A NEW HYBRID AC-DC TRANSIENT STABILITY PROGRAM

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1.0 INTRODUCTION

Conventional stability analysis of ac systems incorporating HVdc links use either steady state or quasi-steady state representations of the Hvdc converter. While these programs are entirely adequate for representing the dynamic behaviour of generators, they are compromised by their limited representation of non-linear components. Dynamic electromagnetic solutions such as EMTP and EMTDC can provide detailed elemental analysis of converters but are computationally expensive. In these types of simulations, the ac system representation must be restricted and consequently the ac system dynamic response is limited.

A hybrid simulation package takes advantage of the computationally inexpensive dynamic representation of the ac system in a stability program, with the accurate dynamic modelling of non-linearities. The slow dynamics of the ac system are sufficiently represented by the stability program, while at the same time, the fast dynamic response of say an HVdc system, is accurately modelled by electromagnetic means.

1.1 A Hybrid Historical Review

Heffernan et al. first proposed the detailed modelling of an HVdc system within a stability based ac system framework[1]. The dc system was modelled using state variable techniques while the ac system was represented by a conventional stability program. The interface locations were the converter terminals and the interface variables were rms power and an FFT derived fundamental frequency voltage.

Reeve and Adapa modified this hybrid idea by moving the interface location away from the converter terminals where distortion and phase imbalance were less prevalent[2]. An EMTP solution was used for the detailed analysis while the rest of the ac network was again modelled conventionally with a stability program. A curve fitting approach to data extraction replaced the rms and FFT methods of Heffernan et al. allowing more flexibility for the stability step length to change.

A type of hybrid approach is also used in the digital program NETOMAC[3] for analyzing electro-mechanical and electromagnetic transient phenomena. This program uses two separate modes for modelling to reduce the computational requirements. An instantaneous mode models components in three phase detail while a stability mode models the system in rms quantities at fundamental frequency. The program can switch between the two modes as required while running. In either mode however, the entire system must be modelled in the same way. When it is necessary to run in the instantaneous mode, a system model of any substantial size is still very computationally intensive.

This paper presents a new hybrid algorithm to enhance the modelling accuracy of ac-dc systems. The hybrid approach, however, is not restricted to ac-dc applications only. A particular part of an ac system may require detailed three phase modelling and this same hybrid approach can then be used. Applications include the detailed analysis of synchronous or static compensators and FACTS devices.

Detailed modelling can also be applied to more than one independent part of the complete system. For example, if an ac system contained two HVdc links, then both links could be modelled independently in detail and included in one overall solution.

2.0 THE TS-EMTDC HYBRID

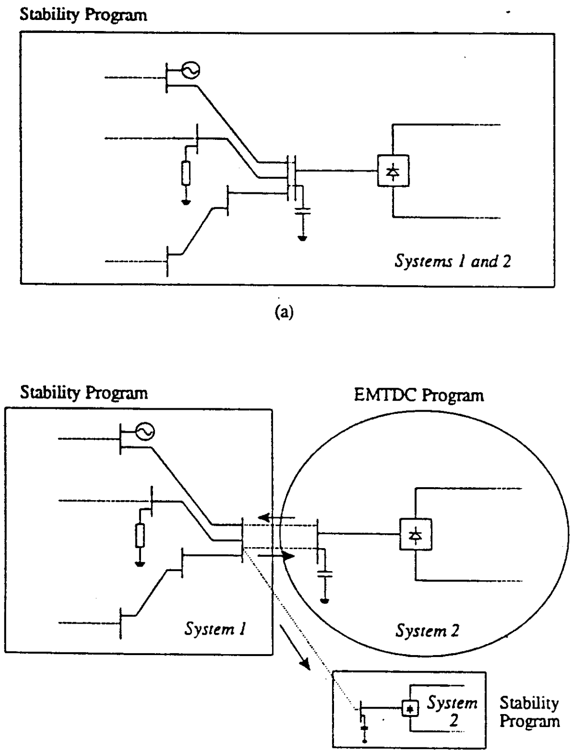
The hybrid developed consists of a conventional electro-mechanical stability program, TS[4], and an established electromagnetic transient program EMTDC[5].

