Chandrapur - Padghe HVDC Schemes Coordination Study

K M Abbott, P T Griffiths, H Duchen and M Aten
ALSTOM T&D Power Electronics Systems, Ltd., Stafford, UK

Abstract– This paper presents the Chandrapur - Padghe Co-ordination Simulator Study performed as part of the Chandrapur 2 x 500MW HVDC Back-to-Back (BtB) and the Chandrapur-Padghe 2 x 750MW HVDC Transmission (CTP) Projects. The BtB project [ALSTOM] has been in service since 1998 for the Power Grid Corporation of India Limited (POWERGRID) and the CTP Project [ABB] is presently being completed for the Maharashtra State Electricity Board (MSEB). This study was performed to investigate interaction between the two HVDC schemes.

The study was carried out jointly by ALSTOM and ABB using ALSTOM's Real Time Digital Simulator (RTDS) facility to model the two HVDC schemes and associated ac systems. The RTDS model was interfaced to physical functional duplicates of the actual controls which are to be used on the two HVDC schemes. A large number of cases were studied, including AC and DC system disturbances, AC network reconfigurations, load changes and generator trips. The conclusion of this study is that good system stability exists when interconnecting the two HVDC schemes.

Index Terms–HVDC, Coordination, RTDS, Simulation.

I. INTRODUCTION

The behaviour of the Chandrapur 2 x 500MW HVDC Back-to-Back (BtB) the Chandrapur-Padghe 2 x 750MW HVDC Transmission (CTP) schemes have been investigated previously during separate dynamic performance studies. When both HVDC schemes are operational they will be interconnected by two short (approximately 20 km long) parallel 400kV ac transmission lines (see Figure 1). Therefore, to identify any mutual influence which might result from their close electrical interconnection, this interaction study has been performed. The main objective of this investigation was to verify that no system instability or system collapse could be caused by the interconnection of the two HVDC schemes in the cases studied. The results of the different cases studied are presented in this paper and indicate in general that good system stability exists when interconnecting the two HVDC schemes. This is valid even when the equivalent network used for the study has greater sensitivity to changes than the full network.

