Impacts of HVAC Interconnection Parameters on Inter-area Ocsillation

Mai H. Nguyen[1,2], Tapan K. Saha[1,2], Mehdi Eghbal[2]

[1] School of Information Technology & Electrical Engineering
The University of Queensland
Brisbane, Australia

[2] Queensland Geothermal Energy Centre of Excellence
The University of Queensland
Brisbane, Australia

Abstract-**This paper investigates the impacts of distance and power flow of transmission line interconnections on the inter-area oscillations. The effectiveness of Power System Stabiliser (PSS) in damping the inter-area oscillations is studied considering various combinations of interconnection power flows and distances. Simulations are carried out on a two area 4 generator test system as well as on the simplified South East Australian power system. Time domain simulations are also used to explain the behaviour of the system subjected to a small disturbance. Simulation results show that the inter-area mode is less stable when the length of the interconnection increases. However, with the presence of PSS, satisfactory performance is observed. It is also shown that power flow of the interconnection does not have a considerable impact on the damping ratio.**

Keywords-Interarea oscillation; interconnection; small signal stability;damping

I. INTRODUCTION

As the sources of fossil energy decrease and demands for electricity increase, renewable energy gains more and more importance throughout the world, especially when pricing the Greenhouse Gas (GHG) emissions is started. Major zero-emission energy sources are: hydro, wind, solar, biomass, geothermal and ocean. Among the renewable energy sources, only geothermal energy can supply base-load with no emissions or environmental hazards and has enough reserves for many more years. Remote location of geothermal resources is one of the major challenges in large scale integration of geothermal power into the Australian electricity network. To deliver the power to the load centres, building long distance transmission lines is inevitable.

Inter-area oscillation is an important issue for long distance interconnections. The inter-area oscillations are caused by interactions among large groups of generators at two end of an interconnection. The analysis of low frequency electromechanical oscillations in longitudinal power systems has attracted much attention of several researchers and utilities in the last few decades [1, 2]. A fundamental study on inter-area oscillations in power system has been done in [3, 4]. Installing power system stabilizer (PSS) inside synchronous generators is an effective method in damping system oscillations. Different types of stabilizers are based on different input signals [5].

An investigation on the impacts of connecting large wind-farms to weak networks with long transmission lines on inter-area mode was conducted in [6]. It has been shown that the inter-area mode for wind turbine tends to become more stable when the real power generation of the wind turbine increases and wind turbine generator does not interface with the network, whereas the opposite is true for the system with synchronous generator.

The impacts of line impedance and power flow were analysed in [3]. Manually controlled and fast exciter models were considered. However, the impacts of PSS on the damping of the inter-area mode were not studied. It has been shown that the frequency and damping ratio of the inter-area mode decreases when the line impedance or power flow increases.

In this paper, the impacts of interconnection distance and power flow on the inter-area oscillations are investigated. The effectiveness of PSS in damping the inter-area oscillations is studied considering various combinations of interconnection power flow and distances. Small signal stability analysis is conducted to determine the characteristics of a two area power system [7] and Simplified Southern Eastern Australian network [8]. Time domain simulations are also used to explain the behaviour of system subjected to a small disturbance. Simulations are carried out using Power Factory software package [9] and Mudpack [10]. The results explain the fundamental nature of inter-area oscillations while taking into account the effect of PSS.

The rest of the paper is organized as follows. Section II reviews a background of small signal stability and inter-area oscillations. Sections III and IV discuss and demonstrate the simulation results on a two area sample power system and 14-generator simplified Australian Southern and Eastern power system, respectively. The last section explains concluding remarks and future perspectives.

II. BACKGROUND

Small signal stability is the ability of a power system to maintain synchronism when subjected to small disturbances, such as changes in power demand. The phenomenon is analysed using linear techniques based on valuable information about the natural dynamic characteristics of the system [7].

In many cases, instability and loss of synchronism are initiated by some small disturbances in the system resulting oscillatory behaviour. Instability may result from steady increase in generator rotor angle or rotor oscillation of increasing amplitude. In a multi machine power system, the oscillations can be divided into two categories [7]:

- Local oscillation, in which a single generator participates in an oscillation mode.

- Inter-area oscillation, in which generators in one region oscillate against another group of generators in another region, through long interconnected transmission lines.

