Advancements on the Integration of Electromagnetic Transients Simulator and Transient Stability Simulator

Hongtian Su, Ka Wing Chan, *MIEEE*, Laurence A. Snider, *SMIEEE* and Jean-Claude Soumagne, *SMIEEE*

***Abstract* - This paper presents new developments in hybrid simulation. A hybrid simulator can simulate very large networks with speed of transient stability (TS) simulators, while delivering accuracy of electromagnetic transients (EMT) simulators for key components, while running in real-time or in accelerated time modes. It can be used as a system operation tool, offering extended contingency lists (such as mal-operation of power electronic devices) for dynamic security assessment. In real-time operation, the simulator can be interfaced with real control system hardware for detailed study, including the effects of waveform distortion, and mal-operation of switching devices. General issues on how to develop the hybrid simulation have been discussed, and achievements based on serial implementation of interaction protocol have been reported. The paper concentrates on the extended contingency lists simulation and new developments on parallel implementation of interaction protocol.**

Keywords: Electromagnetic transients, transient stability, hybrid simulation, equivalent modeling, interaction protocol.

I. Introduction

This paper is devoted to the theoretical analysis and performance evaluation of hybrid simulation. Hybrid simulation can take advantage of the computational inexpensive dynamic representation of the main network in a transient stability (TS) program, with the accurate dynamic modeling of nonlinear elements, such as FACTS devices or HVDC terminals simulated in an electromagnetics transients (EMT) program. The underlying idea of the hybrid simulation is to partition a network into two parts, one for the TS program and the other for the EMT program, where the former includes most of the system, while the latter includes the components that require detailed simulation, as well as parts of the network close to where they are connected. Thus, the slow dynamics of machines are adequately modeled by the stability program while the fast dynamic responses of selected devices are accurately represented by EMT simulation models.

While EMT simulators are generally accepted as the most efficient simulation tool for detailed representation of power electronic devices in power systems, they are computationally demanding, and are not practicable for simulation of very large systems. Transient stability (TS) simulators, on the other hand, have a very fast simulation speed, but use relatively long integration steps; consequently, highly non-linear elements common in HVDC and FACTS can only be represented as modified steady-state models. Since switching devices and control systems are not represented in detail, the overall accuracy of conventional transient stability programs suffers, and contingencies involving mal-operation of FACTS devices cannot be adequately represented. For this reason detailed studies of control system and bridge operation of HVDC and FACTS devices have traditionally been carried out using TNAs and HVDC simulators, where the actual control system hardware can be interfaced and evaluated.

Heffernan et al [1] first proposed to interface two distinct simulators for solving HVAC-HVDC systems. They modeled an HVDC link in detail within a stability based ac system framework, thus exploiting the advantages of both EMT program and TS program. They achieved this by running the TS program and EMT program concurrently with periodic coordination of the results. Reeve et al. [2] proposed that the location of interface should be extended into the AC network further for taking into consideration of the effect of harmonics generated by power electronics on the AC network. Anderson et al. [3] presented another approach to take the harmonics into account. In the EMT program, the network part simulated by the TS program is represented by frequency-dependent equivalent, instead of a simple fundamental frequency equivalent circuit used by Heffernan and Reeve.

The paper presented by Sultan et al. [4] basically adopts the approaches described above, i.e. extending the interface location into the AC network to some extent, and at the same time representing the network simulated by the TS program with frequency-dependent equivalent. Also, Kasztenny et al. [5] have discussed a general method for linking different modeling techniques such as waveform-type, phasor-type, and algebraic-type simulation techniques into one complete model.

Many issues have been discussed so far [6,7], including

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how to guarantee the credibility of waveforms outputted from EMT simulators, where to do interfacing, and how to coordinate two simulators. More importantly, a parallel implementation of interaction protocol has been proposed, which is the basis for real-time operation.

In this paper issues related to the establishment of proper interaction between the EMT and TS simulators are discussed. A new approach to selecting the interface location, techniques to overcome the waveform distortion caused by frequency mismatch during the transient and interaction protocol are presented, as well as verification of an appropriate communication protocol to allow the hybrid simulator to operate in real time. Full assessments of the hybrid simulation, from the points of view of TS and EMT, on two different sized power networks are also given.