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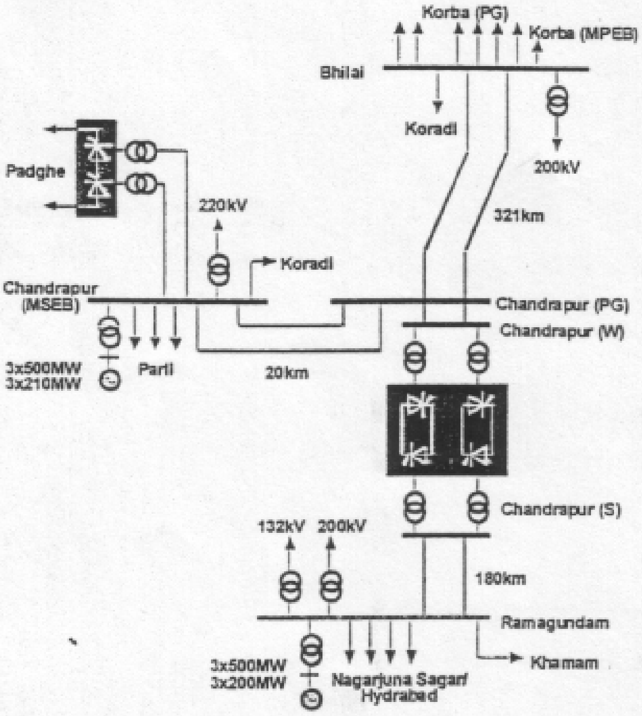
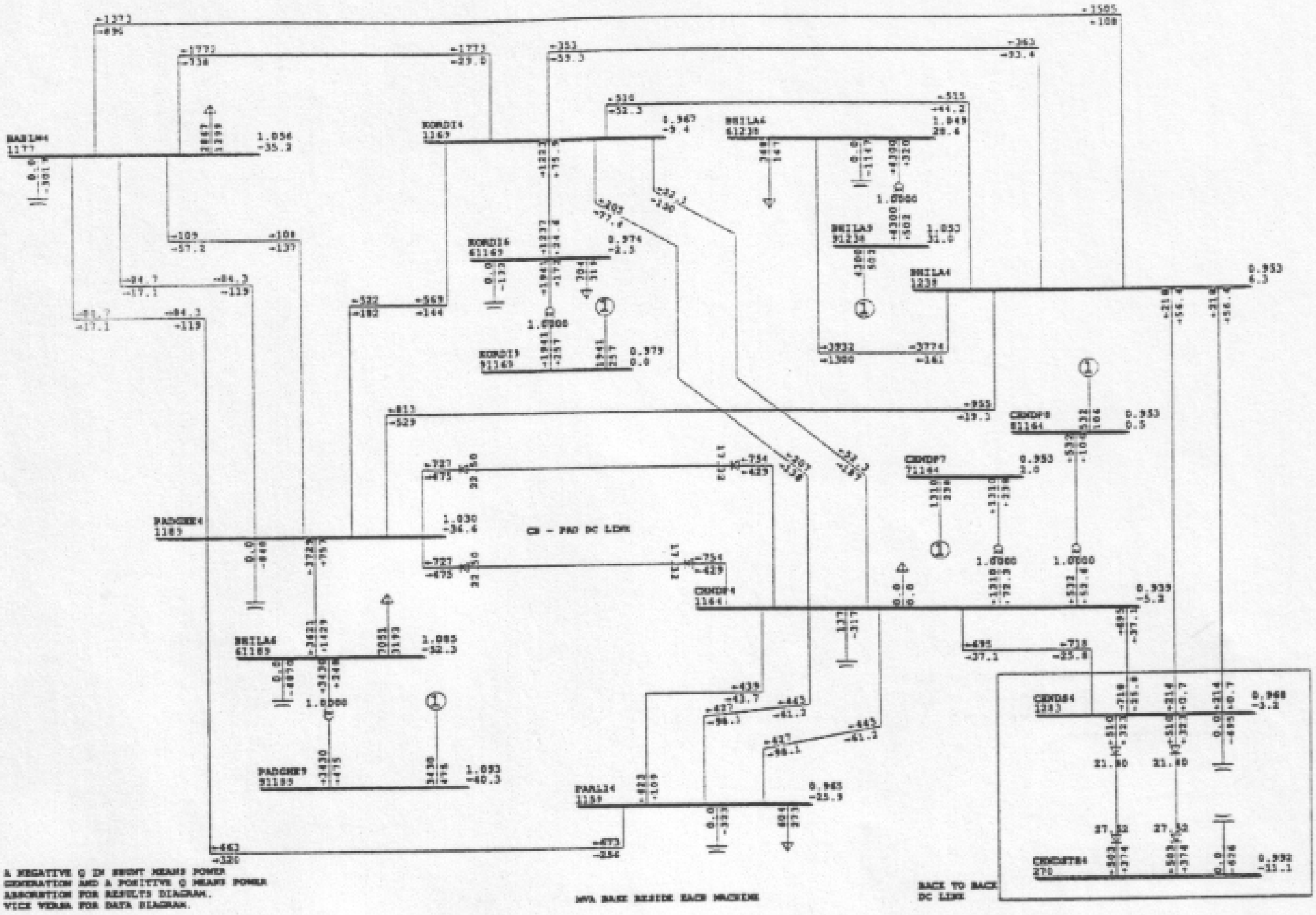


Figure 1. Schematic Diagram

II. EQUIVALENT NETWORKS AND SIMULATOR SET-UP

The Chandrapur Co-ordination Simulator Study was performed using reduced network equivalents to represent the western and southern AC systems. It had been originally intended that only two equivalent networks (i.e. base networks) representing two different typical load configurations (i.e. BtB power flow from south to west and from west to south) would be used during the Study. However, during the Study and following consultation between POWERGRID, MSEB, ALSTOM and ABB, it was agreed that additional case studies would be performed using two additional equivalent networks representing 'light load' configurations. In these cases the networks were configured to be representative of lightly loaded systems with reduced generation available at both Chandrapur MSEB and Ramagundam and reduced short circuit levels at the converter terminals. An example of the form of equivalent network used is shown in Figure 2.