In fact, there are also many other oscillation modes, which belong to power system controllers and generator exciters. The term local and inter-area oscillations refer to modes in which the generator rotors are the strongest participant. Hence these oscillations can be referred as electromechanical oscillations. Typically the electromechanical modes will become weakly damped as the power transfer level increases. As a result, the power transfer capacity is limited. In extreme cases, these oscillations can lead to severe problems, such as relay malfunctioning, or power system blackout. For this reason and to study the power system small signal stability thoroughly, detailed models of the generators and also various controllers (PSS/exciters) are required.

The most common approach for studying power system small signal stability is to use a linearised model of the power system. A power system can be described using a set of ordinary differential equations in the following form:

$$\dot{x} = f(x, u) \qquad (1)$$

Where x is vector of state variables, u is vector of control input (or input variables). The state variables may be physical quantities in a system such as angle, speed, voltage, or they may be abstract mathematical variables associated with the differential equations describing the dynamics of the system.

The output variables which can be observed in the system maybe expressed in the following way as a function of state variables and input variables.

$$y = g(x, u) \qquad (2)$$

Linearization

$$\Delta\dot{X} = A\Delta X + B\Delta U \qquad (3)$$

$$\Delta Y = C\Delta X + D$$

A: State or Plant Matrix
B: Control or Input Matrix
C: Output Matrix
D: Feed forward Matrix

A. The eigenvalues and eigenvectors

The values of scalar parameter λ that satisfy the following equations are known as eigenvalues of matrix A. The complex eigen values ($\lambda_i = \alpha_i \pm j\beta_i$) are only considered.

$$\det(A - \lambda I) = 0 \qquad (4)$$

The frequency of oscillation in Hz, representing the actual or damped, is given by:

$$f_i = \frac{\beta_i}{2\pi} \qquad (5)$$

For a particular eigen value (λ_i), the damping ratio (ζ_i) is defined as:

$$\xi_i = \frac{-\alpha_i}{\sqrt{\alpha_i^2 + \beta_i^2}} \qquad (6)$$

The damping ratio determines the rate of decay of the amplitude of the oscillation. The system is only stable if the damping ratios of all the modes are positive. The larger the damping ratio is, the quicker the oscillation is damped.

Right eigenvector: By solving $A\phi_i = \lambda_i\phi_i$ for i=1, 2 … n, ϕ_i a column vector can be obtained for each eigenvalue; ϕ_i is known as the right eigenvector.

Left eigenvector: By solving $\psi_i A = \psi_i\lambda_i$ for i=1, 2 ... n, ψ_i a row vector can be obtained for each eigenvalue; ψ_i is known as the left eigenvector.

Since eigenvectors are determined only to within scalar multiplier, it is common practice to normalize these vectors so that $\phi_i\psi_i = 1$

Dominant state variables in a particular mode can be identified with the help of participation factors. *Participation factors* are combination of left and right eigenvectors.

$$P = [P_1, P_2, \ldots, P_n] \qquad (7)$$

$$P_i = \begin{bmatrix} P_{1i} \\ P_{2i} \\ \vdots \\ P_{ni} \end{bmatrix} = \begin{bmatrix} \phi_{1i}\Psi_{i1} \\ \phi_{2i}\Psi_{i2} \\ \vdots \quad \vdots \\ \Phi_{ni}\Psi_{in} \end{bmatrix} \qquad (8)$$

In general $P_{ki}=\phi_{ki}\psi ik$; ϕ_{ki} is the k^{th} entry of the right eigenvector with i^{th} mode and ψ_{ik} is the k^{th} entry of left eigenvector associated with i^{th} mode. Participation factor is a measure of relative participation of the k^{th} state variable in the i^{th} mode.

As stated above, oscillation modes can be divided into electromechanical modes and control modes. One can determine that a mode is an electromechanical mode if the generator speed variables have largest participation factor in this mode. Besides, participation factors also help to identify local modes (only one generator with significant participation factor) and inter-area mode (several inter-area with significant participation factors) [7].

III. INTER-AREA OSCILLATION ANALYSIS FOR A SIMPLE POWER SYSTEM

The study is carried out on a two area power system having 11 buses and 4 generators with total generation of 2820MW. Data for this system are taken from [7]. All the modelling details provided within the base set of data are retained and represented in the analysis. Fig.1 illustrates the test system.

