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A FUNDAMENTAL STUDY OF INTER-AREA OSCILLATIONS IN POWER SYSTEMS

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Abstract

A fundamental study of the nature of inter-area oscillations in power systems is presented. The effects of the system structure, generator modelling, excitation type, and system loads are discussed in detail. In the study, both small signal and transient stability analyses are used to determine the characteristics of the system.

Keywords

Inter-area oscillations, modal analysis, mode shape, generators, exciters, loads.

1.0 INTRODUCTION

Electro-mechanical oscillations between interconnected synchronous generators are phenomena inherent to power systems. The stability of these oscillations is of vital concern, and is a prerequisite for secure system operation. For many years, the oscillations observed to be troublesome in power systems, were associated with a single generator, or a very closely connected group of units at a generating plant. Some low frequency unstable oscillations were also observed when large systems were connected by relatively weak tie lines, and special control methods were used to stabilize the interconnected system [1]. These low frequency modes were found to involve groups of generators, or generating plants, on one side of the tie oscillating against groups of generators on the other side of the tie.

Oscillations associated with a single generator or a single plant are called local modes, or plant modes. Local modes normally have frequencies in the range 0.7 to 2.0 Hz. The characteristics of these oscillations are well understood. They may be studied adequately, and satisfactory solutions to stability problems developed, from a system which has detailed representation only in the vicinity of the plant [2].

Oscillations associated with groups of generators, or groups of plants, are called inter-area modes. Inter-area modes have frequencies in the range 0.1 to 0.8 Hz. The characteristics of these modes of oscillation, and the factors influencing them, are not fully understood. They are far more complex to study, and to control. Generally, a detailed representation of the entire interconnected system is required to study inter-area modes [3].

In recent times, many instances of unstable oscillations, involving inter-area modes in large power systems, have been observed, both in studies and in practice [4,5,6]. Such oscillations are, increasingly, becoming a cause of concern. This has led to a renewed interest in the nature of these modes, methods for systematically studying them, and control methods by which they can be stabilized. The Canadian Electrical Association is currently funding a research project, at Ontario Hydro, with the aim of addressing these interests. The objectives of the research are to determine the fundamental nature of low frequency inter-area modes of oscillation, to develop analysis techniques for large power systems, to develop methods for reduced order system modelling, and to develop procedures for designing and modifying system controls.

The results of the first phase of this research, into the fundamental nature of inter-area oscillations, are presented in this paper. In particular, we deal with the effects of the following on inter-area oscillations:

- System structure
- Operating conditions
- Excitation systems
- System loads
- DC links

2.0 DESCRIPTION OF THE STUDY SYSTEM

Inter-area oscillations in large interconnected systems are complex. There are generally many such modes, each involving a large number of generators. The complexity of the system models necessary to determine the stability of specific power systems, obscures the fundamental nature of inter-area modes. Therefore, in order to be able to concentrate on those factors which affect inter-area modes, we have constructed the hypothetical, simple system, shown in Figure 1, which has both inter-area and local modes. Although small, the system parameters, and structure are realistic. The system is particularly useful for parametric studies.

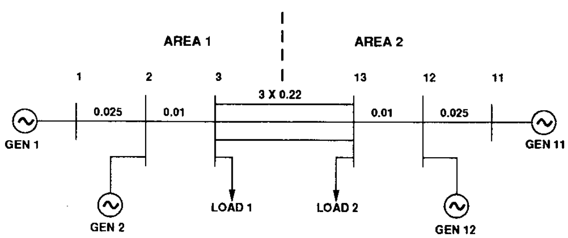

FIGURE 1
Two-Area System

The base system is symmetric; it consists of two identical areas connected through a relatively weak tie. Each area includes two generating units with equal power outputs. The full symmetry of the base system clarifies the effect that various factors have on the inter-area mode. Dynamic data for the generators and excitation systems used in the study are given in Appendix A. In setting up the various power flows used in the studies, capacitors were added as necessary to ensure that the system voltage profile was satisfactory.

Three electro-mechanical modes of oscillation are present in this system; two inter-plant modes, one in each area, and one inter-area low frequency mode, in which the generating units in one area oscillate against those in the other area.

Our experience with large interconnected systems confirms some of the results of our studies using the small system, and we are confident that the general conclusions drawn from our work, will apply to large systems.

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3.0 METHODS OF ANALYSIS

Both small signal stability analysis and transient stability analysis were used, in a complementary way, in our study of inter-area oscillations. Small signal stability analysis, using modal techniques [7], is most appropriate for determining the nature of inter-area modes in power systems. In this case, the system studied was small enough to allow the analysis of all system modes, using MASS computer program [8]. The system eigenvalues, eigenvectors, and participation factors [7] were computed for a number of different system conditions and configurations.

In some instances, in particular in our investigation of the effects of loads, we found it useful to augment the small signal stability analysis with transient stability runs. The graphic nature of the output of the transient stability program aids in picturing the pattern of voltage oscillations, and their relationship with the eigenvectors calculated using modal analysis.

4.0 EFFECTS OF TIE LINE IMPEDANCE AND FLOW

In these tests, all four generating units were represented identically by detailed generator and fast static exciter models. All loads were represented as constant impedances. The tie line impedance was varied by changing the number of tie circuits in service. Power transfers between the two areas were created, either by an uneven distribution of generation between the areas, or by an uneven split of the total system load.