A NEGATIVE Q IN SHUNT MEANS POWER GENERATION AND A POSITIVE Q MEANS POWER ABSORPTION FOR RESULTS DIAGRAM. VICE VERSA FOR DATA DIAGRAM.

MVA BASE BESIDE EACH MACHINE

BACK TO BACK DC LINK

Figure 2. Typical Equivalent Network

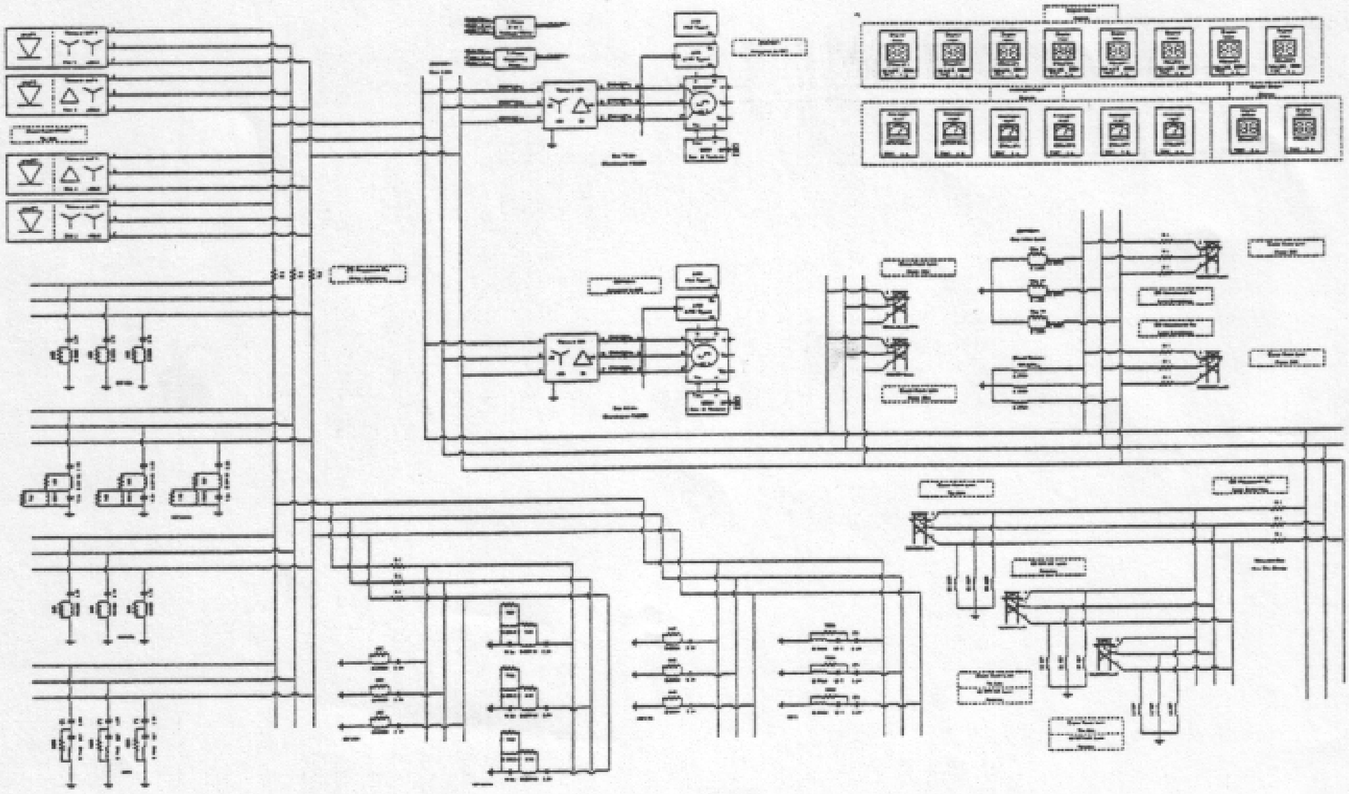


Figure 3. Example of RTDS Draft

With the exception of the load models and generator output, system data for the two base networks are identical. The magnetisation characteristics of the BtB and CTP converter transformers are also represented. The first of the two light load equivalent networks used during the Study is representative of a lightly loaded system when the BtB link is transferring power from the southern AC system to the western AC system, while the other is representative of a lightly loaded system when the BtB link is transferring power from west to south. The CTP scheme was operated in the normal direction of power transfer from Chandrapur to Padghe in all equivalent networks. Both poles of both HVDC schemes operate at 1.0 pu power.

