

# OSCILLATION DAMPING WITH DIRECT LOAD CONTROL BASED ON PMU MEASUREMENT DATA

Eko Aptono Tri Yuwono<sup>1</sup>, Muhammad Nurdin<sup>2</sup>, Nanang Hariyanto<sup>3</sup>  
Institut Teknologi Bandung  
Jl. Ganesha 10, Bandung, Indonesia,  
<sup>1</sup>eko.aptono@gmail.com, <sup>2</sup>nurdin@power.ee.itb.ac.id, <sup>3</sup>nanang.hariyanto@stei.itb.ac.id

Khairudin<sup>4</sup>, Yasunori Mitani<sup>5</sup>  
Kyushu Institute of Technology  
Sensuicho, Tobata, Kitakyushu, Japan,  
<sup>4</sup>m589505b@mail.kyutech.jp, <sup>5</sup>mitani@ele.kyutech.ac.jp

## ABSTRACT

*To prevent loss of synchronism, power oscillations should be damped with an adequate damping torque so that system can regain a new equilibrium point. There are several methods that have been used to improve the damping such as using Power System Stabilizer (PSS), Flexible AC Transmission System (FACTS) device or HVDC Transmission system.*

*The implementation of PSS needs valid and detail power system parameter data such as line data, generator data, etc. These data are required to get the correct setting of PSS. Un-proper PSS setting can lead to power system instability instead of strengthen the power system. In Indonesian power system, line data and transformer data can be easily collected but generator parameters data are very hard to obtain especially for old generator. The large number of generator installed in the system made the data collections took a lot of time. These conditions makes implementation of PSS is not a simple task in Indonesia*

*The main principle of damping controller that is installed in the transmission line such as FACTS device is to control the power flows. Based on these principles, direct load control can be used to improve the power oscillation damping. Simulation using a simple Kundur's two area power systems is conducted as model. Modal analysis and sensitivity analysis are used to identify the load that having significant effect to the power oscillations. Phase plane analysis is conducted to identify the switching time of the loads.*

*Simulation shows with the proper switching time, power oscillations can be damped with direct load control. Loads in each area are switched off in particular order to control the power flows in transmission line. PMU measurement data are used as an input. This method can be used for temporary solution as long as damping controller with PSS has not implemented yet.*

**KEYWORDS:** *Power oscillation, direct Load control, PMU, damping ratio*

## 1 INTRODUCTION

Power System is a complex system consisting of generations, transmissions and loads. Load centers are connected to generator through transmission network. When the growth of demand is not followed by expanding constructions of new power plants and transmission line, it will possibly make power systems operate near to its operation limits. Power systems in Indonesia mostly consist of generations that un-evenly distributed. Large amount of power is flowing in a weak transmission lines between subsystem having surplus of generations and heavily loaded subsystem. These conditions weakened the power systems and hence becoming more vulnerable to any disturbance. If a disturbance occurs, generators will oscillate each other. Lack of damping torque will lead to an un-damped oscillation, and cause loss of synchronism among generators.

## 2 MAIN CONTENTS

### 2.1 Damping Enhancement Methods

Damping is defined as the energy dissipation properties of a system. Power oscillation can be damped, when extra energy is injected or consumed to compensate the decelerated or accelerated system. The damping energy must have the correct phase shift relative to the accelerated or decelerated system as incorrect phase angles can even excite the oscillations. Figure 1 shows the different possibilities to damp power system oscillations [1]

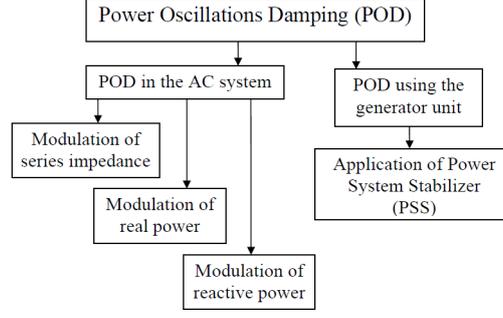


Figure 1 Strategies to damp power oscillations [1]

## 2.2 Power transfer and Small Signal Stability

To understand the relationship between power flow/load and stability, let's observe a simple Single machine infinite bus (SMIB) system. Transfer function of SMIB considering the field circuit dynamic and effect of excitation system can be seen as follow