2.1 System Splitting

Initially, the hybrid reads in the data files, and runs the entire network of systems 1 and 2 in the stability program, until electro-mechanical steady state equilibrium is reached. This is shown in the example of Figure 1(a). The quasi-steady state representation of the converter is sufficient for this as no fault or disturbance has yet been applied. At a selectable point in time, prior to a network disturbance occurring, the TS network is split up into the two independent and isolated systems, system 1 and system 2.

System 1 is classified as the ac part of the system modelled by the stability program TS, while system 2 is the part of the system modelled in detail by EMTDC.

A snapshot data file is now used to initialise the EMTDC replacement of the TS representation of system 2. The two programs are then interfaced and the



(a)

(b)

Figure 1: Interfacing Procedure

network disturbance can be applied. The system 2 representation in TS is isolated but kept up to date during the interfacing at each TS time-step to allow tracking between programs. The ac network of system 1 modelled in TS also supplies interface data to this system 2 network in TS as shown in Figure 1(b).

While the disturbance effects abate, the quasi-steady state representation of system 2 in TS and the EMTDC representation of system 2 are tracked. If both of these system 2 models produce the same results within a predefined tolerance and over a set period, the complete system is reconnected in TS and the EMTDC representation terminated. This allows better computational efficiency, particularly for long simulation runs.

3.0 INTERFACING

3.1 Variable Choice

Hybrid simulation requires information interchange to occur between the two separate algorithms. An equivalent circuit representing the network modelled in the stability program is used in EMTDC, and vice versa.

Obtaining the required information to transfer from EMTDC to TS is the difficult problem. The parameters are 'point on wave' and require a method such as curve fitting to translate them. The measurements must also be made at discrete points in time necessary for the transfer of data. A significant difference between TS and EMTDC is that in TS, sinusoidal waveforms are assumed. EMTDC waveforms however, particularly during faults, can be very non-sinusoidal.

The information that must be transferred from one program to the other must be sufficient to determine the power flow in or out of the interface. The generally available parameters that can be measured include real power, reactive power, voltage, and current through the interface. Phase angle information is also required if separate phase frames of reference are to be maintained.

In the hybrid program proposed by Heffernan, the total rms real power was used as one of two interfacing parameters chosen to transfer information. This rms power is very simple to extract from point oriented waveforms and Fourier transform or curve fitting methods are not necessary. The choice of rms power was made on the basis that harmonic power flow will result only from in-phase components of harmonic voltage and current. The assumption was made that if a system contains only a low resistive component, then the harmonic power flow is not significant.

This however, is not valid for every situation, and particularly at the inverter end of an HVdc link, the resistive component of the network is not insignificant[6]. Certain harmonic frequencies in a network may also be parallel resonant or close to parallel resonance and exhibit more resistance than reactance. The presence of a transient may excite the resonant frequency and greatly affect the results.

Another factor to consider is that the direction of fundamental power may not necessarily be the same as the direction of harmonic power. While certain loads such as lighting and resistive heating may benefit from harmonic power, in general, it is not accurate to lump the entire rms real power measured into an effective rotational power of fundamental frequency.

A potentially larger problem exists when the three phase network is unbalanced. The fundamental frequency real power can then consist of positive, negative, and zero sequence components.

Fundamental frequency negative sequence currents, in the presence of damper or armotisseur windings, can produce a braking torque which will retard the rotor[7]. Retardation of the rotor can also be caused by dc components in the armature windings. Three phase faults at or near machine terminals can cause dc components of short circuit armature current which can have a definite braking effect on the machine[8].

The total rms power then, is not always equivalent to either the fundamental frequency power nor the fundamental frequency positive sequence power. The difference between total rms power and the positive sequence power can be highly significant, especially during a fault.

The most appropriate power to transfer from EMTDC to TS is then the fundamental frequency positive sequence power. This, however, requires knowledge of both fundamental frequency positive sequence voltage and fundamental frequency positive sequence current. These two variables constitute enough information on their own and hence the use of any power variable to transfer information becomes redundant.