RTDS representations of the equivalent networks are typified by Figure 3. Eight racks of RTDS were used to model each of the equivalent networks. The RTDS model incorporated representation of both poles of both HVDC schemes (including converter transformers, valve groups, AC filters, DC filters, DC transmission lines and electrode lines as required) and the surrounding AC networks including eight generators (four real units and four remote equivalents each incorporating representations of the step-up transformers, governors, turbines, AVRs and power system stabilisers as required) and 25 transmission lines (13 real and 12 equivalent) interconnecting thirteen 400kV busbars (ten real and three equivalent).

The three-phase short circuit levels of the four equivalent networks (i.e. two base networks and two light load networks), at the commutation busbars of the two HVDC schemes, operating under the given load flow conditions are listed in Table 1. These values are typical of what is expected in the actual system under the prescribed operating conditions. In practice, lower and higher short circuit levels are possible but are less probable. Post fault network reconfiguration cases examined during the study operate at short circuit levels lower than those listed in Table 1.

Table 1. - Three Phase Short Circuit Levels (MVA)

Equiv. Network	Padghe PADGHE4	Chandrapur MSEB CHNDP4	Chandrapur West CHNDS4	Chandrapur South CHSTH4
B S_W	10 760	11 880	9 930	3 950
B W_S	10 900	12 830	10 180	3 810
L S_W	10 600	10 420	9 020	3 360
L W_S	10 800	10 630	8 920	3 120

III. CASES STUDIED

A total of 90 cases were studied. During the study both HVDC schemes were operated in Station/Bipole Control Mode whereby equal power orders were requested of each pole. In the special cases where a pole was being started or stopped, the starting/stopping pole was operated independently. Swing damping (also known as power modulation) control was active on both HVDC schemes by default. In the case of the BtB link, swing damping responded simultaneously to measurements from both the western and southern ac systems.

Unless otherwise specified, all cases had an initial steady state operating frequency of 50 Hz for both the western and southern AC systems. Also by default, the BtB link had frequency control activated so as to regulate the frequency of the weaker (i.e. southern) AC system. Island conditions associated with the CTP or BtB schemes preclude interaction and therefore were not considered. Consequently, frequency control by the CTP scheme, required only during island conditions, was not activated during the Co-ordination Study.

A. Base Network - South to West BtB Power Flow

1) Energisation of Converter Transformers

Saturation characteristics of the converter transformers were implemented within the RTDS models of all cases studied. Transformer energisation cases were each repeated 20 times to find the worst case conditions (i.e. maximum amplitude of oscillation of the inrush current which also results in maximum oscillation of the firing angles). Each of the 20 tests for each case were performed with random points of energisation and de-energisation. The random nature of these tests allowed the effects of the worst case remenance conditions to be demonstrated while the effects associated with circuit breaker timing discrepancy were not expected to be significant. Consequently all circuit breaker poles were closed simultaneously in all cases. CTP and BtB HVDC schemes both perform well at transformer energisation.

2) Response tests

Pole starting, ramping of power, steady state measurements, step responses, pole stopping were all covered.

3) AC Filter Energisation / Trip

AC filter energisation/trip tests were performed without pre- or post-conditioning on either scheme. Therefore, the effects exhibited by these cases will be worse than those expected in practice.