4.1 Effect on Frequency and Damping

The frequency and damping ratio of the inter-area mode for various combinations of tie line power flow and number of tie circuits in service are given in Table 1. As is to be expected; the frequency and damping ratio, of the inter-area mode, drop as the tie line impedance or power flow is increased.

TABLE 1
Effects of Tie Line Impedance and Flow on Frequency and Damping of the Inter-Area Mode

POWER FLOW AREA 1 to 2 (MW)	TIES I/S	GENERATION/LOAD AREA 1	GENERATION/LOAD AREA 2	FREQ (Hz)	DAMPING RATIO
0	3	1400/1367	1400/1367	0.748	0.018
"	2	"	"	0.661	0.011
"	1	"	"	0.513	0.002
400	3	1400/967	1450/1767	0.732	0.015
600	3	1400/767	1457/1967	0.683	0.008
400	1	1400/967	1450/1767	0.359	-0.002
380	1	1800/1367	1045/1367	0.363	-0.021

4.2 Effect on Mode Shape

The normalized eigenvector components, corresponding to rotor speeds, of the inter-area mode, for various tie line impedances and power flows, are shown in Figure 2. The results lead to the following conclusions.

1. In a symmetric system with no power transfer between the two areas, as in tests 1 and 2, the generating units in one area oscillate exactly in anti-phase to the ones in the second area (generator 1 versus 11, and 2 versus 12). The units which oscillate in anti-phase, have the same amplitude. The outer units oscillate more than the inner ones.

2. In an asymmetric system, as in test 3, where the generation in each area supplies the area load and hence, there is no flow on the tie line, the phase difference between the generating units in the two areas is slightly less than 180°.

3. In an asymmetric system with power flow on the tie line, as in tests 4 and 5, the phase difference between the generating units in the two areas is noticeably less than 180°, about 150° in this case. The generating units in the receiving area oscillate with a higher amplitude than the ones in the sending area.

Results of time domain simulations for the systems in test 2 and 4 are shown in Figures 3 and 4 respectively. These results correlate well with those of the eigenvalue/vector analysis.

5.0 EFFECT OF EXCITATION SYSTEMS

5.1 Effect on Frequency and Damping

To test the effect of the excitation systems on the frequency and damping of the inter-area mode we carried out two sets of tests: one set with identical exciters on all four units and the other set with one fast exciter and three slow or manually controlled exciters.

5.1.1 Tests with Identical Exciters

In this set of tests we explored the effect of the following four types of exciters on the inter-area mode:

- Manually controlled exciters
- Slow dc exciters
- Fast static exciters with and without transient gain reduction (TGR).

Only the automatic voltage regulator effects were investigated. Other controls, such as power system stabilizers, were not considered.

We considered two operating conditions: a stressed system with only one tie circuit I/S and 400 MW power transfer from Area 1 to 2, and an unstressed system with no power transfer between the areas. Constant impedance loads were assumed in these tests.

The results, summarized in Table 2, show that the inter-area mode is best damped with manually controlled exciters, and worst damped with fast exciters with TGR. The frequency is highest for fast exciters without TGR and lowest for slow exciters.

TEST	1	2	3	4	5
TEST I/S	3	1	1	1	1
AREA 1 GEN./LOAD	1400 / 1367	1400 / 1367	1120 / 1100	1400 / 967	1800 / 1367
AREA 2 GEN./LOAD	1400 / 1367	1400 / 1367	1700 / 1650	1450 / 1767	1045/ 1367
FLOW AREA 1 TO 2 (MW)	0	0	0	400	380