3.2 Interface Location

In the initial hybrid interfacing described by Heffernan et al., the intention was to model the ac and dc solutions separately. The point of interface location was consequently the converter bus terminal. The detailed dc link model included all equipment connected to the converter bus, such as the ac filters, however every other ac component was modelled within the stability analysis. A fundamental frequency Thevenin equivalent was used to represent the stability program in the detailed solution and vice versa.

A different approach to hybrid analysis was proposed by Reeve and Adapa where the interface location was extended out from the converter bus into the ac system. Reeve and Adapa maintained that, particularly for weak ac systems, a fundamental frequency equivalent representing the ac system was not sufficient at the converter terminals of the detailed dc solution. Other frequencies present in the detailed dc solution are not taken into account. How much ac system to be included in the detailed analysis depended on two factors, phase imbalance and the waveform distortion.

Although the concept of extending the interface location further out into the ac system has its advantages, it also suffers many disadvantages.

The primary reason for a hybrid solution is in accurately providing the dc dynamic response to a transient stability program, and in efficiently representing the dynamic response of a considerably sized ac system to the dc solution. Extending the interface some distance into the ac system where the effects of a system disturbance are almost negligible diminishes the hybrid advantage. If a sizeable portion of the ac system requires modelling in detail before an interface to a transient stability program can occur, then one might question the use of a hybrid solution at all and instead use a more conventional approach of a detailed solution with ac equivalent circuits at the system cut-off points.

Another significant disadvantage in an extended interface is that ac systems may well be heavily interconnected. The further into the system that an interface is moved, the greater the number of interface locations required.

The advantages of using the converter bus are clear :-

- The detailed system is kept to a minimum
- Interfacing complexity is low
- Computational expense is minimised
- Converter equipment can still be modelled in detail

Reeve and Adapa rightly pointed out that the major drawback of the detailed solution is in not seeing a true picture of the ac system, since the equivalent circuit is fundamental frequency based. A simple fundamental frequency equivalent circuit is insufficient to present the correct impedance of the ac system at other frequencies to the converter.

Reeve and Adapa countered this by representing more of the ac system in detail through use of the extended interface bus. The impedance at the converter bus was then more accurate for other frequencies and not just for the fundamental.

An alternative solution is to present a fully frequency dependent equivalent circuit of the ac system at the converter terminal instead of a fundamental frequency equivalent. A frequency dependent equivalent prevents the necessity of modelling any significant portion of the ac system in detail yet still provides an accurate picture of the system impedance across its frequency spectra. Frequency dependent equivalents can be easily derived by such methods as that proposed by Watson[9].

3.2 Interaction Protocol

Curve fitting analysis is applied to measure the variables from EMTDC over staggered discrete fundamental period window lengths, while the transient stability program variables are read directly at the interface. The data from each program must then be interchanged at appropriate points during the hybrid simulation run. The timing of this data interchange between the TS and EMTDC programs is important, particularly around discontinuities caused by fault application and removal.

The information exchange protocol for the hybrid is shown in Figure 2 with the stability step length exactly one half a fundamental period in this example.

Following the sequential numbering, at a particular point in time, the EMTDC and TS programs are concurrent and the TS information from system 1 is passed to update the system 1 equivalent in EMTDC. This is shown by the arrow marked '1'. EMTDC is then called for a length of half a fundamental period (arrow '2') and the curve fitted results over the last *full* fundamental period processed and passed back to update