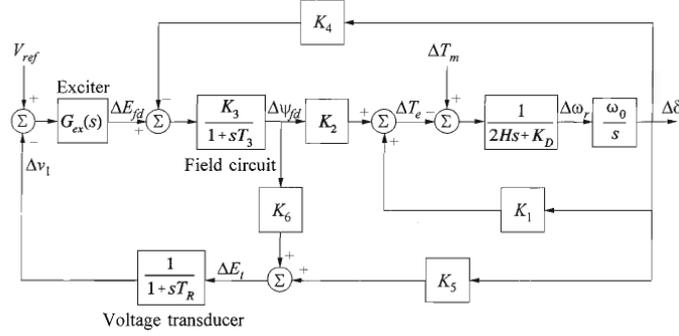


Figure 2 Transfer function SMIB with simple excitation system [2]

With AVR, the field flux variations are caused by the field voltage variations, in addition to the armature reaction.

$$\Delta\psi_{fd} = \frac{-K_3(K_4(1+sT_R)+K_5G_{ex}(s))}{s^2T_3T_R+s(T_3+T_R)+1+K_3K_6G_{ex}(s)} \Delta\delta \quad (1)$$

Air gap torque due to change in field flux linkage is:

$$\Delta T_e = K_2\Delta\psi_{fd} \quad (2)$$

Since the effect of term  $K_3(K_4(1+sT_R))$  relatively small compared to term  $K_5G_{ex}(s)$ , damping torque is primary influenced by  $K_5$ . Torque due to change of flux linkage is depends on  $K_2, K_3, K_4, K_5$  and  $K_6$ . The constant  $K_2, K_3, K_4$  and  $K_6$  usually positive, however  $K_5$  can be positive or negative depending on the external network and operating condition (generator output). With  $K_5$  positive, the effect of the AVR is to introduce a positive damping torque component. The constant  $K_5$  is positive for low value of external system reactance and low generator output. High value of external system reactance and high generator output cause  $K_5$  become negative. [2]

## 2.3 Modal Analysis [2][3]

Modal analysis study requires dynamic modeling of most of the power system components. Dynamic modeling of power system includes a set of differential and algebraic equation (DAE). A general mathematical model of power system is given as follow:

$$\dot{x} = f(x, y, l, p) \quad (3)$$

$$0 = g(x, y, l, p) \quad (4)$$

Where  $x$  is a vector of state variable,  $y$  is a vector of algebraic variables,  $l$  and  $p$  are uncontrollable and controllable parameter respectively. Machine and control dynamic will be included in the differential equations while basic load flow and other network equations will be included in algebraic equations. The small signal

stability of the system can be determined by system eigenvalues at an operating point. Once the operation point is identified, DAE model can be linearized around the operating point.

$$\begin{bmatrix} \Delta \dot{x} \\ 0 \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \Delta x \\ \Delta y \end{bmatrix} \quad (5)$$

$$\Delta \dot{x} = (J_1 - J_2 \cdot J_4^{-1} \cdot J_3) \Delta x = A \cdot \Delta x \quad (6)$$

Where:  $J_1 = \nabla x \cdot f$ ,  $J_2 = \nabla y \cdot f$ ,  $J_3 = \nabla x \cdot g$ ,  $J_4 = \nabla y \cdot g$

Matrix A in equation above referred to as reduced system state matrix. Small signal stability of the system can be analyzed by evaluating the eigenvalue of this matrix.

$$[A - \lambda I] \phi = 0 \quad (7)$$

$$\psi [A - \lambda I] = 0 \quad (8)$$

Where  $\lambda$  is the eigenvalues,  $\phi$  represents the right eigenvector, and  $\psi$  represent the left eigenvector. In order for the system to be stable all the eigenvalues should be located in the left side of the y axis in other words all the real parts of the eigenvalues should be negative. The relative participation of the state variables and their contribution in oscillation mode is determined by the corresponding element in the right and left eigenvectors.

$$P_i = \begin{bmatrix} P_{1i} \\ P_{2i} \\ \vdots \\ P_{ni} \end{bmatrix} = \begin{bmatrix} \phi_{1i} \psi_{1i} \\ \phi_{2i} \psi_{2i} \\ \vdots \\ \phi_{ni} \psi_{ni} \end{bmatrix} \quad (9)$$

Element  $P_{ki} = \phi_{ki} \psi_{ik}$  where  $\phi_{ki}$  is the  $k^{\text{th}}$  entry of the right eigenvector with  $i^{\text{th}}$  mode,  $\psi_{ik}$  is the  $k^{\text{th}}$  entry of the left eigenvector associated with  $i^{\text{th}}$  mode.

