Development of a Broadband Real-Time Fully Digital Simulator for the Study and Control of Large Power Systems

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Abstract - **In this paper we present the basis of a broadband fully digital simulator, which would be capable of meeting the challenge obtaining real-time solutions of very large networks using sufficiently small integration time steps such that power electronic devices (FACTS or HVDC) could be modelled at the device level with sufficient time resolution. One of the challenges in developing a general-purpose broadband fully digital simulator is the interface of simulation algorithms working with very different time steps and time/frequency domains. For example, transient stability programs, which can represent very large systems, use relatively large time steps and balanced representation of the network, whereas electromagnetic transients simulators model relatively small systems and use small time steps. Interfacing the two simulators will result in a broadband simulator capable of modelling large systems, but including detailed representation where required. The simulator would provide for studies ranging from fast transient to transient, dynamic, and voltage stability, with applications including closed-loop protection and control studies, as well as on-line dynamic security assessment.**

Keywords: Real-Time Simulation, Digital Simulation, EMTP, Transient Stability Analysis.

I. INTRODUCTION

An interconnected power system consisting of generating plant and transmission lines is a high order non-linear dynamic system. Its response ranges from fast (microsecond) electromagnetic transients, through electromechanical power swings (milliseconds), to slower modes influenced by the prime mover boiler and fuel feed systems (seconds to minutes). For the study of electromagnetic transients, time step as small as 50μs is needed in order to have good representation of power electronics devices [1]. For the modelling of electro-mechanical transients caused by large disturbances such as network faults and/or plant outages, system states must be evaluated at intervals of the order of milliseconds over time scales of seconds [2]. For dynamic stability assessment, the time scale needs to be extended to minutes and for voltage security tens of minutes to hours. Currently all these tasks are performed on separate simulators. A very large bandwidth hybrid digital simulator, on the other hand, would be capable of performing the full range of simulations on a single high-speed parallel processing server. It would also be feasible to incorporate contingency ranking as well as static and dynamic security assessment (DSA) onto the same platform such that the simulator would become the heart of a much-improved Energy Management System (EMS).

At the Hong Kong Polytechnic University (HKPolyU), we have been involved in the development of a real-time parallel-processor based transient stability program. This program can solve very large systems in real time, but the representation of individual components of the system, in particular power electronic devices and control systems associated with FACTS and HVDC transmission systems cannot be represented in detail. A real-time electro-magnetic transients simulator such as HYPERSIM [3-5], on the other hand, can represent system components and control systems in detail, but is impracticable for the modelling of very large systems. It is our intention to expand the HKPolyU real-time transient stability program from single phase to three-phase representation and develop a hybrid simulator through the interface of the expanded transient stability program with HYPERSIM. It will allow us to model extensive power systems comprehensively, and with the capability of 'zooming in' on parts of the system incorporating, for example, power electronic devices such as FACTS or HVDC. Further developments would include incorporation of real time or faster than real time dynamic and voltage stability simulators.

II. BOARDBAND DIGITAL SIMULATOR

Electromagnetic and electromechanical transients studies are traditionally carried out using separate simulators. Significant compromises are required to deal with the respective shortcomings of the different simulations. For example, transient stability programs can solve very large systems but the representation of individual components of the system cannot be represented in detail. Furthermore, unbalances and cascading faults are not well represented. Whereas, an electromagnetic transients simulator can represent system components and control systems in detail, but is impracticable for the simulation of very large systems, and dynamic equivalents are required. While it is possible to make dynamic equivalents, confidence is not high and it is generally accepted that the representation is not good beyond a relatively short simulation time. Consequently, fully digital real-time electromagnetic transients simulators are not practicable for transient stability studies of large systems, while transient stability programs are not practicable for the study of unbalanced faults and representation of mal-operation of power electronic equipment at the device level.

Modern scalable fully digital simulators represent larger and larger systems by becoming larger and larger simulators. However there has to be a limit, and it is unlikely that 'conventional' electromagnetic transients simulators will ever practicably represent fully a two thousand bus system. It is readily apparent that the future of simulation lies in the development of very large bandwidth digital simulators capable of modelling large scale power systems in real time or faster than real time. These hybrid simulators would allow practicable simulation of extensive power systems comprehensively with no need for dynamic equivalents, and would provide the capability of 'zooming in' on parts of the system, incorporating, for example, power electronic devices such as FACTS or HVDC.