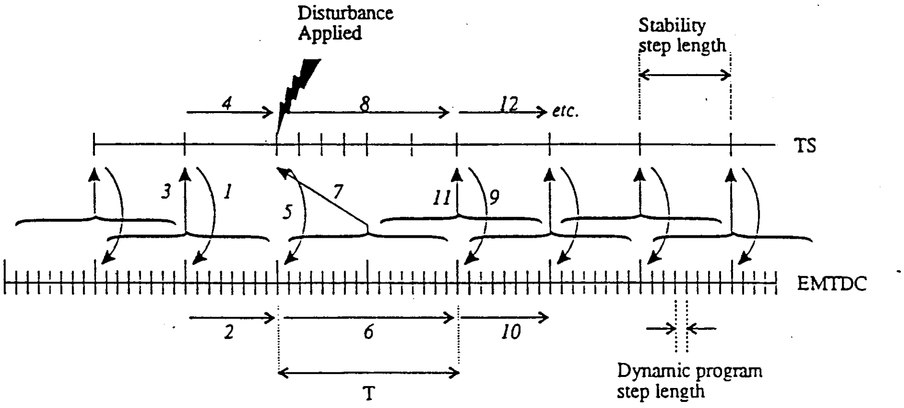


Figure 2: Interaction Protocol

the system 2 equivalent in TS. The information over this period is passed back to TS at the mid-point of the EMTDC analysis window which is half a period behind the current EMTDC time. TS is then run to catch up to EMTDC, and the new information over this simulation run used to again update the system 1 equivalent in EMTDC (arrow '5'). This protocol continues until any discontinuity in the network occurs. When a network change such as a fault application or removal occurs, the interaction protocol is modified.

At the fault time, neither system 1 or system 2 have yet been solved with the network change. The fault is now applied in EMTDC which is then run for a full fundamental period length past the fault application and the information obtained over this period passed back to TS. The fault is now also applied to the TS program which is then solved for a period until it has again reached EMTDC's position in time. The normal interaction protocol is then followed until any other discontinuity time is reached.

A full period analysis after the fault is applied is necessary to accurately extract the fundamental frequency component of the interface variables. The mechanically controlled nature of the ac system implies a dynamically slow response to any disturbance and so for this reason, it is considered acceptable to run EMTDC for a full period without updating the system 1 equivalent circuit during this time.

4.0 RESULTS

4.1 Test System

The test system consisted of a two-terminal 1000 MW mono-polar HVdc link connected on the inverter side to a simple ac system, and on the rectifier side to a more complex ac system incorporating a number of generating buses (Figure 3).

The HVdc system is based on the CIGRE benchmark model while the rectifier ac system represents a simplified portion of the New Zealand South Island system[10].

The HVdc control system for TS is largely inherent in the program, with one of the two terminals specified in constant current mode, and the other in constant voltage at a specified firing order. For the test system, the rectifier is specified under constant current control and the inverter under minimum gamma control. The TS program is only one example of transient stability programs available, many of which can model dc controls in more comprehensive detail. For this reason, shut-down and start-up procedures around a fault were included in EMTDC to match the TS program constraints.

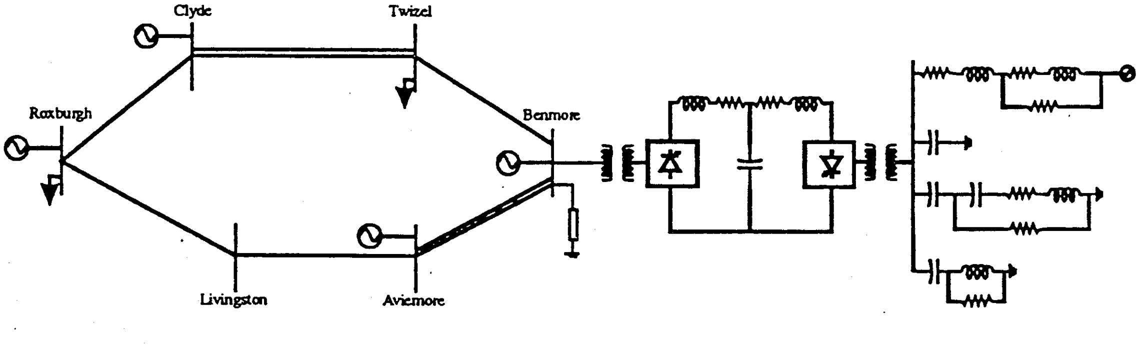


Figure 3: Test System

4.2 Fault Disturbance

A three phase fault was applied at the rectifier ac system terminal and cleared in three cycles. Various ac fault types have differing severities, however a three phase fault at a converter terminal is the most severe in blocking all power flow.