4) AC System Faults

Fault Cases at the PADGHE4 AC Busbar

The CTP scheme link fails commutation immediately following the AC system fault at the PADGHE4 busbar. Under the conditions studied, the combined effect of the AC system fault and the commutation failure current supplied by the rectifier of the CTP link produces a significant reduction (greater than 20%) in the AC system voltage at CHNDS4 busbar. This reduction in AC system in turn causes the BtB to experience a single commutation failure. Fine tuning of the controls could not eliminate the occurrence of this single commutation failure on the BtB scheme due to the significant voltage reduction.

For a deep 3-phase fault, a second sudden current increase on the CTP link is attributed to the sudden phase angle displacement as well as uncharacteristic alpha values at fault clearance. A second commutation failure in the BtB link is attributed to the disturbance of the CTP recovery while the BtB is operating with a reduced margin during the application of the fault. It is shown that no second commutation failure on the BtB link occurs when sufficient voltage (>10%) is available at the inverter of the CTP scheme.

Importantly and despite the equivalent system used for this study having greater sensitivity to system changes than the full network model, the results of all these cases show that both HVDC schemes recover satisfactorily without the occurrence of repetitive commutation failures.

Fault Cases at the CHNDP4/CHNDS4 AC Busbars

In all cases the voltage depression at CHNDS4 busbar results in a single commutation failure of the BtB poles. The CTP link fails commutation following the application of the low impedance single phase fault which realises significant voltage depression (>20%) at PADGHE4 busbar.

Recovery to full power transfer by the BtB scheme is generally within 500ms in most cases, this recovery being influenced by the power modulation control which improves the total network recovery performance. If required, the BtB can recover full power transfer within 130ms, as shown in previous BtB dynamic performance studies.

50Hz oscillations in CHANDP7 and CHANDP8 real and reactive power, particularly following removal of the three phase faults, are due to the re-energisation inrush current of the converter transformers of both links being supplied by these machines.

Fault Cases at the CHSTH4 AC Busbar

No commutation failures are experience by either the BtB or CTP schemes. The CTP scheme experiences very little disturbance due to faults within the southern AC system.

5) DC Line Faults

a) DC line fault on pole 1 of the CTP scheme for a duration of 100ms (detection time after fault inception 10ms, de-ionisation after fault clearance equal to 150ms), restart to normal voltage operation 250ms after fault inception. All poles at 1.0pu power level before disturbance.

b) DC line fault on pole 1 of the CTP scheme for a duration of 350ms (first fault detection 10ms after fault inception, first attempt to restart 250ms after fault inception, second fault detection 270ms after fault inception, de-ionisation after fault clearance equal to 200ms), second (successful) restart to normal voltage operation 550ms after fault inception. All poles at 1.0pu power level before disturbance.

In both the cases there is a single commutation failure on BtB at the onset of the CTP pole fault. The commutation failure on the BtB scheme is attributed to the sudden drop in the magnitude and shift in phase of the AC voltage at CHNDP4 and CHNDS4. The severity of this change in the AC system voltage is also evidenced by the sudden drop in the firing angle of the healthy CTP pole. Fine tuning of the BtB controls could not prevent the commutation failure from occurring under these conditions. However, both schemes were found to recovery satisfactorily without the occurrence of repetitive commutation failures.

6) Load Rejection Cases

During these tests, filter tripping and block orders were applied simultaneously. Simultaneous tripping of the filters is considered a more onerous interaction condition because this results in greater voltage drops at the relevant busbars. All poles were operating at 1.1pu power before the disturbances.

CTP Load Rejection

a) Following a 200ms. single phase fault on the PADGHE4 AC busbar, block one pole of the CTP scheme and trip relevant filters.

Filters before rejection		Filters after rejection	
Padghe	Chandrapur	Padghe	Chandrapur
8 (800MVar)	8 (800MVar)	4 (400Mvar)	4 (400MVar)

For a single pole rejection, power on the remaining pole of the CTP scheme was left at 1.5pu for more than 10 seconds. A single commutation failure in the BtB scheme is due to the voltage depression (≈ 30%) at CHNDS4.

b) Following a 100ms. three phase fault on the CHNDP4 AC busbar, block both poles of the CTP scheme and trip relevant filters.