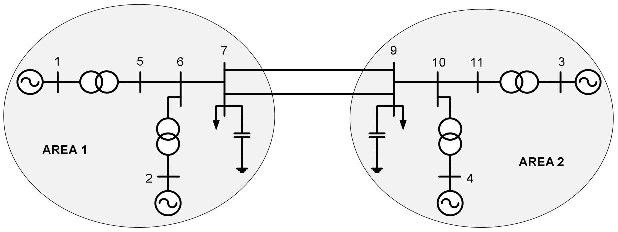

Figure 1. Two area test system [7]

The interconnection, connecting areas 1 and 2, is originally 220km and transfers 400MW power from area 1 to area 2. The analysis performed is based on the information provided with regard to the existing and planned increases in interconnection distance and power transferred level between two areas.

Three different cases are analysed: DC exciter, high gain exciter without PSS and high gain exciter with PSS are installed at all the generators. Excitation and PSS models are taken from [7].

There are two local modes and one inter-area mode for the original system. Detail information for inter-area mode of the system with three different excitation and PSS systems are shown in Table I. As can be seen in Table I, system is stable with DC exciter. With high gain exciter, PSSs need to be installed to maintain the small signal stability.

TABLE I. EIGENVALUE INFORMATION OF THE TWO AREA TEST SYSTEM[7]

	Real	Imaginary	Freq.	Damp. ratio
DC exciter	-0.04664	3.063131	0.48751	0.015226
High gain exciter	0.18716	3.269983	0.52043	-0.05714
High gain exciter +PSS	-0.13926	3.605416	0.57382	0.038597

A. Impact of interconnection distance on the damping of inter-area oscillation

The impact of interconnection distance on the damping ratio is analysed for all the cases. Length of line 7-9 is increased from 50km to 400km.

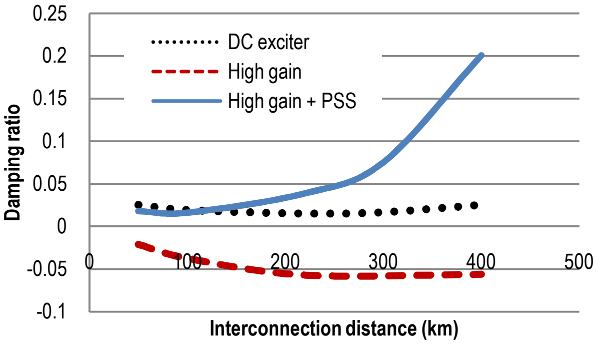

Figure 2. Impact of interconnection distance on damping ratio of inter-area oscillation

The parameters of line 7-9 are r_o=0.001 pu/km and x_o=0.01pu/km. When length of the line increases, normally, the increase in the line resistance adds more damping in the system. However, the reactance of the line increases much more than the line resistance; which in this case is considered to be 10 times. Therefore, the system is expected to be less stable when the length of the line increases. It can be seen in Fig. 2 that the oscillation damping behaviour of the system with DC exciter and high gain exciter are normal when the interconnection distance increases from 50km to 400km. Nevertheless, with the presence of PSS, the system is damped much better for longer interconnections. The damping ratio of 400km line is 20%, which is more than 5 times larger than that of 220km line, where it is 3.86%. Fig. 3 shows the movement of eigenvalues when the length of the interconnection increases.

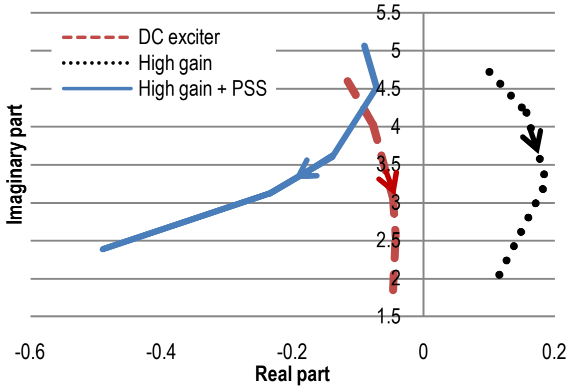

Figure 3. Eigenvalue movement when the interconnection distance increased

The eigenvalue of inter-area mode for high gain exciter with PSS system moves far from vertical axis when the length of the interconnection increases. In this case, the system becomes more stable as the length of the line increases. On the other hand, the eigenvalue of inter-area mode of the system with DC exciter moves toward the vertical axis. The movements of eigenvalue show that the system with high gain exciter and PSS is more stable when the line is longer. This conclusion appears to be in agreement with the one draws from the results of the above mentioned damping ratio simulations.