II. Overview of Hybrid Simulation

The basic approach adopted for the development of the hybrid simulator is to incorporate both the detailed device level simulation and system wide functional modeling within an integrated analysis tool [1]. The two simulations proceed in parallel and communicate with each other at specified time points as shown in Fig. 1. With the interchange of information each part of the network is represented to the other by a dynamically updated equivalent.

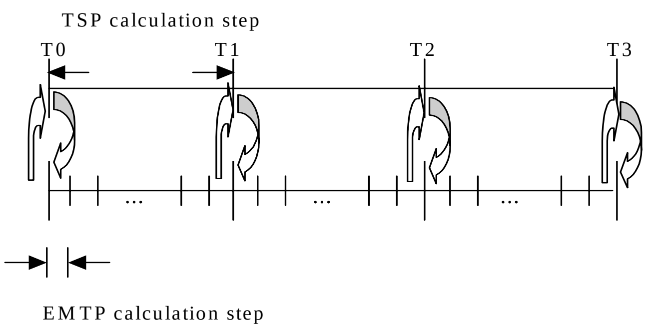

Fig. 1 Interface Protocol of Hybrid Simulation

The parts of the network modeled in EMT and TS simulators are called, respectively, the detailed system and the external system. The interaction and communication between the detailed and external systems are maintained through a data exchange interface. In other words, the EMT simulator and TS simulator are interfaced via an interfacing bus as shown in Fig. 2.

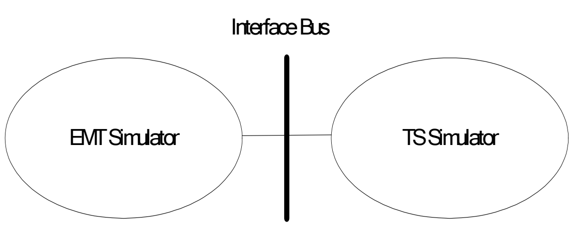

Fig. 2 EMT Simulator - TS Simulator Integration

EMT and TS simulators are two distinct kinds of simulators. They adopt integration time intervals on different time scale, employing different modeling for network components. In order to enable them to interface and run as a single package, issues needed to be resolved include [2] i) how to represent each of the two systems in each other, ii) where to locate the interface bus, and iii) the protocol for interaction between TS and EMT simulators.

III. Modeling of equivalent

A. *The external system*

In order to ensure that the hybrid simulation can predict the correct dynamics of the detailed system, the EMT simulator requires the external system to be represented by a correct driving point impedance. The TS simulation is a fundamental frequency phasor-type solution, and at each interchange it can provide voltage, current and equivalent impedance under the system frequency. This is presented to the EMT simulator at the interface bus as a Norton equivalent which includes a dynamically updated current source and an RLC circuit.

For a simple Norton equivalent circuit, there is only one series RLC shunt-connected circuit, which is derived from the impedance under power frequency. However this simple equivalent cannot adequately represent the harmonic impedances resulting from the distortion following changes of topology within the detailed system. A frequency dependent equivalent is required, and a number of RLC shunt-connected circuits is used to synthesize the frequency spectra to the original network [3,4].

B. *The detailed system*

There are several different ways to represent a detailed network in the transient stability program. Roughly they can be classified into two groups: one is mathematical modeling at the system level based on the expected performance of the system, and is usually developed for a particular disturbance (we will refer to this as system-level modeling). The other comprises mathematical models of the components of system devices based on their known performance (we will refer to this as device-level modeling).

System-level models presuppose that devices work as designed, consequently, malfunctions, such as valve failures, cannot be adequately represented. This limitation does not exist in the device-level modeling.

Generally, the outputs from the EMT simulator (which is device-level modeling) can be unbalanced, distorted waveforms and may include dc offsets; whereas, TS simulation (system-level modeling) is based on fundamental frequency modeling techniques. Consequently the information transferred from the EMT simulator to the TS simulator must comprise only fundamental frequency quantities, which have to be extracted from the unbalanced distorted waveforms.