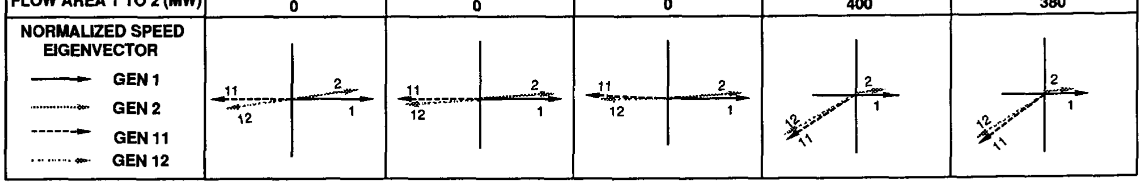

FIGURE 2
Effect of Tie Line Impedance and Flow on Mode Shape

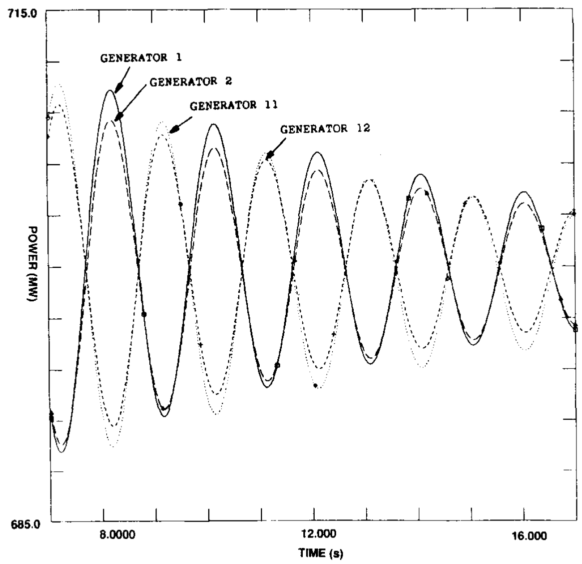

FIGURE 3
Generators' Active Power

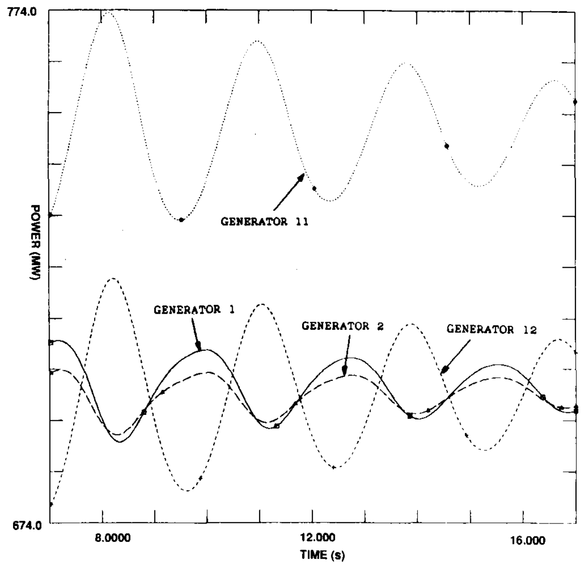

FIGURE 4
Generators' Active Power

5.1.2 Tests with One Fast Exciter

One slow, or manually controlled exciter, was replaced in turn with a fast exciter, with the objective of studying the impact that the relative locations of the generating unit have. Except for the exciter, the generating units are identical; therefore, the differences in the results of the tests are due only to the location of the generating unit having the fast exciter.

The results, summarized in Table 3, lead to the following conclusions:

1. The effect of one fast exciter on the damping of the inter-area mode depends on its location and on the other types of exciters in the system.

   In the case of one fast exciter and three manually controlled exciters, a fast exciter in the receiving area significantly improves the damping of the mode, while a fast exciter in the sending area reduces the damping. In the case of one fast exciter and three slow exciter the opposite is true.

2. The effect of a fast exciter on the frequency of the inter-area mode depends on the location of the exciter. A fast exciter in the sending area increases the frequency, while one in the receiving area reduces it.

In an attempt to understand these results, we examined the open loop (no AVR) transfer function between field voltage and terminal voltage $(E_t(s)/E_{fd}(s))$ for GEN 2 and GEN 12 under various power transfers between the areas and found that this transfer function has a zero around 0.3 Hz. Obviously, when there is no flow on the tie line, this transfer function for GEN 2 is identical to that for GEN 12. As the flow on the tie line is increased, these two transfer functions begin to differ mainly in terms of this zero. When the loop is closed through the exciter, the inter-area pole migrates towards this zero and so causing the difference in the effect of the fast exciter on GEN 2 and GEN 12.

For example, in the case of manually controlled exciters, with no flow on the tie line, the zero has a negative real part. As the inter-area power transfer is increased, the zero associated with the transfer function of the sending area generator, GEN 2, moves to the right and crosses into the right half of the s-plane. The zero associated with the transfer function of the generator in the receiving area, GEN 12, moves to the left.

TABLE 2
Effect of Excitation Systems on Frequency and Damping of the Inter-Area Mode

POWER FLOW AREA 1 to 2 (MW)	EXCITER MODEL	FREQ (Hz)	DAMPING RATIO
0	MANUALLY CONTROLLED	0.481	0.023
"	FAST WITHOUT TGR	0.513	0.002
"	FAST WITH TGR	0.485	-0.016
"	SLOW	0.470	0.004
400	MANUALLY CONTROLLED	0.340	0.033
"	FAST WITHOUT TGR	0.358	-0.002
"	FAST WITH TGR	0.341	-0.017
"	SLOW	0.330	0.009

TABLE 3
Effect of One Fast Exciter on the Inter-Area Mode

	EXCITERS ON THE REMAINING UNITS			
	SLOW		MANUALLY CONTROLLED	
GENERATOR WITH FAST EXCITER	FREQ (Hz)	DAMPING RATIO	FREQ (Hz)	DAMPING RATIO
None	0.330	0.009	0.340	0.033
1	0.419	0.019	0.388	-0.048
2	0.467	-0.010	0.440	-0.062
11	0.286	-0.163	0.289	0.140
12	0.241	-0.283	0.208	0.357

5.2 Effect on Mode Shape

The effect of different generator and excitation system models on the mode shape were explored under two operating conditions: an unstressed system with no power flow on the tie, and a stressed system with 400 MW flow from Area 1 to Area 2 on a single tie circuit.

