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Effect of Generator Controls on Inter-area Oscillations on Stressed Tie-Line

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Abstract: A study of electromechanical oscillation in power systems is presented. The effect of excitation, governor and power system stabilizer are discussed. In the study both of linearized techniques and non-linear analysis are used to determine the characteristics of the system.

Keywords: Inter-area oscillations, Modal Analysis, Mode Shape, Participation Factor, PSS.

1. INTRODUCTION

Low frequency oscillations are inherent phenomena of power systems, since electric power systems have non-linear dynamics in nature that's lead to rise of many modes in the system, namely local modes, torsional modes and inter-area modes. Inter-area modes are those in which synchronous generators in one area oscillates against generators in another area, interconnected by a weak tie-line. These oscillations are in the range of 0.1 to 1 Hz. However, the major cause of unstable inter area modes is the increase in synchronizing torque provided by the automatic voltage regulators [4]. The aim of this paper is to discuss the effect generator controls (i.e. AVR, governor and PSS) on inter-area mode and to put the use of PSS to improve the damping of these low frequency oscillations. Two machine system has two generating areas interconnected by a tie line. This system originally created for research report commissioned from Ontario Hydro by the Canadian electric Association [1, 2]. Section 2 of this paper provides a brief description on system model. Analytical techniques and the simulation tool used in this work have been presented in Section. Results have been presented in section 4.

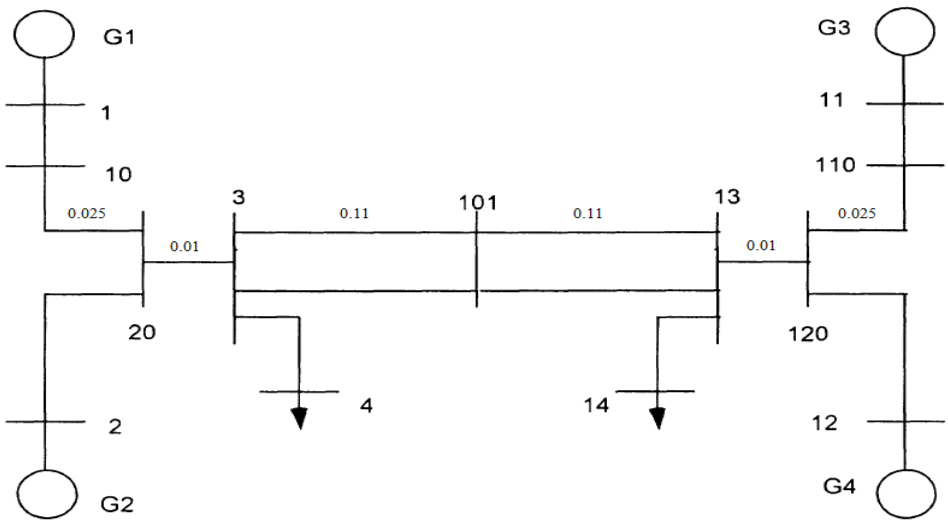

Fig -1: Two-Area system

2. SYSTEM STRUCTURE AND MODELLING

Study of inter-area mode requires detailed representation of the system. A single line diagram of the system is shown in Fig. 1. There are two generation and load areas interconnected by a relatively weak transmission line. The basic system formed by two symmetrical operational areas. Each region has two generators. The generators and their controls are identical. The system is quit heavily stressed, it has 400 MW flowing in the tie lines from area 1 to area 2. Dynamic data for generators and excitation system may found in [3]. There are three modes of oscillation presented in this system, two local-modes, one in each area, and one inter-area mode, in which generators in one area oscillates against those in the other area.

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2.1 Synchronous Generators and Controls

In power system studies the synchronous generators model vary from a simple classical model to the more detailed ones depending on the accurate dynamics of the system required. As the study deals with low frequency modes, a detailed sub-transient model of synchronous is used in this study [7, 8]. Generators are equipped with simplified static exciters and simplified turbine-governor model.