When operating in synchronous real time, the hybrid simulator would offer the closed-loop protection and control studies currently available with specialized real-time simulators. It would also be feasible to incorporate contingency ranking as well as static and dynamic security assessment (SSA & DSA) onto the same platform. In the faster than real time mode, transient, dynamic, and voltage stability assessment would allow for on-line dynamic security assessment associated with modern Energy Management Systems (EMS). On-line DSA is currently difficult to achieve owing to the large computational requirements. It would allows power system operators to operate the system closer to the stability limits, and this would have considerable economic benefits when out of merit generation is used.

The first step towards realising this goal is the interfacing of a digital real-time electromagnetic transients (EMT) simulator with a real-time transient stability (TST) simulator. The two simulators will be described in the following sections.

III. REAL-TIME TRANSIENT STABILITY (TST) SIMULATORS

Transient stability simulations of power systems are essential for the determination of the capability of these large systems to withstand disturbances [10]. According to the required time scales of the studies, power systems models with different levels of detail are developed. For transient stability studies, models must include the effects of system dynamics down to 10 ms in general and the system states are required to be evaluated at intervals of 10 to 100 ms over time scales around 10 seconds. Although large interconnected multi-machine power system responses can be simulated with high accuracy, large amounts of computational power are required. However, if enough processing power is provided, the model equations can be solved within the simulated time-step and the resultant output can then be displayed graphically to visualise the system dynamics, as it would happen in real time. Such real-time simulation also allows user interaction with the computer simulation, which is particularly useful for education and training purposes.

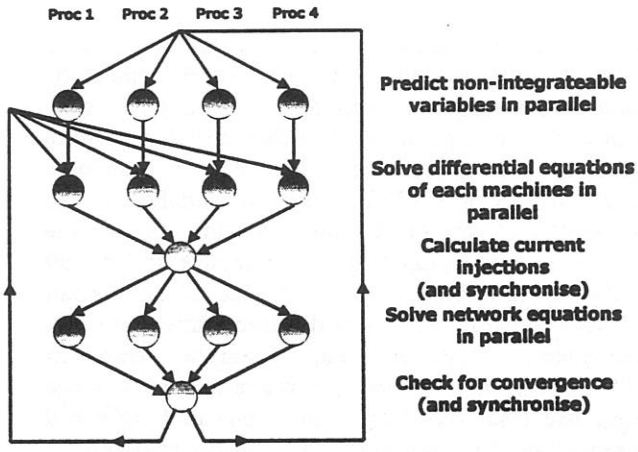

Fig.1: Basic parallel algorithm for transient stability (TST) simulation for 4 processors

Early studies showed that power system simulation could be divided into several concurrent tasks [6,7]. User interaction and graphical output can be processed in parallel with the main calculation of model equations. The power system model itself has inherent parallelism in that each generator is only affected by other generators via the transmission network. This is exploited by a partitioned solution method such that each set of equations can be solved concurrently on a different processor. A complete solution is obtained by solving the network equations. Exploiting concurrency in the network solution is less obvious and requires detailed analysis of the numerical algorithms. Fig.1 shows the basic algorithm for the transient stability simulation with parallel machine and parallel network solutions using 4 processors.

A. Network partitioning

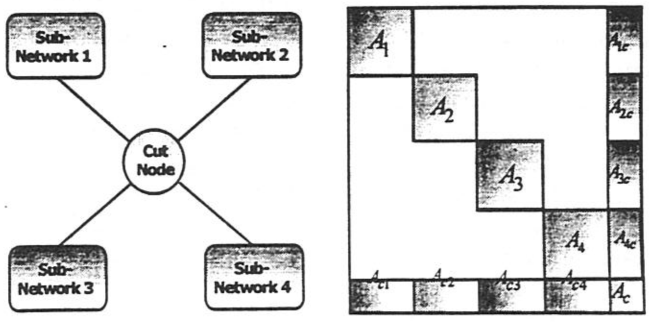

Fig.2: Bordered block diagonal form (BBDF) partitioning for 4 processors

A large power system network can be considered as comprising of a number of subnetworks connected via tie-lines to a group of busbars known as cut-nodes. If the network admittance matrix is arranged to follow this configuration, it will have the bordered block diagonal form (BBDF), as shown in Fig.2.