## 2.4 Lyapunov Energy Function

The influence of damping can be demonstrated by the use of energy functions or Lyapunov functions that quantify the swing energy of the system. By formulating the energy function, it can help to determine if a certain control action will stabilize the system. Entering the parameters of the single machine infinite bus system with no load into the energy function in[4] [5]

$$\dot{V} = \delta \left[ \frac{2H}{\omega_R} \ddot{\delta} - P_m + \frac{EE_t}{x'_d + x_t + x_{tl}} \sin \delta \right] = -P_d \dot{\delta} \quad (10)$$

When the system is at the equilibrium state V is zero, while an un-damped oscillation gives a constant value greater than zero. A control action that contributes to damping is characterized by its ability to make V decrease.

## 2.5 Phase Plane Analysis [4][6]

Phase plane plot shows the trajectory of speed deviation as the function of phase angle. Phase plane plot with load event can be seen in figure 3. In the first case (red line) 10% of load suddenly added on single machine infinite bus system, while the other case the load is removed (blue line). Figure 4 shows the phase plane plot during disturbance

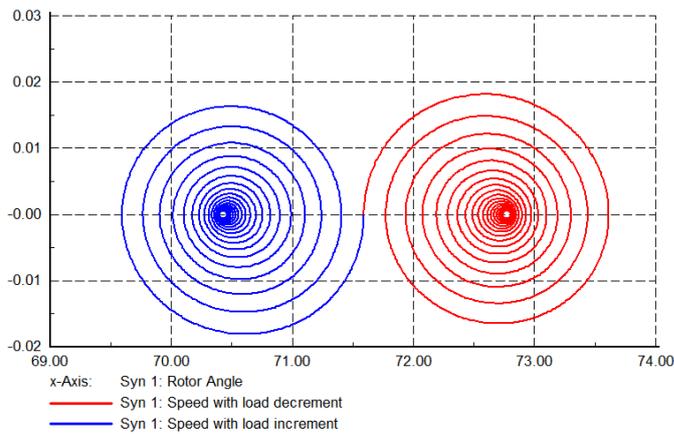


Figure 3 Speed deviation vs phase angle with load event

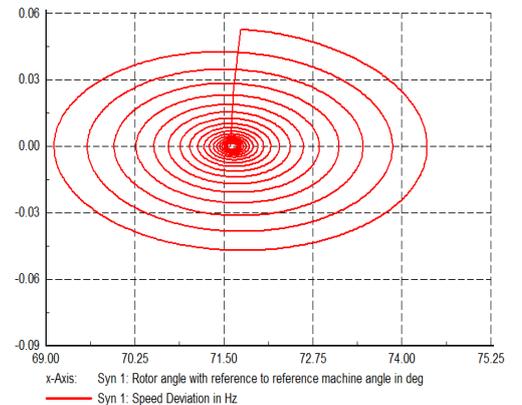


Figure 4 Speed deviation vs phase angle during disturbance

When the loads were increased or decreased, the phase plane characteristic will follow the trajectory of the corresponding angle. In order to decrease the energy of oscillation during disturbance, load must be increased or decreased in the proper time. Noticing the direction of the phase plane motion above is clockwise, then the power transfer should increase when the phase plane facing upward (minimum peak of the rotor angle) and the power transfer should decrease when the phase plane facing downward (maximum peak of the rotor angle) [6]