Since power flow in and out of the interface bus is of prime concern in the TS simulator, the most appropriate variables to transfer from the EMT simulator are the fundamental frequency active and reactive powers. In our approach, they are extracted from the distorted waveforms using a curve fitting approach and the system modeled in the EMT simulator is effectively viewed by the TS simulator as a variable load.

IV. Selection of Interfacing Location and Variables

A. Conventional approach – waveform distortion

The choice of the location of the interface bus is at first glance obvious: for an HVDC system it could be the filter bus, and for a FACTS device, it could be the terminals of the device. However, there may be other considerations which would lead to a different location. There are two different views to choose the interface location as discussed in [1-4].

For the first hybrid described by Heffernan et al [1], the intention was to model the ac and dc solutions separately. The point of interface location was consequently the converter bus terminal. A fundamental frequency equivalent was used to represent the stability program in the detailed solution and vice versa. The advantage of this choice is that the scale of the detailed system can be reduced to minimum.

Reeve et al [2] later correctly pointed out that the major drawback of the detailed solution is in not seeing a true picture of the external system, since the equivalent circuit is fundamental frequency based. A simple fundamental frequency equivalent circuit is insufficient to present the correct impedance of the external system at other frequencies to the converter. The countermeasure proposed is to represent more of the external system in detail through the use of extended interface bus. Therefore, the waveforms at the interfacing buses become closer to the actual waveforms, and the detailed solution is more credible. This will also facilitate data transfer as the waveforms on the extended interface bus are less distorted. However, exactly how far should the interface location be extended is hard to predict and depends on the phase imbalance and waveform distortion.

As more components are involved in the detailed solution, the complexity of interfacing increases generally. Anderson et al [3,4] proposed that frequency dependent equivalent circuit should be employed instead of a simple form. The frequency dependent equivalent can provide an accurate picture of the system impedance across its frequency spectra. Correct waveforms can be obtained at the interfacing buses without the effort of extending the interface location.

B. Alternative approach – extraction quality

Previously, the main concern in determining the interaction location was consideration of the effects of waveform distortion on the equivalent modeling. However, with the use of a frequency dependent equivalent, this consideration has become less important, and instead, the quality of the variables transferred across the interface bus has now become more of a concern.

The fundamental components of the distorted waveforms produced by the EMT simulation have to be extracted. In case the number of data samples within one cycle is not sufficient for the extraction when the degree of distortion is too high, the interface location has to be extended. The quality of extraction can be assessed by continuously monitoring the curve fittings using the accumulated samples as the simulation progresses within one time period. If the results converge to consistent values, the number of data samples is sufficient and the extraction is credible. This approach can be used as a simple assessment criterion for determining the optimum interface location.

C. Choose of transferred variables

In order to extract the equivalent fundamental frequency powers from the distorted EMT waveforms, phasor values of the bus voltages and currents are needed. However, because of the existence of dc offsets, the phasor value of the current cannot be extracted accurately from the EMT simulation output, and an alternative approach is needed.

The remedy is to derive the powers indirectly from the equivalent which is included in the detailed system representing the external system as shown in Fig.3. Since both the current source and Norton admittance are known, the injected powers can be derived by the curve-fitting extraction once the bus voltage is known in phasor form.

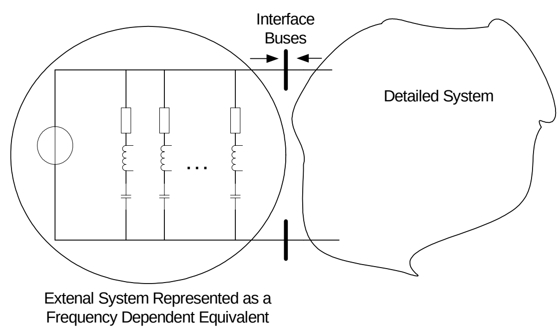

Fig. 3 EMT Simulation with External System as Equivalent

V. Interaction Protocol

The purpose of interaction protocol is to organize the sequence of operations, such that the hybrid simulator faithfully simulates both the detailed and the external systems. In TS simulators the integration step is in the order of milliseconds while in EMT simulators it is in the order of microseconds. Because of the different integration time steps, information exchanging occurs only at discrete common points in time: conventionally this has been at the TS simulators time steps. This conventional protocol is illustrated in Fig.1.