The following alternative generator-excitation system models were considered:

- Classical machine model (Fixed voltage behind transient reactance)
- Detailed machine model with a manually controlled exciter
- Detailed machine model with a fast exciter (no TGR)
- Detailed machine with a slow exciter

The results of these tests are depicted in Figure 5. It can be seen that in a symmetric system, with no power flow on the tie line, the generating units in one area oscillate in anti-phase to those in the

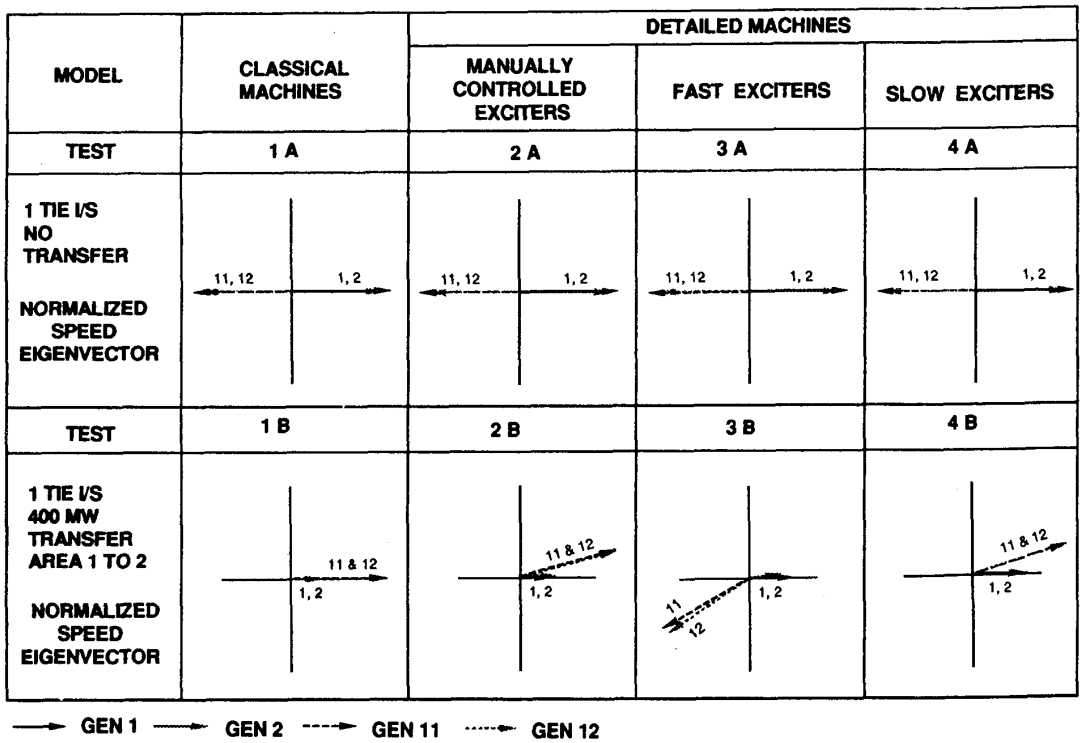

FIGURE 5
Effect of Generator and Excitation Systems
Models on the Inter-Area Mode Shape

second area, regardless of the generators and exciters characteristics. The outer units oscillate with a higher amplitude than the inner ones.

The characteristics of the generators and excitation systems are more crucial in a stressed system as tests 1B-4B show. When the generating units are represented by classical machine models (test 1B) they appear to oscillate in phase, ie., fully coherent. With manual control or with slow exciters (tests 2B and 4B), the generating units in the two areas oscillate with a small phase difference of about 20°. A more typical inter-area oscillation with about 150° phase difference between the areas occurs with fast exciter models, as test 3B shows. In all tests, the generating units in the receiving area oscillate with a higher amplitude than those in the sending area.

Time domain simulations were carried out to gain further insight into the phenomenon observed in tests 1B, 2B and 4B. The last 10 s of a 17 s transient simulation are shown in Figure 6 and 7. In these tests, a constant field voltage was assumed and the loads were represented as constant impedances as in test 2B. The curves in Figure 6 confirm the results of test 2B as far as the phase and amplitude of oscillation are concerned. The power oscillations associated with the generators and the loads are shown in Figure 7. The loads in the two areas, oscillate in phase with each other and in phase with the power outputs of the generators. This indicates that the stressed system, coupled with the lack of voltage control, has altered the power exchange associated with the inter-area mode to include a more significant contribution from the load.

6.0 EFFECT OF LOAD CHARACTERISTICS

The effects of the following load models on the inter-area mode were investigated:

- Constant current
- Constant power
- Induction motor
- Synchronous motor

The nonlinear loads were assumed to constitute 30% of the total load at each bus. The remainder of the load was modelled as constant impedance. The tests were carried out with fast exciters on all generating units and repeated with slow exciters under two system conditions: an unstressed system with no inter-area power transfer and a stressed system with inter-area power transfer of about 380 MW from Area 1 to 2. The loads in the two areas were kept the same, the power flow on the tie line was achieved by adjusting generation so that the effect of the location of the nonlinear load could also be studied.