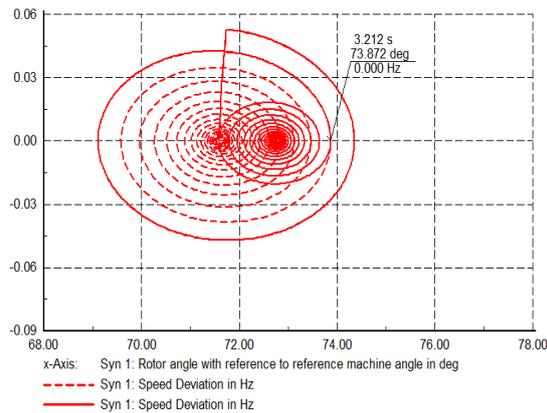


Figure 5 Phase plane plot of disturbance with load decrement

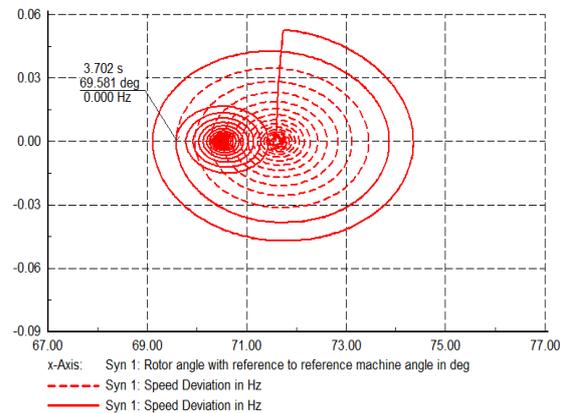


Figure 6 Phase plane plot of disturbance with load increment

## 2.6 Prony Analysis [7]

Prony analysis is a signal processing method that extracts valuable information from a uniformly sampled signal and builds a series of damped sinusoids. This method is very useful not only in signal processing but also in system identification, such as estimation of the frequency, amplitude, phase and damping components of a signal. Prony toolbox (PT box), an open source MATLAB Toolbox, is used to calculate the frequency and damping ratio of the oscillation. This toolbox can be downloaded at <http://www.mathworks.com>. PT box utilized built in MATLAB Signal Processing function prony to perform the prony analysis. It models a signal using a specified number of poles and zeros. The method uses a variation of the covariance method of autoregressive (AR) modeling to find the denominator coefficients, the  $a_i$ , and then finds the numerator coefficients  $b_i$  for which the resulting filter's impulse response matches exactly the first  $(n + 1)$  samples of the given data sequence. [7]

## 2.7 Phasor Measurement Unit

A phasor measurement unit (PMU) or synchrophasor is a device which measures the electrical parameters on a power system such as voltage, current, frequency, phase angle et cetera using a common time source for synchronization. Time synchronization allows synchronized real-time measurements of multiple remote measurement points on the system. [8][9]

A PMU can measure 50/60 Hz AC waveforms (voltages and currents) typically at a rate of 48 samples per cycle (2880 samples per second). The analog AC waveforms are digitized by an Analog to Digital converter for each phase. A phase-lock oscillator along with a Global Positioning System (GPS) reference source provides the needed high-speed synchronized sampling with 1 microsecond accuracy. The resultant time tagged phasors can be transmitted to a local or remote receiver at rates up to 60 samples per second. [8][9]

## 2.8 Simulation

### 2.8.1 The load controller diagram block

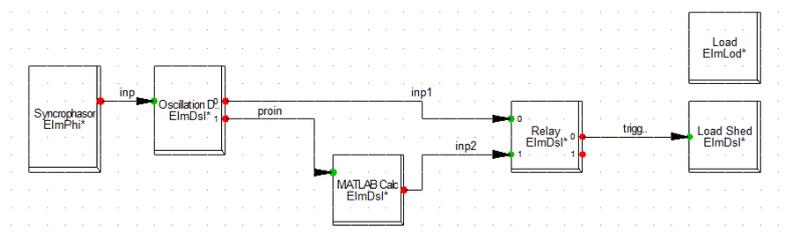


Figure 7 Load controller DSL block

Phase angle measured by Synchrophasor (PMU) being processed by level detector (oscillation detector block) and (MATLAB Calculation block). Oscillation detection block measure the magnitude of the first swing, and give order to MATLAB block to start calculate the natural frequency of the phase angle waveform.[10] Conditions that have to meet in order to trigger the load shed are magnitude of the first swing exceed the set value, frequency range are 0.2 – 0.7 Hz (Inter-area oscillation), and the damping ratio less than set value

### 2.8.2 Test Case

Simple Kundur's two area power system is used as test case. This model consists of four synchronous generators that grouped into two area. These areas are connected through weak transmission line.