A. Hybrid simulation interaction scheme

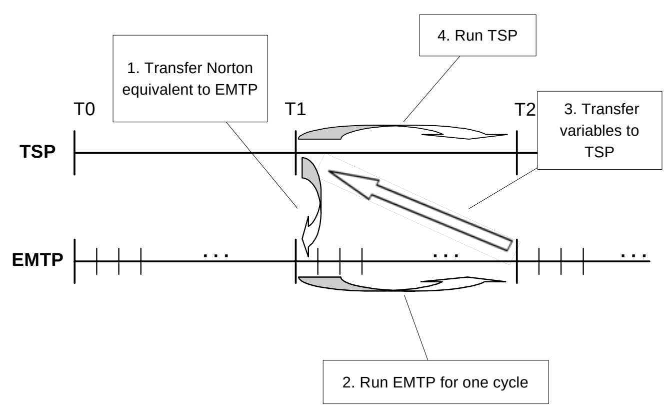

Fig. 4 Interaction Protocol

We have also developed a serial implementation of interaction protocol scheme that corresponds to a one-period TS simulators integration time step and matches the requirements of trapezoidal rule, the conventional numerical method used for establishment of TS simulators. The basis of this scheme is illustrated in Fig.4.

Suppose the hybrid simulator has finished its computation from T0 to T1.

i) The equivalents of the external system are obtained from TS simulators at T1 and are transferred to EMT simulators.
ii) Using the equivalent obtained at T1 from TS simulators, EMT simulators is executed from T1 to T2 while TS simulators are idle.
iii) The equivalent of detailed system is calculated corresponding to time T2.
iv) The TS simulator uses the equivalent from EMT simulator to do the calculation for the interval T1 to T2 while EMT simulator is idle.
v) The above procedure is repeated.

There are significant disadvantages of this protocol. The purpose of developing hybrid simulation is to do simulation on large-size networks with TS-like speed and EMT-like accuracy. Various studies have shown the simulation accuracy, either from the transient stability point of view or from the electromagnetic transient point of view, is satisfactory; however, the issue of speed has not yet been addressed.

TS and EMT simulators are both based on step-by-step time-domain solutions, but they use rather different solution algorithms. Owing to the large time step inherent with TS simulators, their solution algorithm relies on an iterative approach, whereby the bus voltages are predicted, and injection currents from the machines are calculated, the bus voltages are correspondingly calculated and compared with the predicted values, and the process is repeated to convergence. With the EMT solution algorithm, on the other hand, the time step is usually small enough such that a linear approximation of the bus voltages is sufficient and iteration is not required.

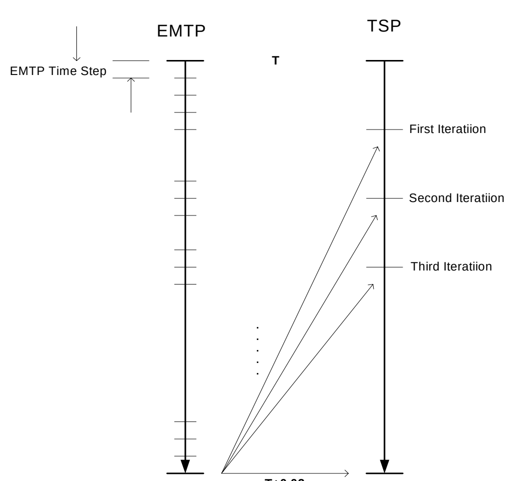

Fig. 5 Serial Implementation of Interaction Protocol

The serial implementation of the protocol was developed to deal with these different solution algorithms. However, as illustrated in Fig.5, the TS simulator is idle while the EMT simulator proceeds until T2 with its solution and passes the data across the interface to the TS simulator, which can then proceed with its solution from T1 to T2, while the EMT simulator is idle. Clearly this protocol is not consistent with the objective of developing a high speed, or real-time simulation, and an alternative protocol is required to achieve this objective.

To overcome these difficulties, we have developed a "parallel protocol".