The time domain simulation was tested for DC exciter and high gain exciter with PSS systems. Fig.4 and Fig.5 show the active power response of generator 1 when a 0.1% increase in loadability of bus 9 occurred at 0.5s for DC exciter and high gain exciter with PSS systems, respectively.

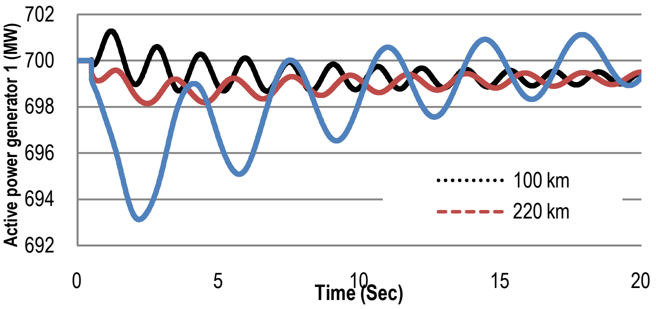

Figure 4. Impact of the interconnection distance on the active power of generator 1 for system with DC exciter

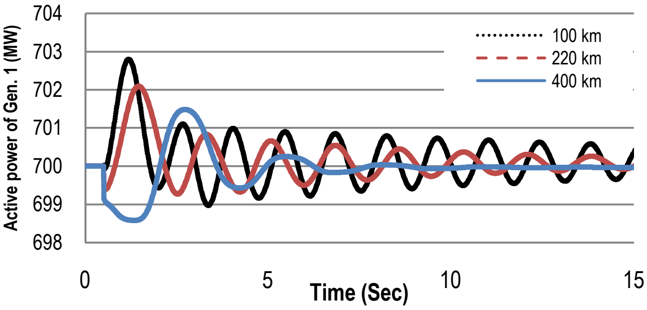

Figure 5. Impact of the interconnection distance on the active power of generator 1 for system with high gain exciter and PSS

It is evident from Fig. 4 that without PSS, the oscillation amplitude is larger for the longer transmission line interconnections. Fig.5 shows that with the presence of PSS, oscillations are damped faster for longer transmission line interconnection. This can be explained that the damping of the closed loop system with PSS is better for longer interconnections. In fact when the length of the interconnection increases, the open loop system becomes weaker but, the influence of the PSS becomes stronger. Hence, the performance of the closed loop system increases. Fig.6 illustrates the active power output of generator 1 after a 10% increase in the load at bus 9. It is observed that the system with 400 km interconnection becomes unstable while the system with shorter interconnections remains stable after the disturbance. It is shown that although PSS is more effective in damping the oscillations for longer interconnections, the system becomes less stable to small disturbances.

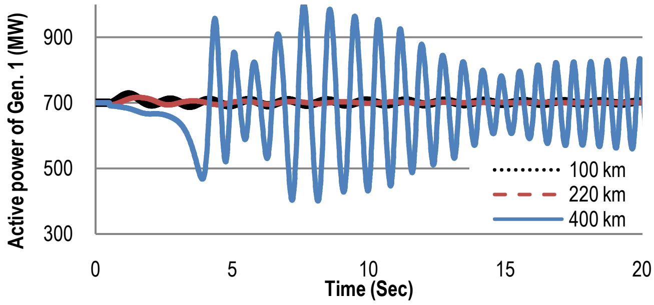

Figure 6. Active power of generator 1 for the system with high gain exciter and PSS for different interconnection distances when load 9 increased by 10%

B. *Impact of transmitted power on inter-area oscillation*

The impact of the level of the transmitted power on damping ratio is also investigated. The power flow from bus 7 to bus 9 is varied by adjusting the loads at two ends of the interconnection to maintain the total balance between loads and generation. Fig. 7 shows the damping ratio of all cases for various levels of the transmitted power.

The damping ratio increases with the increase in power flow of the line. Therefore, it could be concluded that the influence of PSS becomes more effective when the system is weaker.