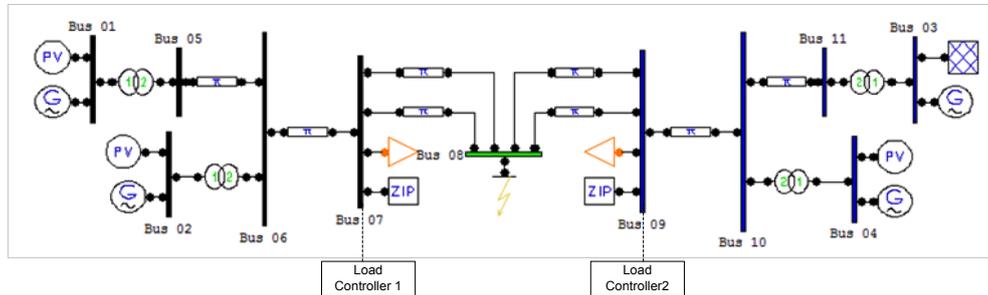


Figure 8 Kundur's Simple Two Area System[2]

Modal analysis in the Kundur's two area system shows that there are two local oscillation modes are indicated by frequency more than 0.8 Hz (mode 9 and 11), and an inter-area oscillation with frequency 0.502 Hz.

Table 1 Participation factor of each generator

Eigenvalues	Real	Imag	Freq	Participation factor				Most associated gen
				Syn 1	Syn 2	Syn 3	Syn 4	
Eig As #9	-0.5174	6.1412	0.977	0.1948	0.2540	0.0012	0.0076	Syn 2
Eig As #11	-0.5239	6.194	0.986	0.0046	0.0038	0.1776	0.2705	Syn 4
Eig As #13	-0.1329	3.1514	0.502	0.1185	0.0730	0.1754	0.1078	Syn 3