Filters before rejection		Filters after rejection	
Padghe	Chandrapur	Padghe	Chandrapur
8 (800MVar)	8 (800MVar)	Nil	Nil

The BtB experiences a single commutation failure but stable recovery of the system is possible following the outage of both CTP poles, without BtB power order runback. However, should BtB power order runback be necessary to prevent overloading of AC transmission lines, then any signals initiating such runback can be provided to the BtB converter station.

Good system recovery is achieved following both CTP single pole and bipole load rejection. Stable operation of both the western and southern AC systems is regained without the need to runback the BtB power order.

BtB Load Rejection

a) Following a 200ms. single phase fault on the CHNDS4 AC busbar, block one pole of the BtB link and trip relevant filters. Repeat by blocking both poles of BtB.

Filters before rejection		Filters after rejection	
Chandrapur West	Chandrapur South	Chandrapur West	Chandrapur South
7 (742MVar)	7 (742Mvar)	5 (530Mvar)	5 (530MVar)

Good system recovery is achieved following both BtB pole and bipole load rejection. The AC system fault has greater effect in initiating machine swings in the western AC system than the blocking the BtB poles. For single BtB pole load rejection, the remaining BtB pole is beneficial in aiding system recovery by way of the BtB swing damping. Maximum power of a BtB pole under contingency conditions is 650MW (i.e. 1.3pu). This is achieved in the first case where the fluctuations in the DC current are due to the swing damping control which aids machine power swing damping. Following the rejection of one BtB pole, the western and southern AC system frequencies recover to approximately 49.9Hz and 50.15Hz respectively. Under such conditions the frequency control of the BtB scheme requests greater power flow from the remaining pole in order to approach 50Hz for the southern AC system.

b) Following a 100ms. three phase fault on the CHSTH4 AC busbar, block both poles of the BtB link and trip relevant filters.

Filters before rejection		Filters after rejection	
Chandrapur West	Chandrapur South	Chandrapur West	Chandrapur South
7 (742MVar)	7 (742Mvar)	Nil	Nil

Subsequent machine swings in the western AC system are relatively small because the fault within the southern system has little influence on the western side.

7) Generator Trips

During all of these cases the frequency controller of the BtB scheme was active on the southern AC system. The target frequency was 50Hz on the southern AC system and the frequency limits on the western system were 48.5Hz and 51.5Hz. Frequency control operates over a much lower bandwidth than swing damping control on the BtB scheme, this ensures that the frequency controller and swing damping controller are properly co-ordinated without adverse interaction.

8) Network Reconfiguration Cases

Table 2. Reconfiguration cases following a fault

Case	Fault	Disconnection
1	3-ph at CHNDS4	1 line, CHNDS4 - BHILA4
2	3-ph at PADGHE4	1 line, PADGHE4 - BABLW4
3	3-ph at CHSTH4	1 line, CHSTH4 - RSTP4
4	3-ph at BHILA4	2 lines, BHILA4 - CHNDS4
5	3-ph at CHNDS4	1 line, CHNDS4 - CHNDP4
6	3-ph at CHNDS4	2 lines, CHNDS4 - CHNDP4
7	3-ph at CHNDP4	Short line CHNDP4 - PARLI4
8	Most critical case from 1 to 7 with 1-ph fault (case 4)	
9	3-ph at CHNDP4	Following reconfiguration of 3

For cases 1, 5, 7, 8 and 9 both the BtB and CTP schemes perform well during and following the AC system fault, recovering with a weaker network configuration. While for case 2, the previous comments regarding faults at the PADGHE4 busbar apply.

Case 3 requires a BtB power order runback to 500MW with slightly increased orders possible if frequency control is active. Following the power runback on the BtB scheme, the frequency of the western system falls below 50Hz and the frequency of the southern system rises above 50Hz according to the frequency-power characteristics of the generators' governors and the frequency control of the BtB scheme.