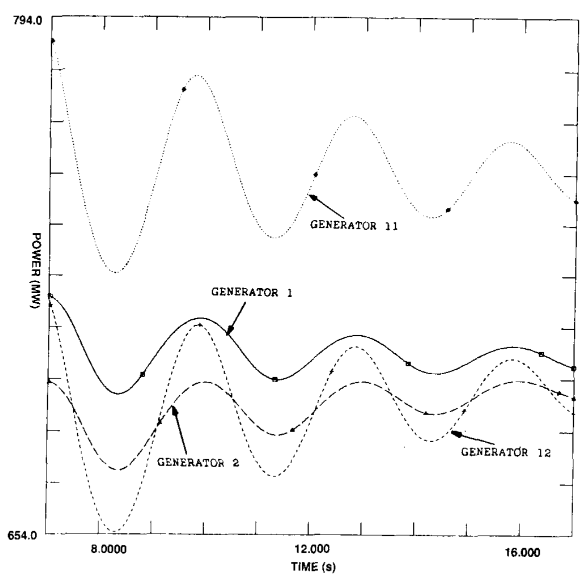

FIGURE 6
Generators' Active Power

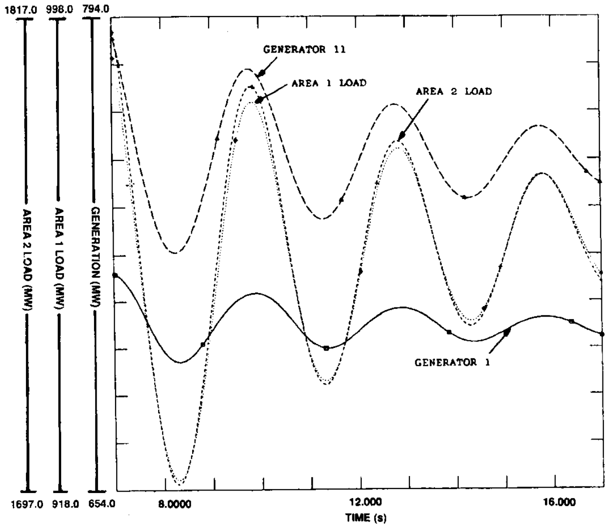

FIGURE 7
Generators' and Loads' Active Power

The results of these tests are summarized in Tables 4A, 4B, 4C and 4D for constant current, constant power, induction motor and synchronous motor load models respectively. In each case for comparison, results are also given for 100% constant impedance load model.

The results show that nonlinear loads, static or dynamic, have more of an impact on the inter-area mode in a stressed system and in a system with slow exciters. This is to be expected since in a stressed system or in a system with slow exciters, the voltage oscillation is higher as compared to an unstressed system, or to a system with fast exciters.

In a stressed system, a nonlinear load in the receiving area has an adverse effect on the damping of the inter-area mode. The opposite is true for a nonlinear load in the sending area, except in the case of induction motor load.

TABLE 4A
Effect of Constant Current Load

POWER FLOW AREA 1 to 2 (MW)	EXCITER TYPE	AREA WITH NONLINEAR LOAD	INTER-AREA MODE FREQ (Hz)	DAMPING RATIO
0	SLOW	—	0.470	0.004
"	"	1 OR 2	0.472	0.005
"	"	1 AND 2	0.475	0.005
380	"	—	0.28	-0.120
"	"	1	0.296	-0.098
"	"	2	0.262	-0.183
"	"	1 AND 2	0.277	-0.158
0	FAST	—	0.513	0.002
"	"	1 OR 2	0.514	0.003
"	"	1 AND 2	0.515	0.004
380	"	—	0.363	-0.021
"	"	1	0.372	-0.015
"	"	2	0.356	-0.028
"	"	1 AND 2	0.365	-0.021

TABLE 4B
Effect of Constant Power Load

POWER FLOW AREA 1 to 2 (MW)	EXCITER TYPE	AREA WITH NONLINEAR LOAD	INTER-AREA MODE FREQ (Hz)	DAMPING RATIO
0	SLOW	—	0.470	0.004
"	"	1 OR 2	0.475	0.005
"	"	1 AND 2	0.480	0.006
380	"	—	0.280	-0.120
"	"	1	0.313	-0.081
"	"	2	0.244	-0.259
"	"	1 AND 2	0.274	-0.195
0	FAST	—	0.513	0.002
"	"	1 OR 2	0.515	0.004
"	"	1 AND 2	0.516	0.006
380	"	—	0.363	-0.021
"	"	1	0.380	-0.008
"	"	2	0.349	-0.036
"	"	1 AND 2	0.367	-0.021

TABLE 4C
Effect of Induction Motor Load

POWER FLOW AREA 1 to 2 (MW)	EXCITER TYPE	AREA WITH MOTOR LOAD	INTER-AREA MODE FREQ (Hz)	DAMPING RATIO
0	SLOW	—	0.470	0.004
"	"	1 OR 2	0.471	0.012
"	"	1 AND 2	0.472	0.020
380	"	—	0.280	-0.120
"	"	1	0.263	-0.199
"	"	2	0.258	-0.186
"	"	1 AND 2	0.246	-0.268
0	FAST	—	0.513	0.002
"	"	1 OR 2	0.513	0.005
"	"	1 AND 2	0.513	0.008
380	"	—	0.363	-0.021
"	"	1	0.375	-0.008
"	"	2	0.348	-0.029
"	"	1 AND 2	0.360	-0.015

TABLE 4D
Effect of Synchronous Motor Load

POWER FLOW AREA 1 to 2 (MW)	EXCITER TYPE	AREA WITH MOTOR LOAD	INTER-AREA MODE FREQ (Hz)	DAMPING RATIO
0	SLOW	—	0.470	0.004
"	"	1 OR 2	0.474	0.009
"	"	1 AND 2	0.478	0.013
380	"	—	0.280	-0.120
"	"	1	0.330	0.019
"	"	2	0.234	-0.313
"	"	1 AND 2	0.272	-0.151
0	FAST	—	0.513	0.002
"	"	1 OR 2	0.510	0.006
"	"	1 AND 2	0.507	0.009
380	"	—	0.363	-0.021
"	"	1	0.379	0.002
"	"	2	0.344	-0.037
"	"	1 AND 2	0.360	-0.011