The rectifier terminal was selected above the inverter since rectifier faults are often worse for transient stability. An inverter fault still allows generation at the rectifier to supply line losses and local load. A rectifier fault however, especially near generators, more totally blocks both ac and dc power. This results in greater transient acceleration of the generators.

4.3 The Hybrid Response

Figure 4 shows the bus voltage of the hybrid TS-EMTDC (TSE) solution along with the response of an EMTDC only solution. The EMTDC only solution uses the same frequency dependent equivalent as the hybrid TSE except the source value in this case is fixed.

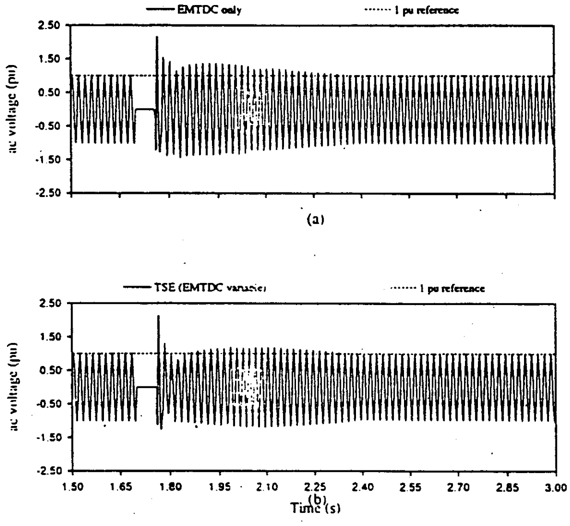


Figure 4: Rectifier ac voltage

Figures 4(a) and 4(b) show a significant difference only between the fault removal and time t=2.1s. The EMTDC waveform, with its fixed source value, displays a higher ac voltage over this period while the link is regaining full load. The TSE waveform shows the behaviour of the ac generators as supplied by TS and is slightly lower than that of EMTDC for this reason.

The rectifier dc current of the hybrid, an EMTDC only solution, and also a TS only solution is shown in Figure 5 while a dc voltage comparison is shown in Figure 6. The TSE current is very similar to that of EMTDC except over the period from time t=2.03s to t=2.14s when the TSE dc current climbs slower than that of EMTDC to its position of power ramping. The TSE solution has a smaller dc voltage overshoot but a higher overall dc voltage during this period. This can also be seen in the firing angle (shown in Figure 7) remaining at a minimum value longer than TS and hence causing this higher voltage. This is due to the lower ac voltage at the rectifier requiring a lower firing angle to maintain the dc voltage required for the ordered current. Since the firing angle is at its minimum value, the dc current in TSE is slower to respond to its ordered value.

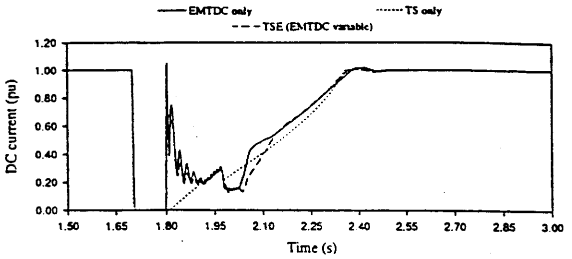
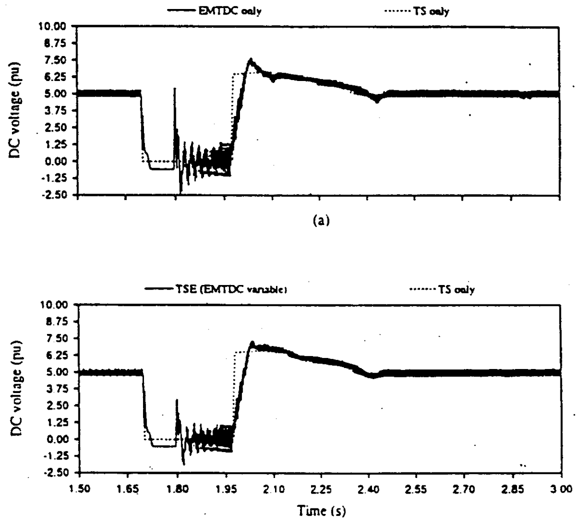