2.2 Load Modelling

The system has two loads one at bus 4 and bus 14. Static load model has been used. All loads are modelled as 50% constant current active loads.

3. ANALYTICAL TECHNEQUE AND TOOL

A brief discussion on analytical technique used in the analysis and demonstration of simulation tool used has been written below.

3.1. Analysis Techniques

Since the study involves oscillations, it's widely in power system studies to use linear analysis. It enables the use of a system model that has been linearized about a steady state operating point. Once we have a linear, the very powerful methods of modal analysis are open to use. The detailed derivation of linearized power system equations is beyond the scope of this work. Detailed model development can be found in references [8, 10]. Based on these references, a brief review has been presented here. After approximation, the linearized form of power system can be represented by the following equations:

$$\Delta\dot{\mathbf{x}} = \mathrm{A}\Delta\mathbf{x} + \mathrm{B}\Delta\mathbf{u} \qquad (1)$$
$$\Delta\dot{\mathbf{y}} = \mathrm{C}\Delta\mathbf{x} + \mathrm{D}\Delta\mathbf{u}$$

Δx is the state vector of length $n\times1$
Δy is the output vector of length $m\times1$
Δu is the input vector of length $r\times1$
A is the state or plant matrix of size $n\times n$
B is the control or input matrix of $n\times r$
C is the output matrix of size $m\times n$
D is the feed forward matrix of size $m\times r$ Where n is number of states.

Now, to find the eigenvalues of system state matrix, we use the characteristic equation of the state matrix

$$\det(A - \lambda I) = 0 \qquad (2)$$

Mathematically, for each eigenvalue there is a one set of two orthogonal eigenvectors, namely the right and left eigenvectors, satisfying the following equation

$$A\Phi_i = \lambda_i\Phi_i \qquad (3)$$
$$\Psi_i A_i = \lambda_i\Psi_i$$

λ_i is the i^{th} eigenvalue
Φ_i is the right eigenvector corresponding to λ_i
Ψ_i is the left eigenvector corresponding to λ_i

After applying certain transformation, the n coupled linear deferential equations of the state matrix transformed to n decoupled linear differential equations.

Introducing new state vector z related to the original state vector Δx.

$$\Delta x = \Phi z \qquad (4)$$

By made some substitution we get.

$$\Delta\dot{z} = \Lambda z \qquad (5)$$

Where Λ is diagonal matrix of eigenvalues. The modes of oscillation are the solutions to these decoupled equations.

Physically, the right eigenvector describes how much each mode of oscillation is distributed among the system states. It is sometimes called mode shape. The left eigenvector, together with the input coefficient matrix and the disturbance determines the amplitude of the mode.

The oscillatory modes are identified by the complex eigenvalues. Since the state matrix is real, the complex eigenvalues occur in complex conjugate pairs, they expressed as:

$$\lambda i = \alpha \pm j\omega \qquad (6)$$

A good measure of damping is the damping ratio. It is defined as:

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$$\zeta = \frac{-\alpha}{\sqrt{\alpha^2+\omega^2}} \quad (7)$$

The real part of a complex eigenvalue indicates whether an oscillations decays (negative real part and negative damping), remains at constant amplitude (zero real part) or growth (positive real part and negative damping).
The Participation Factor is a quit good indication of the importance of state to the mode. In power systems, it is particularly useful as a screen for power system stabilizer placement. Mathematically, the participation factor of the r^{th} state in the i^{th} mode is the product of the r^{th} element in the i^{th} left eigenvector and the r^{th} element in the i^{th} right eigenvector:

$$P_{ir} = \Psi_{ir}\Phi_{ri} \quad (8)$$

3.2 Simulation Tool

Power System Toolbox (PST) version 3.0 has been used for the analysis required by this work. The Power System Toolbox (PST) was conceived and initially developed by Dr. Kwok W. Cheung and Prof. Joe Chow from Rensselaer Polytechnic Institute in the early 1990s. From 1993 to 2009, it was marketed, and further developed, by Graham Rogers (formerly Cherry Tree Scientific Software), and is in use by utilities, consultants and universities worldwide.
PST consists of a set of coordinated MATLAB m-files which model the power system components necessary for power system power flow and stability studies.