7.0 EFFECT OF A DC LINK ON AN INTER-AREA MODE

In this study, the fundamental effects of a dc link on an inter-area low frequency oscillation were investigated. The test system was created by adding a dc link to the two-area system, described previously. Two system configurations, which include a dc link were considered:

- A dc link parallel to the ac tie line between the two areas, as shown in Figure 8
- A dc link joining a remote plant to an ac system, as shown in Figure 9

We considered only the most basic controls associated with a dc link, that is, current, voltage, and extinction angle; modulation of the dc link to improve stability was not considered.

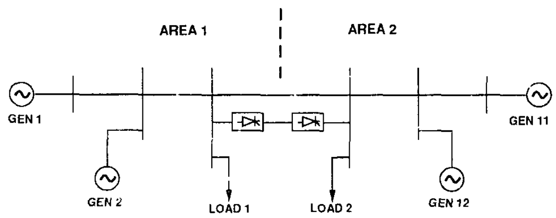

FIGURE 8
Two-Area System with Parallel dc-ac Tie Lines

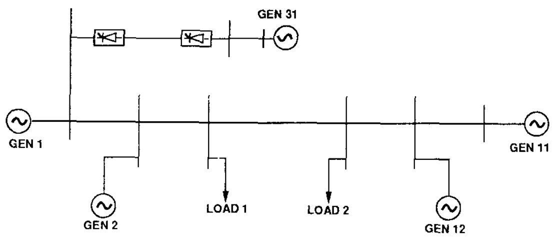

FIGURE 9
Two-Area System with a dc Link to Remote Generation

7.1 System with Parallel dc-ac Tie Lines

The characteristics of the inter-area oscillations were investigated for various power flows on the ac and dc links, as shown in Figure 8. Two types of converter controls were considered:

- The rectifier controls dc current and the inverter controls voltage
- The rectifier controls dc current and the inverter controls extinction angle (GAMA)

The tests were carried out for two types of excitation systems, fast and slow.

The results of these tests are summarized in Tables 5 to 7. They show that a dc tie in parallel with the ac tie has the following effects:

1. The addition of a dc tie line has a similar effect on the inter-area mode to the addition of an ac tie circuit; adding the dc link without increasing the total power transfer between the areas raises the frequency of the mode.

2. The addition of the dc tie line has a small impact on the damping of the inter-area mode.

3. The effects of adding a dc tie on the inter-area mode are basically the same with fast or slow excitation systems.

4. The inter-area mode is not very sensitive to the type of dc controls (basic) used.

5. The inter-area mode does not exist in a system in which the two areas are joined only by a dc link.

TABLE 5
Parallel dc-ac Links
No Power Transfers

INVER	FLOW			INTER-AREA MODE			
				EIGENVECTOR MAG/PHASE		FREQ	DAMPING
CONT	DC	AC	EXC	GEN 1	GEN 11	(Hz)	RATIO
-	O/S	0	SLOW	1.0/0.0	1.0/180.0	0.470	0.004
VOLT	0	"	"	1.0/0.0	1.0/179.1	0.470	0.000
GAMA	"	"	"	1.0/0.0	1.0/178.2	0.470	-0.006
-	O/S	0	FAST	1.0/0.0	1.0/180.0	0.513	0.002
VOLT	0	"	"	1.0/0.0	1.0/179.8	0.513	0.001
GAMA	"	"	"	1.0/10.0	1.0/179.7	0.514	-0.001

TABLE 6
Parallel dc-ac Links
200 MW Transfer on Each Link

INVER	FLOW			INTER-AREA MODE			
				EIGENVECTOR MAG/PHASE		FREQ	DAMPING
CONT	DC	AC	EXC	GEN 1	GEN 11	(Hz)	RATIO
-	O/S	400	SLOW	0.5/13.5	1.0/-3.4	0.330	0.009
VOLT	200	200	"	0.4/176.5	1.0/0.0	0.470	0.018
GAMA	"	"	"	0.3/177.7	1.0/0.0	0.469	-0.004
-	O/S	400	FAST	0.4/152.3	1.0/5.1	0.358	0.002
VOLT	200	200	"	0.9/170.1	1.0/0.0	0.500	0.003
GAMA	"	"	"	0.9/169.0	1.0/0.0	0.498	-0.002

TABLE 7
Parallel dc-ac Links
Total Transfer of 600 MW

INVER	FLOW			INTER-AREA MODE			
				EIGENVECTOR MAG/PHASE		FREQ	DAMPING
CONT	DC	AC	EXC	GEN 1	GEN 11	(Hz)	RATIO
-	O/S	400	SLOW	0.5/13.5	1.0/-3.4	0.330	0.009
VOLT	200	400	"	0.3/27.9	1.0/0.0	0.373	-0.036
GAMA	"	"	"	0.4/17.5	1.0/0.0	0.360	0.005
-	O/S	400	FAST	0.4/152.3	1.0/5.1	0.358	-0.002
VOLT	200	400	"	0.5/155.4	1.0/4.0	0.381	0.013
GAMA	"	NO AC LINK	"	INTER-AREA MODE DOES NOT EXIST			

7.2 System with a dc Link to Remote Generation

This system consists of a remote generator, GEN 31, connected to the two-area system through a dc link. The inverter is connected to Area 1 close to GEN 1. The power supplied by the remote generator was taken off the output of GEN 1, in order to keep the same system load.