B. *Parallel Implementation of Interaction Protocol*

For the hybrid simulator to run in real time, the EMT simulator must run continually, which is not possible under the serial protocol. Under parallel implementation, however, the EMT and TS simulators proceed simultaneously, and the EMT simulator is never idle. The method is illustrated in Fig.6, where we assume that the TS simulator has a time step of 20ms, while the EMT simulator has a time step of 50μs. Furthermore, it is assumed that the solution time for each iteration of the TS solution can be accomplished in significantly less time that 20ms. Thus, several iterations can be accomplished within one TS time step.

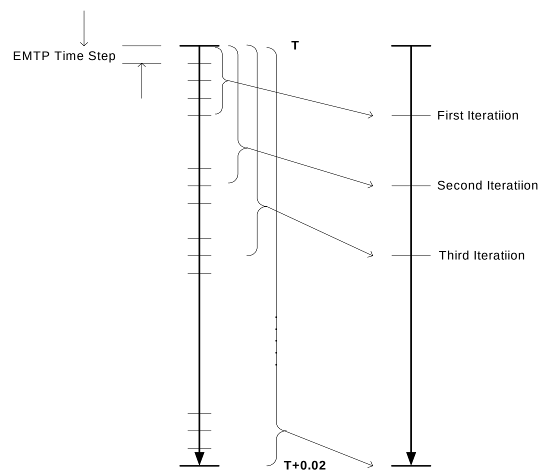

Fig. 6 Parallel Implementation of Interaction Protocol

In fact, the TS simulator and the EMT simulator are never idle under the proposed parallel protocol. For each TS time step, the first iteration proceeds with a prediction of the bus voltages of the external system at T2 (which is basically an extrapolation of the voltage from the previous voltages determined by the TS simulator), as well as a prediction of the P and Q of the detailed system at T2 (which is calculated based on the history data of the EMT simulator by using a curve-fitting extraction method). At the completion of the first iteration, the second iteration proceeds with an updated prediction of the external and detailed system data. The updated prediction of the EMT data makes use of the current solution history data up to the time corresponding to the first iteration. However, since the EMT data from the previous iterations has already been processed, only the new EMT data obtained from each iteration is needed to be processed for updating the prediction. This protocol allows the EMT simulator to run continuously, concurrently with the TS simulator.

For actual implementation the communication protocol is executed as follows. For the first iteration the TS simulator has no data available for prediction since both the TS and EMT simulators begin at the same time. In addition, the extracted values have large errors at the beginning of the TS time step, but converge rapidly to a final value. In order to avoid the large extraction errors at the beginning of the TS time step, the actual start of TS simulation is delayed for several EMT time steps.

When TS simulator completes its iterations the time left before the beginning of the next time step is used to update the current source of the Norton Equivalent. The process is illustrated in Fig. 7.

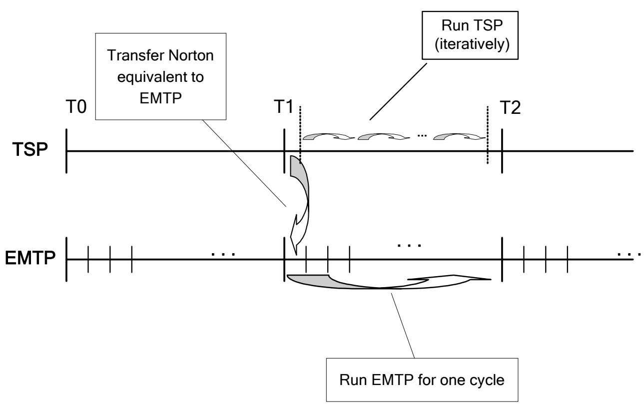

Fig. 7 Practical Parallel Interaction Protocol Diagram

VI. Case Studies

A. SVC Malfunction

Case studies were performed on a 39-bus system, as shown in Fig. 8. An FC/TCR type SVC was connected to Bus 36, and forms the detailed system along with part of the network as shown in Fig. 8. A phase-to-ground fault was applied at bus 38, from 0.2 to 0.22 seconds.