4. RESULT OBTAINED FROM ANALYSIS

The system under study has been analyzed without controls, with controls and with controls supplied andPSS, the result has been written in the following text.

4.1 Detailed Generator Model without Controls.

Analysis has been started with stressed system without PSS. About 400 MW transferred from area 1 to area 2.
To excite the inter-area mode of oscillation a step change in the mechanical power on generator 1 and 3. The change in mechanical torque at generator 1 is 0.03 pu on the generator base, and in generator 3 it is -0.03 pu. Both time-domain and modal analysis has been performed under this condition. From modal analysis, there are one inter-area mode with damping less than 0.05, the damping coefficient and frequency shown in Table 1.

Table -1: Damping and Frequency of the system without controls

Machin model	Eigenvalue	Damping	Frequency
with no control	-0.12149 ± 3.565i	0.03406	0.56738
AVR & Governor	0.044407 ± 4.029i	-0.011021	0.64123
AVR, Governor & PSS	-0.85212 ± 3.8337i	0.21697	0.61016

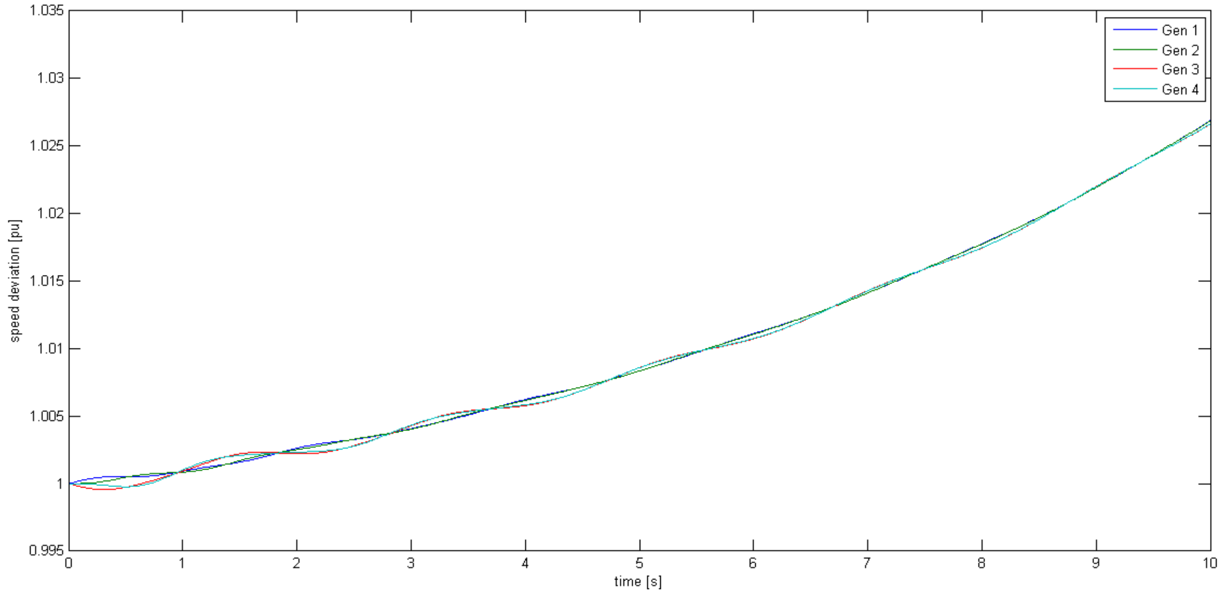

Fig -2: Change in generators speed without controls

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The responses of the generators speeds to generator torque changes is shown in Figure 2. Because there is no governor is modelled, the speeds of the generators are not controlled. The inter-area mode is dominant in the response of all generators. The overall trend is for the speed to increase. The responses of voltages at the tie buses are shown in Figure 3 the inter-area mode is dominant, but the local mode is difficult to detect in the voltage response. As the simulation progresses, the average value of both tie bus voltages reduces, the voltage reduction at the sending end is larger than that at the receiving end.