B. Parallel Algorithms

LU Factorisation

For the parallel network solution, the BBDF admittance matrix is factorised into lower and upper matrices, which are then solved by forward and backward substitution, i.e. solve:

$$\begin{Bmatrix} L_{11}U_{11} = A_{11}, & U_{1c}L_{11} = A_{1c}, & A_{c1} = L_{1c}U_{1c} \\ L_{22}U_{22} = A_{22}, & U_{2c}L_{22} = A_{2c}, & A_{c2} = L_{2c}U_{2c} \\ \cdots & \cdots & \cdots \\ L_{nn}U_{nn} = A_{nn} & U_{nc}L_{nn} = A_{nc}, & A_{c_n} = L_{nc}U_{nc} \end{Bmatrix}$$

in parallel, then calculate

$$L_cU_c = A_c - \sum_{i=1}^{n} A_{ci}$$

Throughout the factorisation process, the BBDF structure is preserved and operations between the diagonal blocks and those between border blocks are completely independent. Dependence exists only between the border blocks and their corresponding diagonal blocks, and there is only one communication step needed for the whole parallel LU factorisation process.

Forward and Backward substitution

Because there is no data dependence among the diagonal blocks, forward substitution on the diagonal and bordered blocks can proceed in parallel, i.e. first solve

$$\begin{Bmatrix} L_{11}w_1 = b_1 & then & b_{c1} = L_{1c}w_1 \\ L_{22}w_2 = b_2 & then & b_{c2} = L_{2c}w_2 \\ \cdots & & \\ L_{nn}w_n = b_n & then & b_{cn} = L_{nc}w_n \end{Bmatrix}$$

in parallel, then calculate

$$L_cw_c = b_c - \sum_{i=1}^{n} b_{c_i}$$

Once the vector w has been determined, the backward substitution can be proceeded in parallel as follows:

First calculate

$$U_cx_c = w_c$$

then solve

$$\begin{Bmatrix} U_{11}x_1 + U_{1c}x_c = w_1 \\ U_{22}x_2 + U_{2c}x_c = w_2 \\ \cdots \\ U_{11}x_1 + U_1x_c = w_1 \end{Bmatrix}$$

in parallel.

Before the cut-node block can be solved, a communication step is required to globally distribute the intermediate results corresponding to the cut-node block. In order to minimise the data exchange, the forward and backward substitution on the cut-node block was combined into one stage and is executed in each processing unit.

III REAL-TIME ELECTROMAGNETIC TRANSIENTS (EMT) SIMULATORS

For transient stability simulation, parallelism is exploited to obtain very fast solutions of very large networks, with relatively long time steps. While the machine solution can be parallelized by means of functional parallelism, parallel network solution is non-trivial. Algorithmic parallelism has to be fully exploited in order to obtain a satisfactory efficiency and speedup. For simulation of fast electromagnetic transients, however, parallelism is exploited to obtain real-time solutions of relatively small networks, with very small integration time steps. Typically, a minimum of a 50μs time step is required for realistic HVDC system studies. Though a very small time step does impose a very heavy burden on processing power, it offers the opportunity for efficient parallelization by exploiting the propagation delay of transmission line.

A. Parallelism in EMT Simulation

A power system is normally composed of substations interconnected by transmission lines. Due to the propagation delay of transmission lines, phenomena which happen at one line terminal can be seen at the other terminal only after the propagation delay. Simulation of each substation can therefore be performed at the same time with the simulation of lines. Inside each substation, there exists also fast and slow subsystems, slow subsystems can be solved in parallel with fast subsystems and results are exchanged at each simulation time-step without significant impact.

Parallelism based on the transmission delay

According to the EMTP method, lines are simulated using the modal approach to decompose from 3 coupled phases into 3 independent modes which are represented at each terminal as current sources and resistors in parallel. The actual value of each current source depends only on the past voltages and currents at both terminals. Lines and substations at their terminals can therefore be simulated in parallel. Node voltages and line currents are then exchanged to use in the subsequent simulation step.