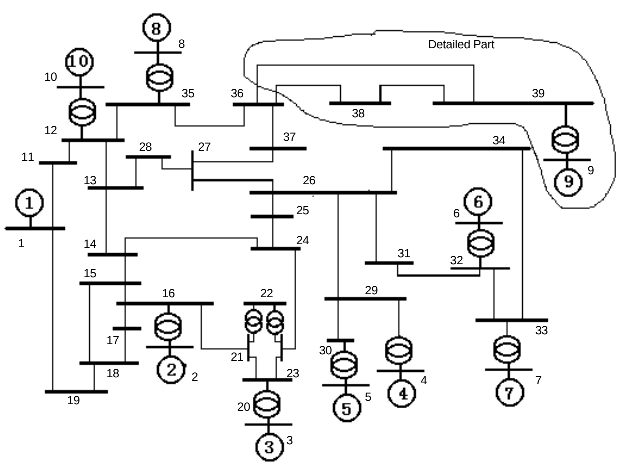

Fig. 8 39-Bus System

The dotted lines of Fig. 9 and 10 are the swing curves from the DCG/EMTP simulation with the SVC working normally. The solid and dashed lines are the swing curves from the DCG/EMTP and the hybrid simulation respectively when the two thyristors valves in one phase are blocked from 0.2 seconds onward. With the SVC malfunctioning, the system becomes unstable, and this contingency, involving the malfunction of a FACTS device would be very difficult to simulate with a conventional transient stability program.

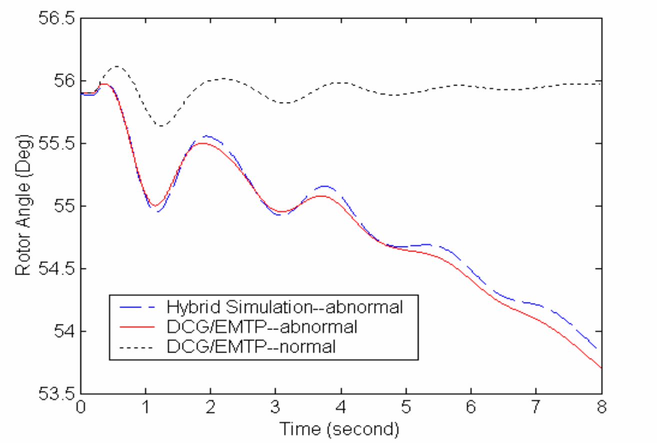

Fig. 9 Swing curve, Generator 2

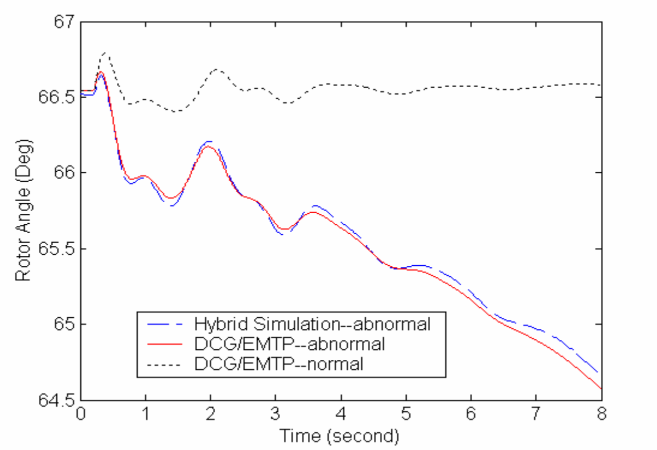

Fig. 10 Swing curve, Generator 8

This type of contingency is important for modern large-size power system characterized by widely application of HVDC links and FACTS devices, and the hybrid simulator is ideally suited for this application, where the EMT simulator would not be practicable for a large system, and the TS simulator is not suitable at all. Thus, hybrid simulator offers the advantage of a substantially extended contingency list.