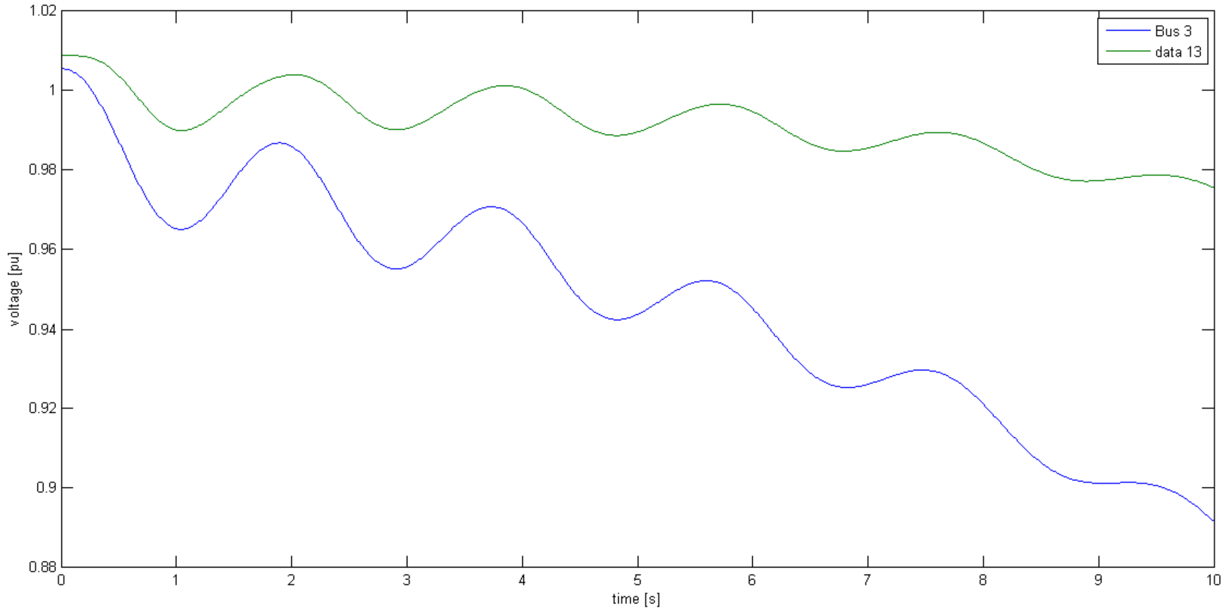

Fig -3: Change in tie-Line Bus Voltage without controls

4.2 Detailed Generator Model with AVR & governor.

It is clear from modal analysis that the damping of inter-area mode is decreased to 0.01. A time-domain analysis has been performed with same condition. The generators speed changes are shown Figure 4 and those of bus voltages are shown in figure 5. However, the speed is held close to synchronous speed by the action of the governors and the local mode oscillations decay. Figure 5 shows that in area 1, the local mode oscillation is initially dominant and damped. In area 2, the inter-area mode is dominant. After the local mode has decayed in area 1, the inter-area mode in area 1 can be seen to be in antiphase with that in area 2.