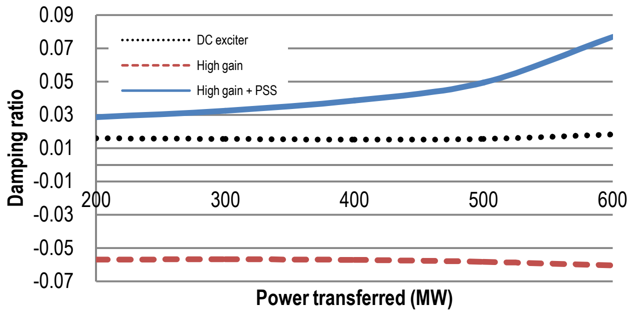

Figure 7. Impact of power transferred level on damping of inter-area oscillation

By comparing Fig. 2 and Fig. 7, it is observed that the length of the interconnection has more impact on the damping ratio than the level of the transmitted power.

For the two-area test system, the inter-area mode is less stable when the length of the interconnection or the level of transmitted power increases. However, with the presence of PSS, damping ratio increases and consequently the oscillations are damped faster.

IV. INTER-AREA OSCILLATION ANALYSIS FOR SIMPLIFIED SE AUSTRALIAN SYSTEM

To verify the above findings for a larger and more complex system, the simplified Southern and Eastern Australian power system [8] has been used. Fig.8 illustrates the single line diagram of the system comprising of 5 areas and 14 generators. Data for this system is available in [8]**.** In the original system, total generation and load under heavy load condition are 23,030MW and 22,300 MW, respectively and is considered as the base case in this study. Areas 1 and 2 are connected to each other by four parallel 330KV HVAC lines transmitting a total of 1134MW power from area 2 to area 1. Mudpack [10] is used to conduct the small signal stability analysis for this system.

Table II lists all the electromechanical modes of the system. It is evident that without PSS, the system has 5 unstable modes, which are modes 2, 3, 11, 12 and 13. Using PSS improves the damping of the system significantly and all these unstable modes become stable. In this system, mode 12 is the dominant and damping ratios with and without PSS are 12.4% and -1.7%, respectively. Fig. 9 shows the eigenvectors for mode 12. Three groups of generators participating in this mode are generators in area 1, 2, and 3; generators in area 4 and generators in area 5.

A. *Impacts of the length of the interconnection on the damping of dominant oscillation*

As stated above, mode 12 is the oscillation between groups of generators in area 4, areas 1, 2, 3 and area 5. Therefore, the interconnection between area 2 and 4 and the one between area 3 and 5 are involved in this oscillation. Therefore, the impacts of the length of the interconnection between areas 3 and 5 on the damping ratio of mode 12 are examined by increasing the length of the line connecting buses 315 and 509 from 1 to 4 times. The result is shown in Fig. 10.

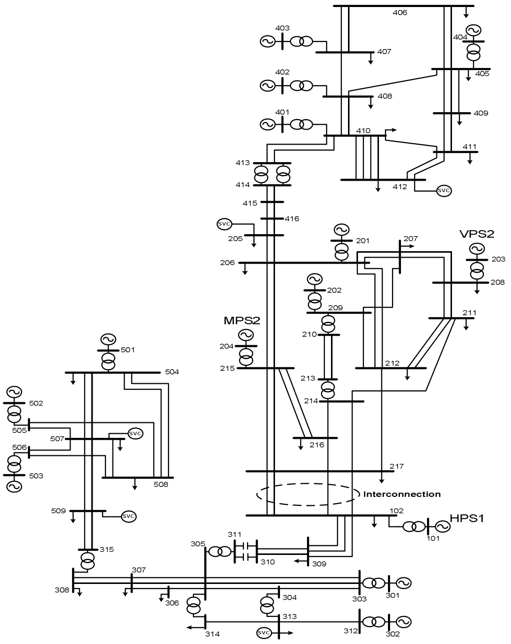

Figure 8. Simplified SE Australian power system diagram [8]

TABLE II. THE ELECTROMECHANICAL MODES OF SIMPLIFIED SE AUSTRALIAN POWER SYSTEM

Mode	PSS on		PSS off	
	Real	Imaginary	Real	Imaginary
1	-0.198	10.396	-2.113	10.277
2	0.13	9.619	-2.012	9.848
3	0.052	8.976	-1.935	9.374
4	-0.558	8.634	-2.505	8.854
5	-0.108	8.539	-1.994	8.454
6	-0.196	8.234	-1.998	8.3
7	-0.495	8.104	-1.929	8.542
8	-0.525	7.917	-1.775	7.73
9	-0.137	7.74	-2.016	7.892
10	-0.621	7.431	-1.876	7.612
11	0.082	4.064	-0.751	3.86
12	0.049	2.829	-0.332	2.659
13	0.002	2.092	-0.267	2.014

