5
RTDS+TSA	82	81.5
RTDS+SIMPLIFIED R-L||R EQUIVALENT	82	81.5
R1 --- Minimum Fault Resistance below which Commutation Failure occurs on DC Link 2 R2 --- Maximum Fault Resistance above which Commutation Failure does not occur on DC Link 1		

The next test considers a 0.1 second single phase to ground fault at Bus #3 with an intermediate resistance value of 60Ω which is between R1 and R2. The inverter side DC voltage of DC Link 2 is shown in Fig. 8. In this case, accurate results are obtained only when both the FDNE and the TSA representations are included in the equivalent.

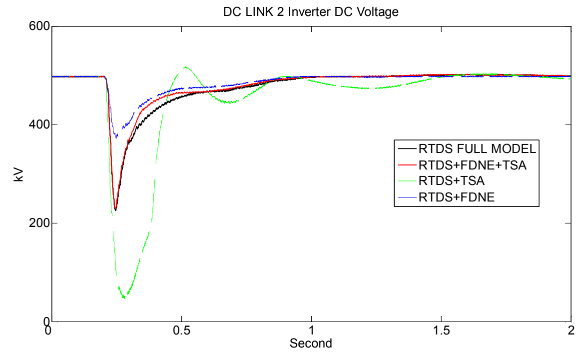

Fig. 8 DC Link 2 Inverter Side DC Voltage, intermediate fault

B. *Simulation of a 470 Bus System Using Multiple Equivalents*

A 470 bus system is used for demonstrating the capability of the proposed equivalencing method of handling large AC system with reduced RTDS hardware. The system has a 345kV network, which is considered as the 'internal' system and is modeled in full EMT detail (62 buses, 17 generators). It feeds lower voltage sub-networks of 161kV, which are considered as the external system and modeled using 11 equivalents, totaling the remaining 408 buses and 28 generators. The 11 equivalents include 1 three-port, 4 two-port and 6 one-port equivalents. The RTDS simulation using equivalents is run on six RTDS racks (A full EMT model on the RTDS would need 20+ racks). Both the detailed model and the equivalents use a 50µs time-step. For comparison, a stand alone pure TSA type simulation is also conducted on a Windows XP based PC, using the TSAT software [15] and a time-step of 0.01s.

Fig. 9 and Fig. 10 show the oscillations in rotor speed following a bus to ground fault in the internal system for two generators - Gen #3212 (which is in the internal system and modeled in full detail) and Gen #230 (which is represented in the equivalent).

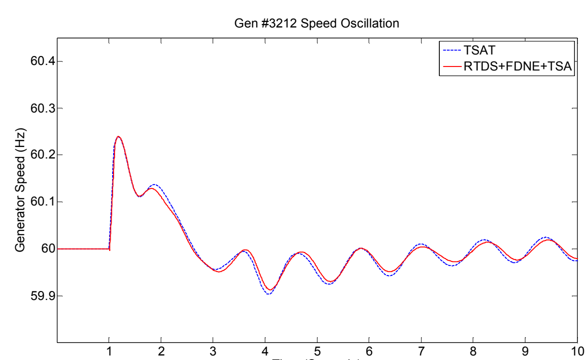

Fig. 9 Generator #3212 speed oscillation curves

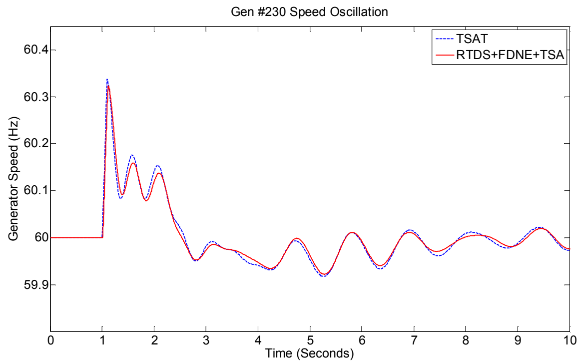

Fig. 10 Generator #230 speed oscillation curves

It can be seen that with the equivalents, the electromechanical transients of the system are accurately simulated in real time and agree with the TSA only simulation. Due to the large size of the system, the hardware available to the author was not adequate for conducting a full EMT solution for comparison.

VI. Conclusions

The paper proposes an accurate wideband multi-port equivalent for real time digital simulator. The proposed equivalent is capable of reproducing the essential electromagnetic response as well as the essential electromechanical response of the large external system with reduced hardware cost. This is achieved by using a multi-port FDNE to reproduce the electromagnetic transient response of the external system and a specially designed real-time TSA type solution for the electromechanical dynamics of the external system.

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VII. References

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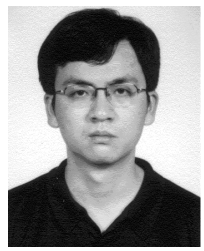
VIII. Biographies



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