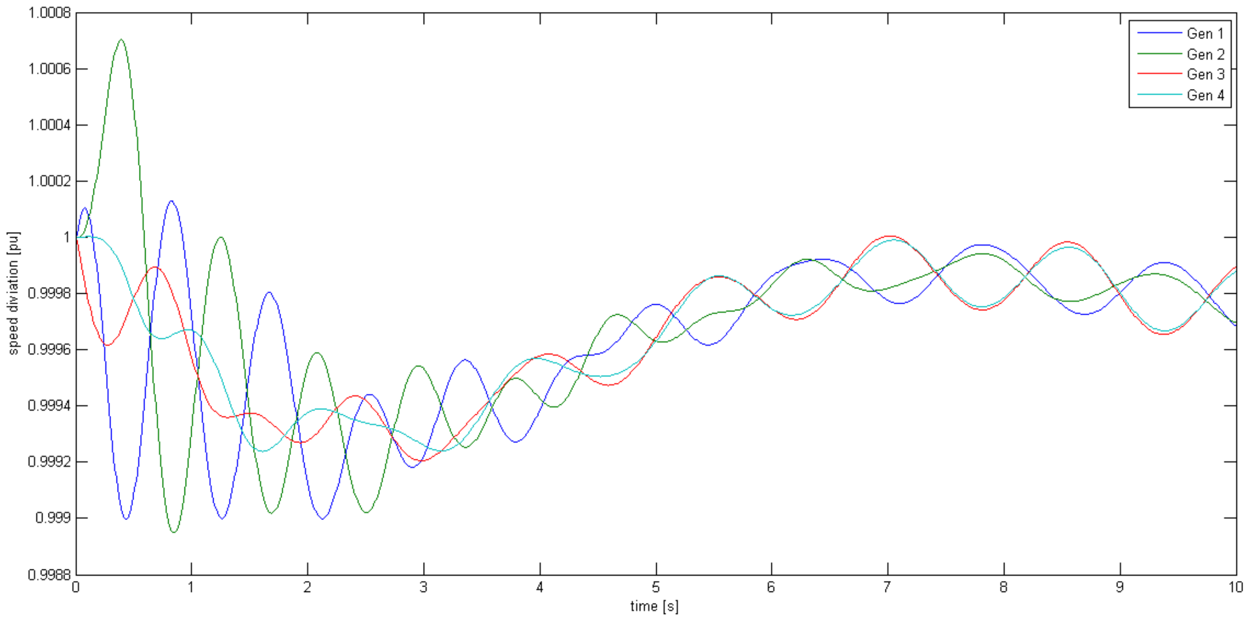

Fig -4: Change in generators speed with AVR & governor.

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Compared to the detailed generator model without controls, the system voltages are held close to their predisturbance level by the action of the automatic voltage regulator. There is less evidence of the local modes. This is to be expected, since the local modes decay with time, while the amplitude of the inter-area mode increases slowly.