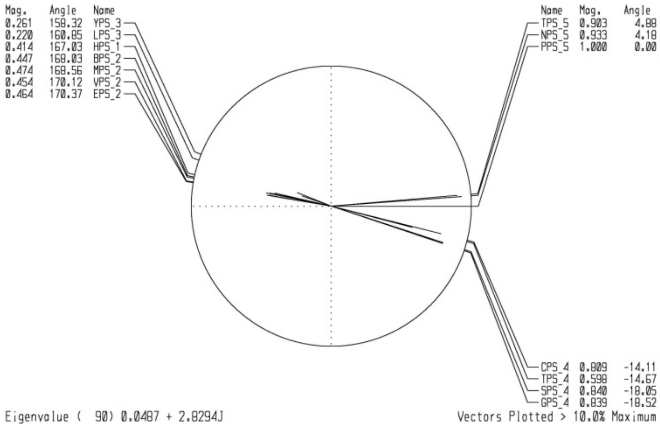

Figure 9. Eigenvectors of the dominant mode (mode 12) in simplified SE Australian system

The impact of the length of the interconnection on the damping ratio of the Simplified SE Australian system is similar with the results for the two area test system, explained in section II. In case of longer interconnections without PSS, the damping ratio of inter-area mode declines; while with PSS, damping ratio increases.

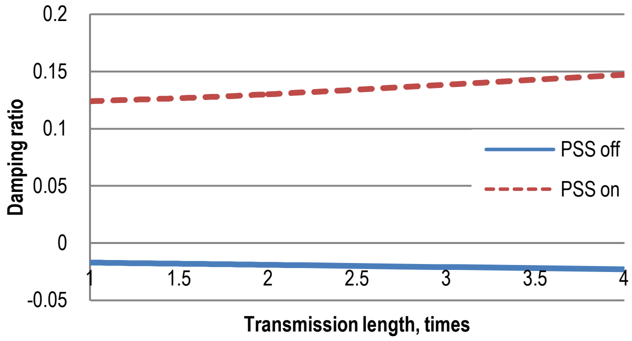

Figure 10. Impacts of the interconnection distance betwwen area 3 and 5 on dominant mode (mode 12)

B. *Impacts of interconnection distance on the damping of other inter-area modes*

The impacts of the length of interconnection between bus 102 and bus 217 on modes 7, 12 and 13 are analysed in this section by increasing the length of the line by up to 4 times. Damping ratios for systems with and without PSS are shown in Fig. 11 and Fig. 12, respectively.

Without PSS, the damping ratios of all of the inter-area modes are decreased when the interconnection distance between areas 1 and 2 increases. This behaviour is in agreement with the results explained in the previous section and those mentioned in [3]. However, with the presence of the PSS, the damping ratio of modes 7 and 13 increases, whereas that of the mode 12 decreases slightly. As stated above, the interconnection between areas 2 and 4 and that between areas 3 and 5 are the only ones related to mode 12.

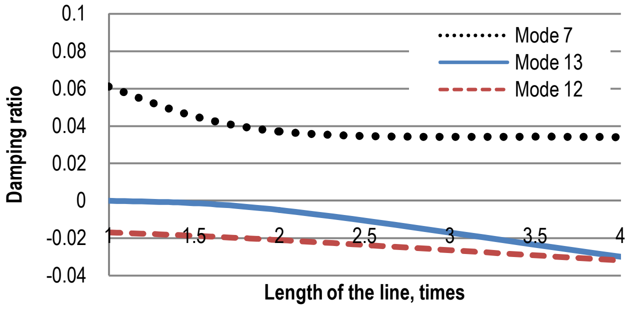

Figure 11. Impacts of the length of the interconnection between areas 1 and 2 on inter-area modes of the system without PSS