Node voltage equation

Inside each substation, all components can also be made equivalent to RLC elements and voltage or current sources. Using the trapezoidal integration method, inductors and capacitors are represented as resistors in parallel to their historic currents. The node equation to be solved at each substation to calculate node voltages is therefore

$$\mathbf{Y}(t)\mathbf{V}(t) = \mathbf{J}(t)$$

where **Y** is the admittance matrix composed of all resistors, **J** is the current vector of all current sources, (t) indicates that all matrices are generally time dependent. This equation is solved using LU transformation technique. **Y** is ordered in such a way to minimize the fill in elements and to reduce the number of operations required by the refactorization needed at every switching or changing of non-linear segment.

Parallelism of component subsystems

In case of power system components which includes many subsystems (such as synchronous machines and their regulators, turbine, stabilizer), they are represented as controlled sources incorporated into the node voltage equation. Control systems are simulated separately but in parallel with the solution of the node voltage equation. The sources are controlled by signals coming from control systems with one time-step delay. Providing that the time-constant of control systems is much larger than the simulation time-step, this delay has little impact on the overall accuracy.

The overall parallelism

In overall, during each simulation time-step, as shown in Fig.3, the following tasks are performed in parallel:

a. Line tasks: calculation of line equivalent current sources.
b. Substation tasks: calculation of substation node voltages.
c. Subsystem tasks: simulation of control systems, which can be separated into parallel tasks.

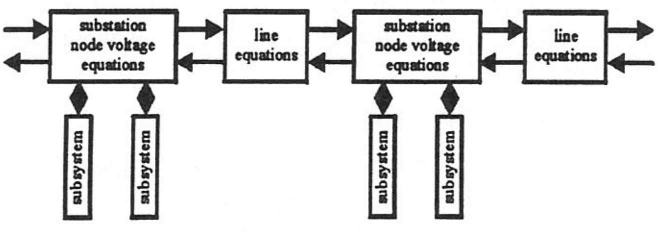

Fig.3: Parallel operation during execution

At the end of each simulation time-step, the following results are exchanged between tasks:

a. Line tasks receive the node voltages from substation tasks and send values of current sources back.
b. Control subsystems tasks receive voltages and currents from substation tasks and send signals back to control sources, breakers, thyristors, etc.

B. General Approach

The IREQ's EMT simulator is implemented using the object-oriented approach for modular design, portability and expansion facility. The methodology used consists of following stages:

a. First, the graphical user interface is used to build the single-line diagram of the network control systems.
b. The topology analysis of the diagram allows to separate lines, substations, control subsystems which can be simulated in parallel tasks.
c. An automatic task mapper distributes tasks into parallel processors in such a way that they can communicate together with a minimum communication overhead.

To achieve the best performance, codes are generated for each task and for each particular network. Codes are then compiled either to run directly on the workstation in the non real-time mode or to download and run on the real-time hardware.

The IREQ's real-time EMT simulator has been designed to run on open-architecture general purpose computer with single or multiple processors [4,5]. The computation engine supports several synchronization signals in order to fit the models time step requirements. This feature allows distinct nodes to be paced at different time steps. For instance, in order to allow large networks to be loaded on the computation engine while applying the right focus to the part of the network under study, some nodes could embed transient stability models running at a 8.3ms time step while neighbouring nodes embed electromagnetic models running at 50μs.

C. EMT Sample Simulations

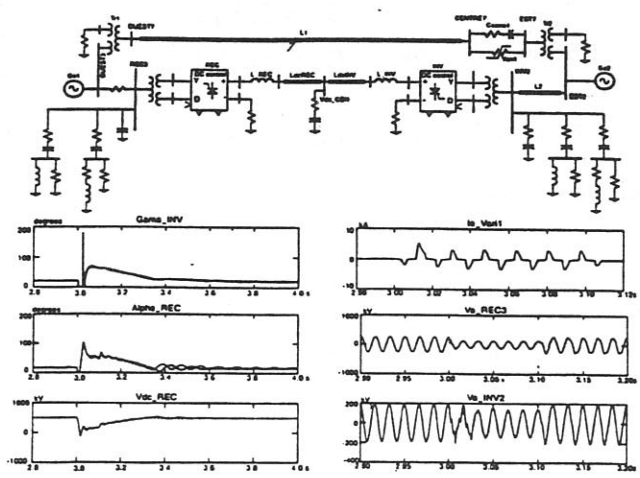

Fig.4: Comparison of real-time EMT with EMTP

A large number of validation tests have been performed with all the developed element models of the power system. These tests are performed in real time and in non-real time on the workstation and the results are compared with EMTP or with the Electrical Power Systems Blockset developed for Matlab Simulink. As an example consider a DC line fault at the rectifier on a 12 pulse AC-DC converter [9]. Fig.4 presents the network and the waveforms on the rectifier and the inverter side. The results are almost identical.