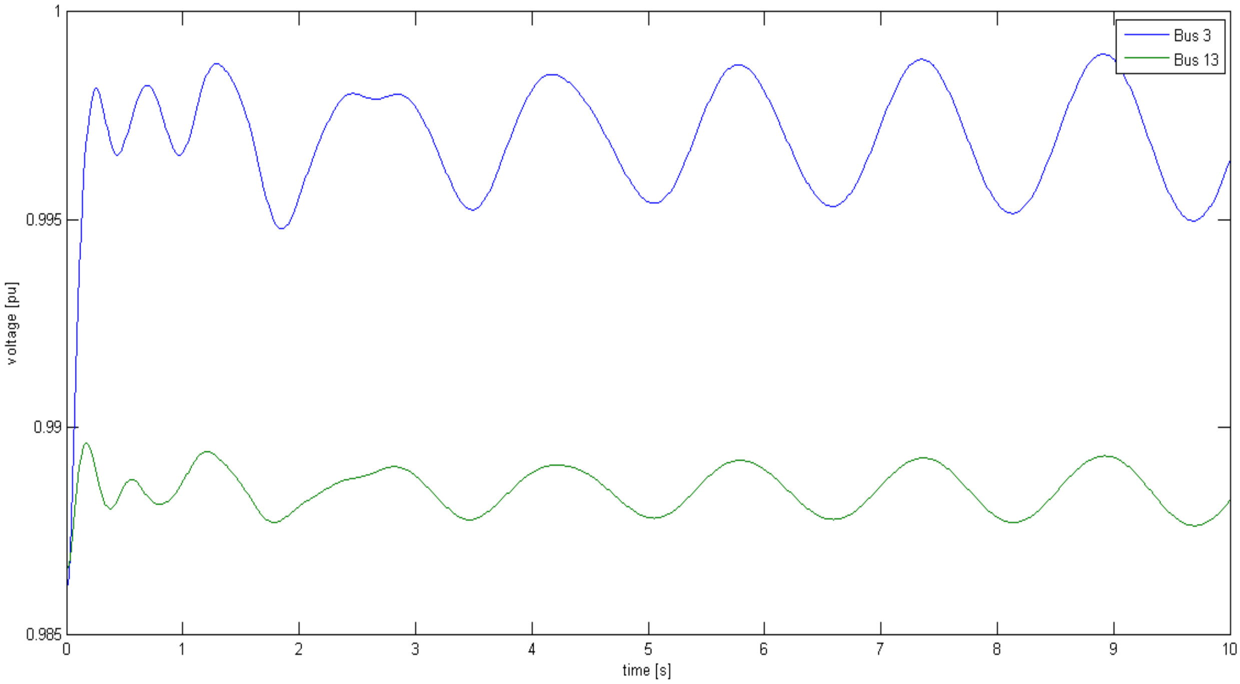

Fig -5: Change in tie-Line Bus Voltage with AVR & governor.

4.3 Analysis with AVR, governor & PSS

To test the effect the PSS on damping of the inter-area mode, we have carried out the same analysis with PSS installed on all generators. From modal analysis, the inter-area mode with PSS is found to be -0.85212 ± 3.8337i, therefore, the damping is improved to 0.22.

A time-domain analysis has been done once again. The generators speed changes are shown Figure 6 and tie-line voltage in Figure 7. It is obvious that all oscillations has been damped.