Figure 5: Rectifier dc current



(a)

(b)

Figure 6: Rectifier dc voltage

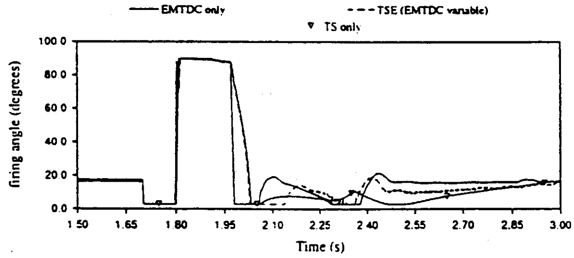
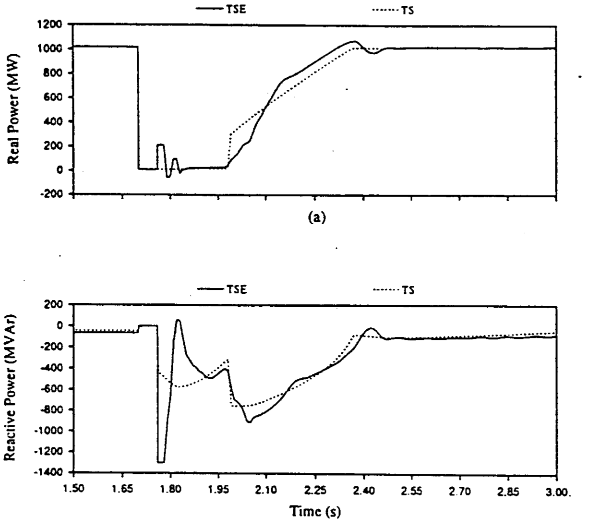


Figure 7: Rectifier dc firing angle

The slightly lower ac voltage in TSE compared with EMTDC also causes the firing angle to be lower further on in time. As the ac voltages of EMTDC and TSE move together, so do the firing angles.

The fundamental, positive sequence, real and reactive power flows were also monitored across the interface converter bus in both TS and TSE and are shown in Figure 8. The main differences in real power occur during the link power ramp. The difference is almost a direct relation to the dc current difference between TS and TSE shown in Figure 5. The oscillation in dc voltage and current as the rectifier terminal is de-blocked is also evident.



(a)

(b)

Figure 8: Real and reactive power across interface

As for the reactive power Q, prior to the fault, a small amount is flowing into the system due to surplus MVAr's at the converter terminal. The fault reduces this power flow to zero. When the fault is removed and the ac voltage overshoots in TSE, the reactive MVAr's also overshoot in TSE and since the dc link is shut down, a considerable amount of reactive power flows into the system.

The differences and cross-over points between reactive power from TS to that of TSE from time t=1.8s on are a direct result of the differences in the firing angle from Figure 7. When the firing angle in TSE is low, compared to TS, the reactive requirements of the link are also low in comparison.

5.0 CONCLUSIONS

An advanced hybrid package has been developed combining an electro-mechanical transient stability program with a detailed electromagnetic transient program. The hybrid allows the flexibility of simulating certain components or sections of a power system in detail while simulating the rest of the system by a computationally efficient positive sequence, fundamental frequency model.

A three phase fault at the rectifier converter terminal was applied to a test system to show the response of the hybrid. The electro-mechanical TS solution showed the slower dynamic response of the ac system while the electromagnetic EMTDC solution displayed the fast dynamics of the rapidly switched converter. In the hybrid, these responses were combined to give a more realistic overall picture of the entire system. The TS modelling of the ac system was improved by the inclusion of the actual response of the fast acting HVdc link, while the link behaviour was also more realistic through the inclusion of the generator controller response varying the ac system voltage at the converter terminal.

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