V. EMT-TST HYBRID SIMULATOR

The approach adopted for the broadband simulator is to incorporate both the detailed device level simulation (i.e. EMT) and system-wide functional modelling (i.e. TST) within an integrated analysis tool. The power system being studied is considered as a multi-layered system. Each layer has its own time resolution. For example, the FACTS device subsystem requires device level modelling which has a time resolution of 50µs whilst slower subsystems such as AVR, GOV and PSS require a time resolution of 10ms.

A. EMT-TST Interfacing

This approach is realised as a hybrid electromagnetic and electromechanical simulation. Traditional transient stability simulation (TST) will host the overall system with individual devices that required more detailed representation 'zoomed-in' to the circuit level. The integration and communication between the detailed and coarse subsystems will be maintained through a well-defined data exchange interface.

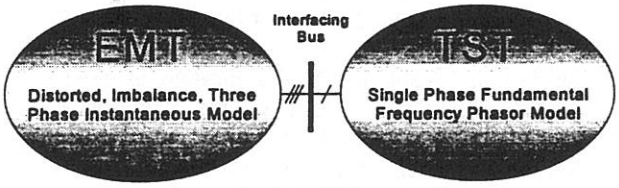

Fig.5: EMT-TST Integration

As illustrated in Fig.5, the EMT and TST subsystems are interfaced via an interfacing bus. From the view point of the EMT simulation as shown in Fig.6, the TST subsystem (i.e. external system), which use a single-phase fundamental frequency representation, is modeled as Norton current source and equivalent impedance, based on the results of the TSP simulation. Similar, from the point of view of the TST simulation, the EMT subsystem (i.e. detailed system), which use a distorted, imbalance, three phase instantaneous representation, as a simple constant or complex frequency dependent impedance. This impedance, of course, will be updated at each synchronization point.

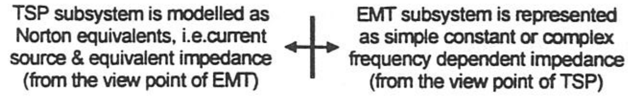

Fig.6: EMT-TSP Interfacing

B. EMT-TST Data Transfer

As there are fundamental differences between the EMT and TST simulations, the interfacing [11-14] between them has to deal with the following differences :-

i) 50µs vs 10ms time step
ii) distorted vs sinusoidal waveforms
iii) instantaneous vs fundamental frequency phasor

EMT-TST Coordination

As there is a large difference in the integration time steps used in EMT and TSP, the following coordination procedure is generally needed to execute both the EMT and TST simulation concurrently.

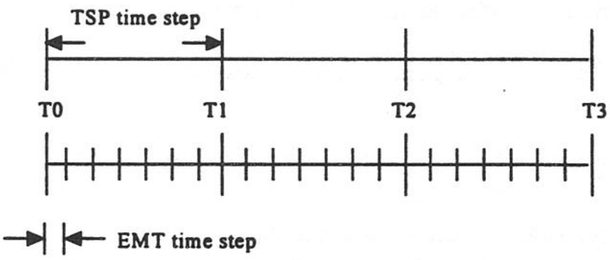

Fig.7: EMT-TST Coordination

Starting from, say, T0, TSP is first simulated for 1 time step to obtain the system states at time T1 with the power injection from the EMT subsystem being constant during this time step. Meanwhile, the equivalent of the TSP subsystem at T0 will be used for the simulation of the EMT session for n steps until T1 is reached. The results obtained during this period will be used to update the EMT equivalent for the TSP simulation from time T1 to T2. This means at each synchronization point (T0, T1, T2 ...), as shown in Fig.7, a new equivalent will be derived based on the history of the system.