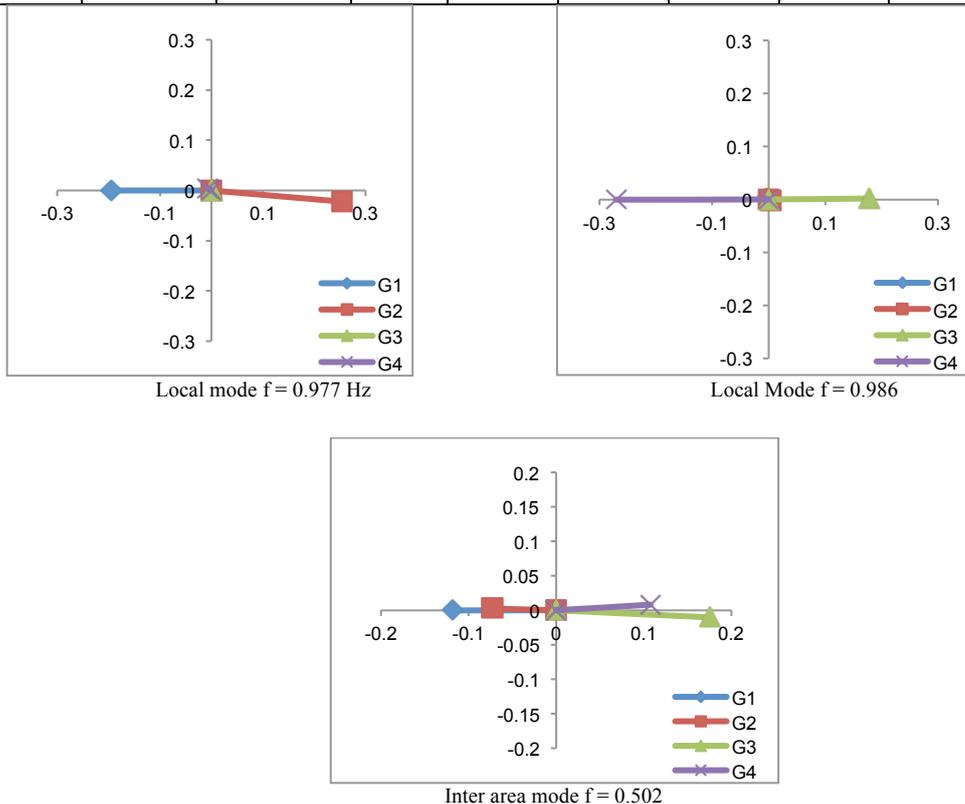


Figure 9 Participation factor of generators for each oscillation mode

Identification of the load that has significant effect to the stability in practice means determining the participation factor of all loads in the system. An Accurate and straightforward way to do this is to extend the model with active power injector at the load bus. [11][12][13]

Table 2 Participation factor of load at bus 7 and bus 9

Mode freq	Load at bus 7		Load at bus 9	
	Mag	Angle	Mag	Angle
0.977	0,78	-129,3	0,52	37
0.986	0,78	-129,3	0,52	37
0.502	0,69	159	0,67	13.4

Since the load cannot turn on and off frequently, load can be turned off but cannot be turned on shortly after that. The simplest approach to control the power transfer in the tie line is to shed the load at the two locations corresponding to the inter-area oscillations.

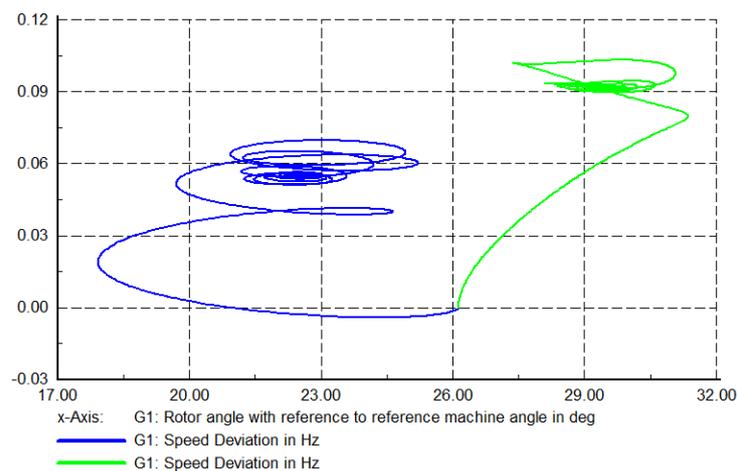


Figure 10 The speed deviation vs phase angle curve of gen 1 with 1 pu load shed at bus 7 (green curve), and bus 9 (blue curve)

Based on the phase plane analysis and Lyapunov energy function the proper time to shed the load at bus 7 is around the maximum peak of phase angle, and at minimum peak of phase angle for load at bus 9. PMU and load controller are placed on each load for this system, the PMU measures the phase angle of the voltage at the load bus, and this phase angle measurement is used as a load controller input. To make sure that an oscillation measured by PMU is an inter-area oscillation, calculate the natural frequency and damping ratio of the voltage phase angle curve. Controller only gives a trip orders to the load if the criteria of inter-area oscillation frequency have been met (0.1 to 0.7 Hz).

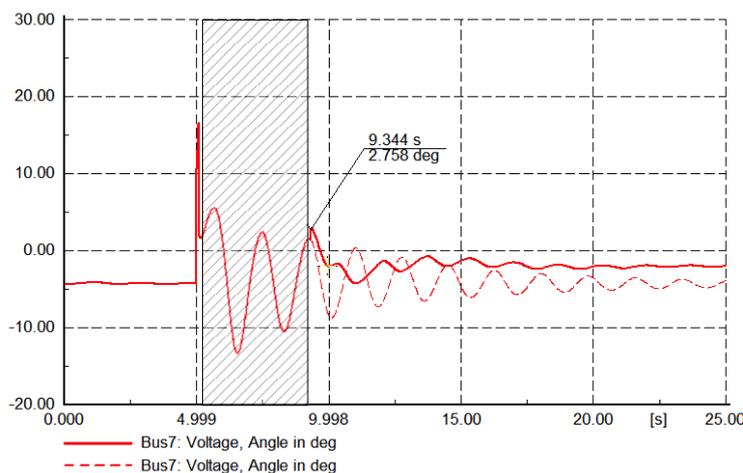


Figure 11 Phase angle measured by PMU at bus 7

As seen in figure 7, the voltage phase angle curves measured by the PMU, it appears that the controller gave the trip order after made calculations of frequency and damping ratio, This calculation is done on a few cycles after the pickup. Prony calculation will decompose the wave into damped sine waves. Comparison between the original sample waveform and the prony approximation waveform is shown in figure 8.