B. Parallel Hybrid Simulation

Based on the communication protocol described above, a parallel hybrid simulator was built on a multi-processor SGI (8-processor, IRIX 6.5 UNIX OS) server, using multi-thread techniques. When the master thread finishes initialization of computation, two threads are created, one for the TS simulator and the other for the EMT simulator, each running on different processors. The master thread controls their coordination. The TS simulator starts to iterate after the EMT simulator completes 10 time steps (this number can be controlled by the user), and ends when the EMT simulator has 10 time steps left (this number can be also controlled by user). When the TS simulator completes one iteration, it fetches updated variables from the EMT simulator. The number of iterations depends on the computer hardware.

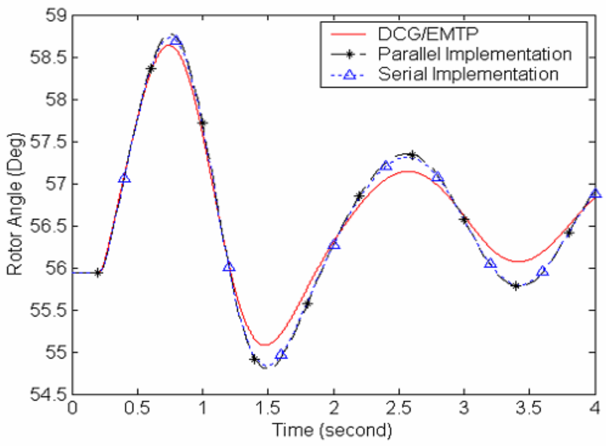

Fig. 11 Generator 2 Swing Curves

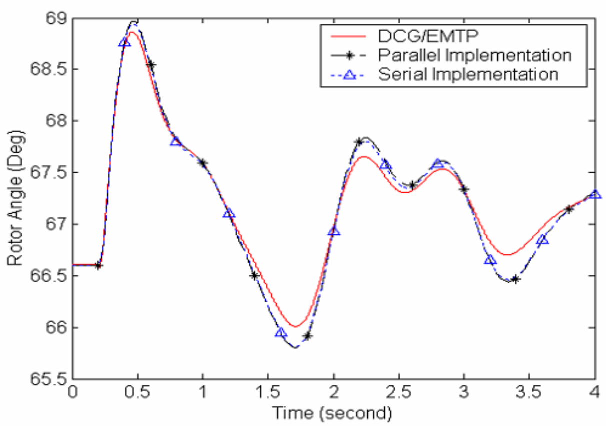

Fig.12 Generator 8 Swing Curves

A case study using this communication protocol was run on the 39-bus system shown in Fig. 8. A three-phase fault was applied at bus 38 from 0.2 to 0.24 seconds. The responses simulated using the DCG/EMTP were plotted in solid line in Fig. 11 and 12 as the reference. The responses obtained with the hybrid simulation were plotted in dash-dot and dotted line for the parallel and serial version of the communication protocol, respectively. Clearly, the parallel implementation produced virtually the same responses as the serial one, and the hybrid simulation could closely match the DCG/EMTP outputs.

VII. Conclusions

Hybrid simulation is significant step towards the realization of a powerful digital power system simulator, capable of efficient simulation of large size networks, while providing accurate representation of highly nonlinear components, such as FACTS devices and HVDC links. In this paper a functional hybrid simulator was presented, where a novel approach has been applied to the communication protocol such that real-time hybrid simulation can be realized. Hybrid simulators are capable of simulating mal-functions of FACTS devices, and this was demonstrated by simulating the response of a 39-bus system with a single-phase fault accompanied by valve failures in a 39 bus power system. To validate the parallel implementation of the interaction protocol, a parallel hybrid simulation was built on a multi-processor computer and the EMT and TS simulators were allocated to different processors running in parallel. The results compared well with those from a simulator using 'conventional' serial communication protocol. The hybrid simulator is an ideal tool to study extended contingency lists, including cascading faults and mal-operation of power electronic devices.

VIII. References

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IX. Biographies

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Jean-Claude Soumagne received the B.Sc. degree in Electrical Engineering from Ecole Supérieure d'Electricité, Paris, in 1977 and the M.Sc. degree in Electrical Engineering from Université Laval, Québec, Canada, in 1981. Since 1983 he has been employed at Institut de recherché d'Hydro-Québec (IREQ) Varennes, Québec, Canada. His principle responsibilities are real-time numerical simulation and the development of the IREQ's simulation facilities.