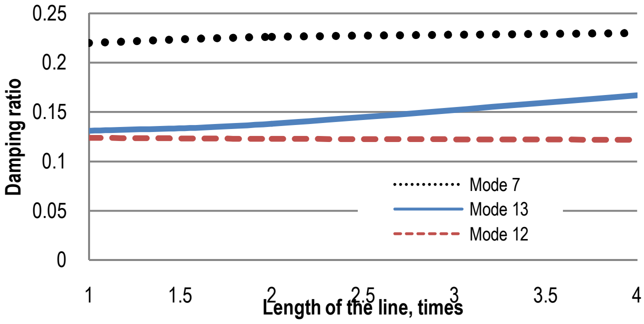

Figure 12. Impacts of the length of the interconnection between areas 1 and 2 on inter-area modes of the system with PSS

C. *Impacts of transmitted power on the damping of the inter-area mode oscilations*

To investigate the impacts the level of transmitted power on the damping ratio of inter-area modes, the output of generator VPS_2 is changed from 375MW to 1800MW. Therefore, the transmitted power of the interconnection from area 2 to area 1 is changed from 448MW to 1800MW. Fig.13 shows the damping ratio of modes 12 and 13 with and without PSS. Without PSS the damping ratio of modes 12 and 13 slightly decreases with the increase in the level of the transmitted power. This is in agreement with the results for the two area test power system explained in section II of this paper and those mentioned in [3]. With the presence of PSS, the damping ratio decreases less sharply with an increase in the transmitted power compared to the case without PSS.

The same results can be seen when the transmitted power from area 3 to area 5 changes from 500MW to 905MW. From both Fig.13 and Fig 14, it can be concluded that the damping ratio of inter-area mode is less sensitive to the changes in transmitted power than to the length of the interconnection.

Simulation results indicate that the impact of length of the interconnection on the damping ratio is similar for both test cases (two area test power system and simplified SE Australian system) with and without PSS.

Simulation results for the impacts of the transmitted power on the damping ratio for both test systems without PSS are consistent. However, with the presence of PSS, the impact of the transmitted power on the damping ratio in case of the two area test system was observed different than that of the simplified Australian test system.

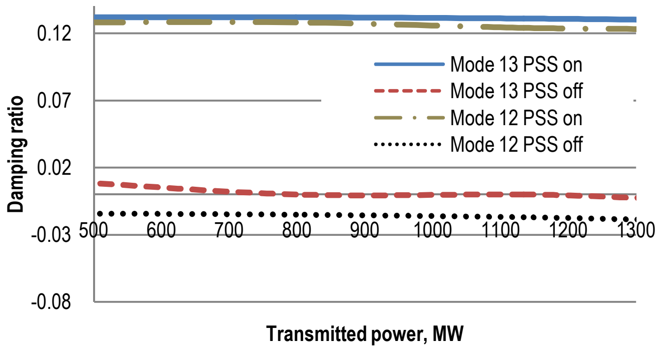

Figure 13. Impacts of the transmitted power between areas 1 and 2 on inter-area modes of the system with PSS

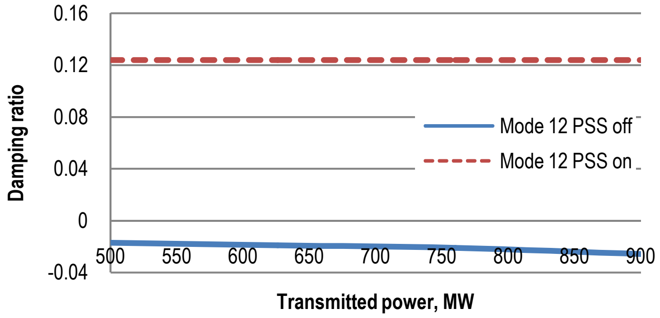

Figure 14. Impacts of the transmitted power between areas 3 and 5 on the inter-area modes of the system with PSS

V. CONCLUSIONS

In this research, the impacts of transmitted power and length of the interconnection on small signal stability were examined for two sample power systems. Analysis of results for the considered operating conditions indicated that the inter-area mode was less stable when the length of the interconnection was increased. The amplitude of the first swing was also proportional with the length of the interconnection. Hence, the system with longer interconnection was less stable. However, with the presence of PSS, satisfactory performance was observed in all cases and all inter-area modes were properly damped. Moreover, it is observed that the longer the interconnection is the better the inter-area oscillation is damped.

The transmitted power through interconnection had less impact on the damping ratio than the interconnection distance does. Without PSS, the damping ratio of inter-area mode was decreased when transmitted power was increased. With PSS, the impact of transmitted power on the damping ratio of inter-area modes was unpredictable. The impacts of transmitted power on the damping ratio of the two test systems were observed differently.

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