The reason why only the system history is considered for the determination of the equivalent is that neither the EMT nor TSP is allowed to run ahead of time under the constraint of synchronous real-time operation, and also the handling of any discontinuity can be simplified. This is a compromise for meeting the real-time simulation objective. The effect of this can be reduced by using a smaller synchronization window (i.e. the time step of TSP), say 1 ms, or even smaller if the computing power permitted.

Effectively, both the EMT and TST will be running concurrently with the equivalent of each other updated at each synchronized point. Data exchange between the two simulation sessions is carried out via a well-defined common communication interface. This interface can be implemented as local library functions or as remote procedure calls such that both the EMT and TST simulation can be running physically in parallel and hence achieved the final goal of real-time operation.

EMT to TSP equivalent

Using the principle of conversion of power, the basic parameter that can be used to link up the EMT and TST simulations is power flow (i.e. voltage and current). The complication involved is that only the fundamental component should be passed to the TST simulation. This is because all of the TST power system models are constructed with the assumption of operating in the fundamental frequency only. It is important to ensure the fundamental power flow is accurately modeled.

The results obtained from the EMT simulation are instantaneous values of $i_a(t), i_b(t), i_c(t)$ and $v_a(t), v_b(t), v_c(t)$. Exactly how to convert those into equivalent TSP phasors $I\angle\theta_I$ and $V\angle\theta_V$ is crucial to the EMT-TSP interfacing. Mathematically, the instantaneous values, say $i_a(t)$ and $v_a(t)$, can be expended using Fourier transformation into:

$$i_a(t) = a_{v0} + \sum_{i=1}^{n} \left(a_{vk} \sin k\omega t + b_{vk} \cos k\omega t\right) \quad (1)$$

$$v_a(t) = a_{v0} + \sum_{i=1}^{n} \left(a_{vk} \sin k\omega t + b_{vk} \cos k\omega t\right) \quad (2)$$

The rms values of the voltage and current on the EMT side can be easily obtained and hence the equivalent impedance of it can be found. Alternatively, the fundamental frequency component of both voltage and current can be derived using a curve-fitting method. Compared with the former method, curve-fitting method is simpler and hence has less impact on the computational burden. The fitting procedure can be considered as minimizing the error E :

$$E = \min \sum_{k=1}^{n} \left(I_m \sin(\omega t_k + \varphi_I) - i_a(t_k)\right)^2 \quad (3)$$

i.e. the parameters I_m and φ_I can be determined using:

$$\frac{\partial E}{\partial I_m} = \sum_{k=1}^{n} 2\left(\left(I_m \sin(\omega t_k + \varphi_I) - i_a(t_k)\right)\sin(\omega t_k + \varphi_I)\right) = 0 \quad (4)$$

$$\frac{\partial E}{\partial \varphi_I} = \sum_{k=1}^{n} 2\left(\left(I_m \sin(\omega t_k + \varphi_I) - i_a(t_k)\right) I_m \cos(\omega t_k + \varphi_I)\right) = 0 \quad (5)$$

Parameter conversion from TSP to EMT is relatively simple. At each synchronization point (T0,T1,T2,...), the current and voltage phasors will be provided by the TSP simulation session and they can be converted to the corresponding instantaneous values at time, say, T1 as:

$$i_a(T1) = I_a \sin(\omega T1 + \varphi_{Ia})$$
$$i_b(T1) = I_b \sin(\omega T1 + \varphi_{Ib})$$
$$i_c(T1) = I_c \sin(\omega T1 + \varphi_{Ic})$$

and

$$v_a(T1) = V_a \sin(\omega T1 + \varphi_{Va})$$
$$v_b(T1) = V_b \sin(\omega T1 + \varphi_{Vb})$$
$$v_c(T1) = V_c \sin(\omega T1 + \varphi_{Vc})$$

VI. CONCLUSIONS

New generation simulators promise a far greater range of applications, particularly in the area of power system operation and control. Large expensive facilities comprising micro machine networks or transient network analysers have evolved into compact fully digital simulators that can operate in real time or much faster than real time. In this paper we presented the basis of a broadband fully digital simulator, which be capable of meeting the challenge obtaining real-time solutions of very large networks using sufficiently small integration time steps such that power electronic devices (FACTS or HVDC) could be modelled at the device level with sufficient time resolution.

VII. ACKNOWLEDGEMENTS

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