The tests performed are similar to the ones described in the previous section. The flow on the dc link, the excitation system, and the dc controls were varied in these tests. The results are summarized in Tables 8 and 9.

Table 8 concerns tests with 400 MW supplied by the remote generation; GEN 31 and GEN 1 rated at 600 and 900 MVA respectively.

Table 9 concerns tests with 650 MW supplied by the remote generator; GEN 31 and GEN 1 rated at 900 and 100 MVA respectively.

The results of Table 8 (400 MW supplied by the dc) lead to the following conclusions:

1. With fast exciters on all generating units, the addition of the dc link has little effect on the inter-area mode, mainly a small increase in frequency.

2. With slow exciters, the effect of adding the dc link is to increase the frequency and the damping ratio of the inter-area mode.

3. The participation factor of the remote generating unit in the inter-area mode is zero, although the mode is present in the speed of this unit.

4. The inter-area mode is not very sensitive to the type of dc controls (basic) used.

The results of Table 9 (650 MW supplied by the dc) lead to the following conclusions:

1. With fast exciters, the effect of adding the dc link is mainly to increase the frequency of the inter-area mode.

2. When slow exciters are used, the addition of the dc link significantly reduces the damping of the inter-area mode.

3. As in the previous case, the participation factor of the remote generating unit in the inter-area mode is zero, although the mode is present in the speed of this unit.

The fact that the participation factor, for the remote unit in the inter-area mode, is zero, implies that a stabilizer on this unit would have no effect on the inter-area mode.

TABLE 8
dc Link to Remote Generation
400 MW Supplied Through the dc Link

		INTER-AREA MODE				
		EIGENVECTOR SPEED PARTICIPATION MAG/PHASE (DEG)				
INVER CONT	EXCITERS	GEN 1	GEN 11	GEN 31	FREQ (Hz)	DAMPING RATIO
NO DC	FAST	0.4/0.0	1.0/-147.2	–	0.358	-0.002
		0.44	0.98	–		
GAMA	"	0.5/156.1	1.0/3.5	0.0/131.0	0.372	0.002
		0.50	1.00	0.00		
VOLT	"	0.5/155.7	1.0/3.6	0.0/-143.6	0.372	0.000
		0.50	1.00	0.00		
NO DC	SLOW	0.5/17.6	1.0/0.0	–	0.330	-0.004
		0.50	1.00	–		
GAMA	"	0.3/22.7	1.0/0.0	0.2/3.7	0.392	0.018
		0.30	1.00	0.00		
VOLT	"	0.3/17.0	1.0/10.0	0.0/90.0	0.380	0.032
		0.30	1.00	0.00		

TABLE 9
dc Link to Remote Generation
650 MW Supplied Through the dc Link

		INTER-AREA MODE				
		EIGENVECTOR SPEED PARTICIPATION MAG/PHASE (DEG)				
INVER CONT	EXCITERS	GEN 1	GEN 11	GEN 31	FREQ (Hz)	DAMPING RATIO
NO DC	FAST	0.4/0.0	1.0/147.2	–	0.358	-0.002
		0.44	0.98	–		
GAMA	"	0.8/159.0	1.0/4.4	0.1/138.5	0.426	0.004
		0.1	1.0	0.0		
VOLT	"	0.8/157.0	1.0/4.7	0.0/-144.5	0.435	-0.019
		0.1	1.0	0.0		
NO DC	SLOW	0.5/17.6	1.0/0.0	–	0.330	0.004
		0.5	1.0	–		
GAMA	"	0.5/17.9	1.0/-42.0	1.0/0.0	0.385	-0.204
		0.1	1.0	0.0		
VOLT	"	0.7/42.2	1.0/0.0	0.0/113.6	0.321	-0.302
		0.1	0.9	0.0		

8.0 DISCUSSION AND CONCLUSIONS

We have presented the results of our study into the fundamental nature of inter-area modes of oscillation in power systems. The study used, in a complimentary manner, small signal and transient stability analyses applied to a small system, specially designed to exhibit both local and inter-area oscillations. The following reiterates the salient points of our research.

8.1 System Structure

The natural frequency and damping of the inter-area mode depends on the weakness of the tie and on the power transferred through the tie. These results were expected and confirm our experience with large systems.

The action of a dc link, parallel to the ac tie, is to strengthen the tie as expected. Connection of two areas, through a dc link alone, does not introduce an inter-area mode owing to the asynchronous nature of a dc tie. Indeed, one reason for the growth of dc links is to allow interconnection without the risk of inter-area mode instability. Generators connected radially through a dc link, although driven to respond to the mode between two areas connected by an ac tie, have no significant impact on the inter-area mode. The dc link itself does, however, affect the inter-area mode: the frequency of the mode is increased and the damping is decreased.

8.2 Generator Models and Excitation Type

Our results on the effects of generator modelling, excitation systems and loads are rather more enlightening.