In Case 4 a 10Hz oscillation was manifested whenever the voltage at Padghe fell below 0.75pu. This 10Hz oscillation is completely damped after 5 seconds when the voltage rises above 0.75pu. The low voltages at Padghe exhibited by the equivalent network were considered pessimistic when compared to the full system and the 10Hz oscillations not expected to be present in practice. It was found that power modulation by the BtB scheme improved the system response and that the source of the 10Hz oscillation lay outside of the BtB scheme's control (this oscillation is present even when both poles of the BtB scheme are blocked).

Both the BtB and CTP schemes perform well in case 6 provided the power order of the BtB scheme is runback to 100MW following the loss of the lines otherwise the western AC system would not recover to a stable operating condition.

9) Modulation Cases

Each scheme was subjected to direct current modulation at 3.0Hz with swing damping disabled. Both the BtB and CTP schemes exhibit stable performance in the presence of this low frequency modulation and no undamped oscillations observed. For natural oscillations in the system, good performance of the power modulation controls was demonstrated by the fault and reconfiguration cases.

10) Low Harmonic Resonance

Here, the direct current in each scheme is modulated with a 50Hz component to initiate a 100Hz component on the AC side. The AC system exhibited stable performance during modulation an no undamped oscillations observed.

B. Base Network - West to South BtB Power Flow

Results for reversed power flow through the BtB are similar to the cases with flow from south to west. The exceptions being that the CTP scheme now fails commutation immediately following a single phase fault at either the CHNDP4 or CHNDS4 busbars. However, no major disturbance is transferred to the southern AC system via the BtB.

Both poles of the BtB experience a commutation failure immediately following the AC system fault on the CHSTH4 busbar without transferring any major disturbance to the western AC system.

C. Light Load Network - South to West BtB Power Flow

1) Filter Tripping

Both the BtB and CTP schemes exhibit good performance following the loss of four 106MVAr filter banks from the western side of the BtB scheme. The representation of Padghe within the equivalent network is pessimistic and sensitive to small disturbances within the western system, hence the tripping of these filters is sufficient to cause oscillations within the equivalent generator at Padghe.

2) Load Rejection Cases

The performance of the remaining poles following the load rejection of either one CTP pole or one BtB pole is good and similar to that exhibited for the base equivalent networks. The BtB frequency controller, which is controlling the southern AC system frequency, does not have a significant effect on the total power order of the BtB HVDC scheme. The nature of the total load within the equivalent circuit is complex in nature because the total powers consumed by the passive loads are dependent on the voltages at the respective busbars. Changes in the network's voltage profile following the pole rejection has a significant effect of the total western AC system load resulting in an increased frequency. In general the average voltages within the western system are lower following the pole rejection resulting in a reduced western AC system load and an increased system frequency. Individual generators in the western system automatically decrease power output in order to lower the system frequency.

3) Network Reconfiguration Cases

Performance is very similar to the base load case, although recovery in the western system is generally faster for single phase faults. Without the Chandrapur West - Chandrapur MSEB transmission lines there is no suitable path for power greater than 100MW to be transmitted into the western system by the BtB link while maintaining a stable AC system. In case 6 discontinuous current operation occurs for 0.4 seconds. Such a short duration of discontinuous current is well within the capabilities of the valve and will not deplete the on-valve power supply.

D. Light Load Network - West to South BtB Power Flow

1) AC Filter Tripping

Both the BtB and CTP schemes exhibit good performance following the loss of four 106MVAr filter banks from the southern side of the BtB scheme.

2) Load Rejection Cases

Good performance is exhibited by the CTP scheme and the remaining pole of the BtB link following the load rejection of a BtB pole. Disturbance to the western AC system is small.

IV. CONCLUSION

The results of the study indicate in all cases that good system stability exists when interconnecting the Chandrapur 2 x 500MW HVDC Back-to-Back Scheme and the Chandrapur-Padghe 2 x 750MW HVDC Transmission Scheme. This is valid even when the equivalent network used for the study has greater sensitivity to changes than the full network model. The study demonstrates that HVDC links in close proximity to each other can show good dynamic performance and fault recovery, even though individual controls are tuned separately and the schemes are not coordinated through telecommunications. RTDS simulation is a valuable tool in evaluating system voltage stability with multiple links and proving oscillation damping.

V. ACKNOWLEDGEMENTS

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