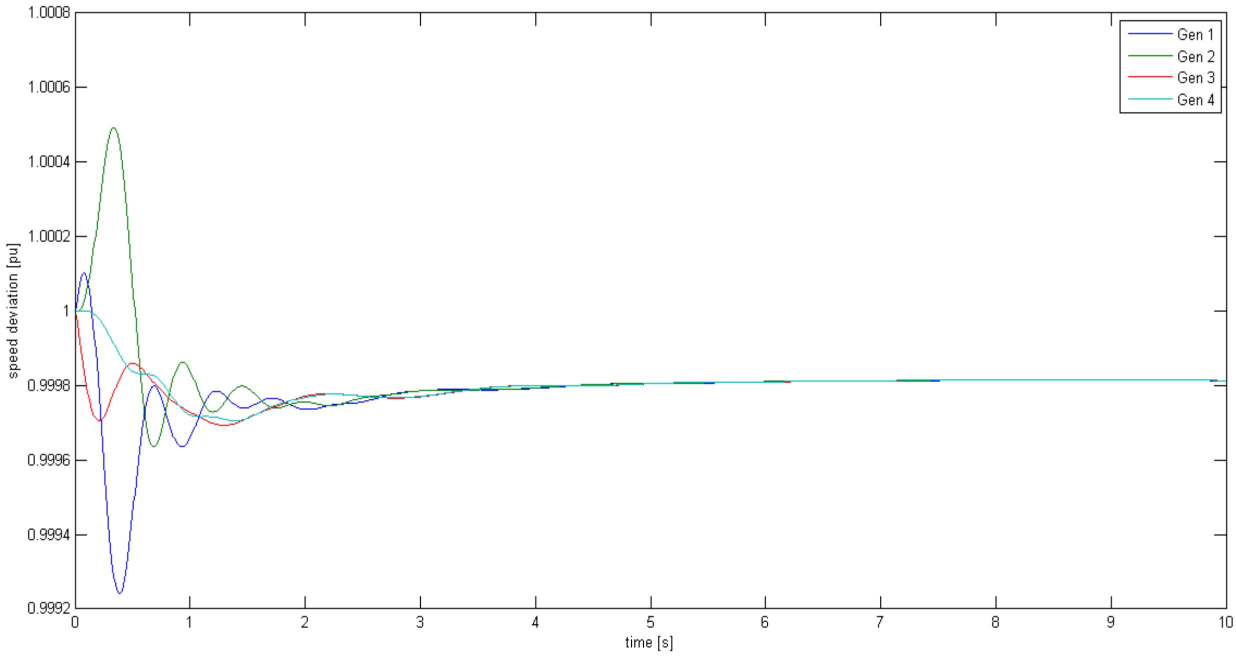

Fig -6: Change in Generators Speed with PSS

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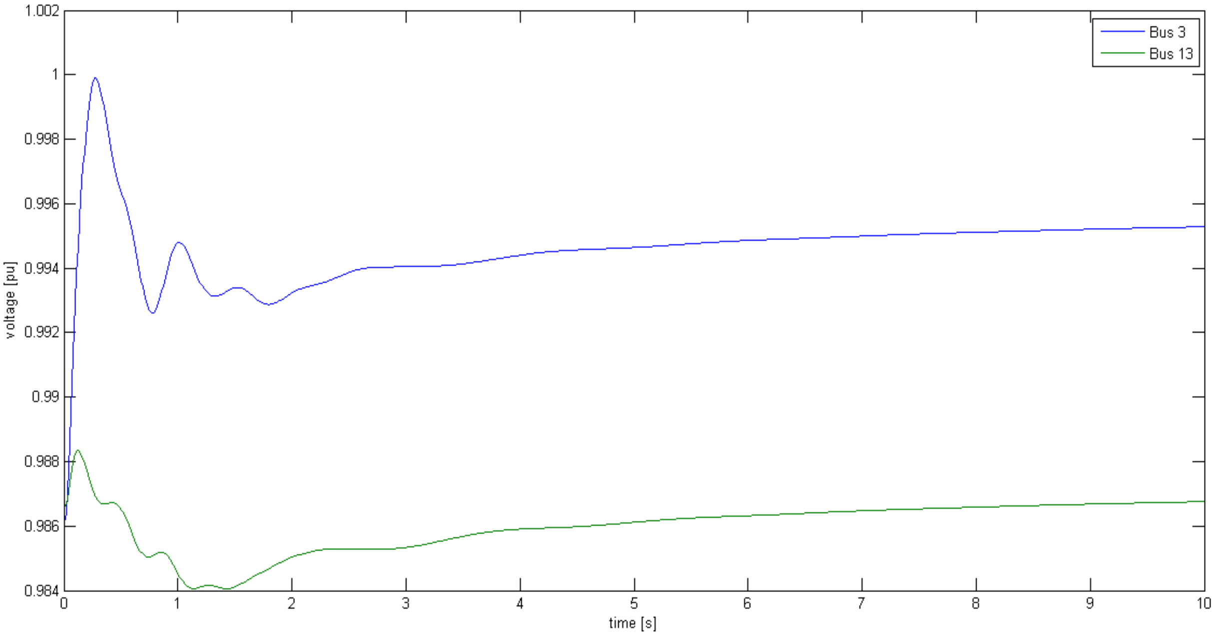

Fig -7: Change in Tie-Line Bus Voltage with PSS

5. CONCLUSIONS

This paper discussed the effect of generator controls on the inter-area oscillations. First the system has been studied without controls on the generators the damping of the inter-area mode was 0.03. Because of the generators' damper windings the inter-area modes of oscillation decay in this case but the speed increased and not controlled. After that, AVR and governor has been added to the generators and the effect was reduction in the damping ratio to 0.01, the unstable inter-area mode is due to the increase in synchronizing torque provided by the automatic voltage regulators. Finally, a PSS has been applied to the generators and result was increasing in the damping ratio of the inter-area mode to a satisfactory value of 0.22 and all of the oscillation has been damped.

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