Under zero tie line flow conditions, the inter-area mode shape clearly shows that, during the oscillation, the generators in one area swing in anti-phase with the generators in the other area. This characteristic is independent of both the generator modelling detail and the type of excitation system.

With non-zero tie line flow, the mode shape alters considerably, and the generators in the two areas no longer oscillate purely in anti-phase. With classical generators models and with detailed generator models having manual and slow excitation control, the generators in both areas swing almost in phase. With detailed generator models and fast excitation systems, the generators in one area are almost in anti-phase with those in the other area. We have shown that the system load plays a significant part in the oscillatory process, under these stressed conditions. The effect is more pronounced when the excitation controls are slow acting, and thus less able to control the load voltage oscillations. In an incremental sense, the load acts as a source and sink of energy, which is exchanged with the kinetic energy of the generators in the oscillatory process. Classical generator models, while giving reasonable estimates of inter-area mode frequency, give mode shapes which are approximations of those for systems having slow or manually controlled exciters.

The effect of a single fast exciter depends on its location in the system, and on the type of control on the other generators. When placed at the receiving end, it causes a reduction in the frequency of the inter-area mode. When placed at the sending end, it increases the frequency of the inter-area mode. With manual excitation control on the other units, the damping of the inter-area mode is increased if the fast exciter is placed at the receiving end, and decreased if the fast exciter is placed at the sending end. With slow exciter control on the other units, a single fast exciter reduces the damping of the inter-area mode. The reduction in damping is worse when the fast exciter is placed at the receiving end. From a mathematical point of view, the difference in location causes a difference in the zeros, associated with excitation control transfer function. Practically, it implies tighter control of the system voltage close to the fast exciter, and a consequent change in the action of the system loads.

In general, the results demonstrate that the effect of a fast exciter on an inter-area mode is not as easily predictable as its effect on a local mode, where a fast exciter normally increases the frequency of the mode and reduces its damping. The results also show that the use of transient gain reduction has a detrimental effect on the damping of inter-area modes; this is consistent with our experience with a large scale system [3].

8.3 Load Models

Non-linear and dynamic load models at the receiving end cause a detrimental effect on the damping of the inter-area mode, while similar load models at the sending end have a slightly beneficial effect. With fast excitation systems, the effects of load are much smaller than with slow excitation systems.

8.4 Implications on Study Practice

In todays, complex, interconnected power systems it is important to fully understand the basis for modelling the overall system. Models of generators and their controls must be accurate within the range of influence on critical inter-area modes. The use of a wrong model, or an over simplified model, in a critical location may produce completely erroneous results.

The stability of an inter-area mode is not a simple function of the load characteristics; it depends also on the operating conditions and on the location of the load. This implies that the wide spread practice of using a global load model that is believed to be conservative is risky. Because of the variation in the effect of load models, a large number of sensitivity tests is required to verify that a certain load model is indeed conservative.

8.5 Future Work

In this study, we have deliberately ignored the effect of special controls (such as power system stabilizers and dc modulation controls) on the stability of inter-area modes. Obviously, these controls are vital to ensure the secure operation of modern highly interconnected, highly stressed power systems. In order to perform satisfactorily under varying system conditions, from the viewpoint of all aspects of system performance, the design of these controls needs to be robust. Under the research project funded by the Canadian Electrical Association, we are currently working on this aspect of inter-area oscillations.

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APPENDIX A

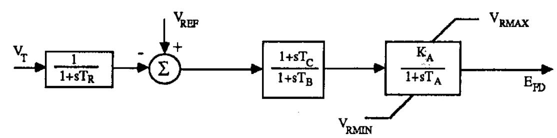
SYNCHRONOUS GENERATOR

$R_a = 0.0025$ $X_d = 1.8$ $X_q = 1.7$ $X_l = 0.2$ $X'_d = 0.3$ $X'_q = 0.55$ $X''_d = X''_q = 0.25$

$T'_{do} = 8.0$ s $T'_{qo} = 0.40$ s $T''_{do} = 0.03$ s $T''_{qo} = 0.05$ s

$H = 6.5$ RATING = 900 MVA

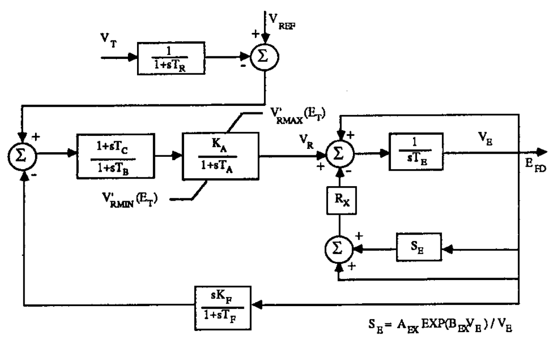
FAST EXCITER (STATIC EXCITER)



$K_A = 200$ $T_R = 0.01$

$T_C = T_B = 0$ (NO TGR) $T_C = 1.0$ $T_B = 10.0$ (WITH TGR)

SLOW EXCITER (SELF EXCITED DC GENERATOR EXCITER)



$K_A = 20.0$ $T_A = 0.055$ $T_E = 0.36$ $A_{EX} = 0.00555$ $B_{EX} = 1.075$ $K_F = 0.125$ $T_F = 1.8$ $T_R = 0.05$

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