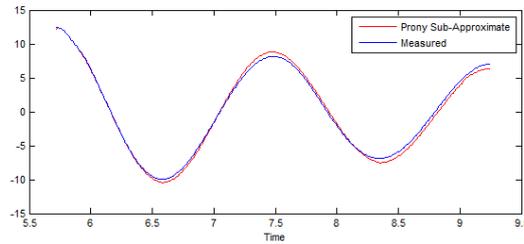


Figure 12 Sampled measured data and the approximation data (bus 7)

Based on the parameters obtained from the Prony analysis calculations it can be identified the parameters of natural frequency and damping ratio of each component. By using the same analysis of the obtained natural frequencies and damping ratios for the voltage phase angle curve at the load bus 9, with the following results.

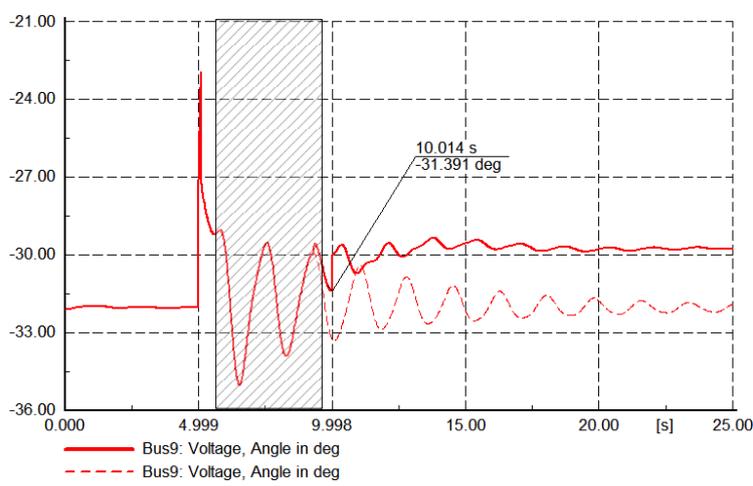


Figure 13 Phase angle measured by PMU at bus 9

Simulation shows that both load controllers perform very well. Load at bus 7 and 9 is trip/shed at proper time. Inter-area oscillation between area 1 (generator 1 and 2) and area 2 (generator 3 and 4) can be damped.

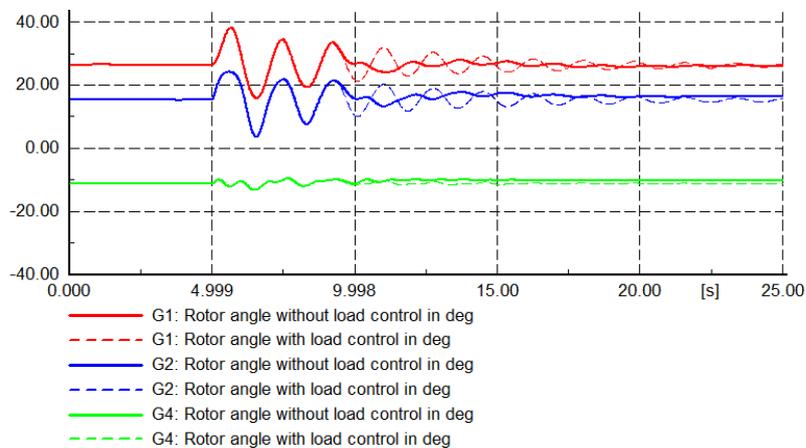


Figure 14 Rotor angle gen 1 (red), rotor angle gen 2 (blue), rotor angle gen 4 (green)

### 3 CONCLUSION

In this paper the small signal stability analysis, modal analysis, and phase plane analysis have been studied to analyze the damping ratio enhancement using direct load control. From the simulation results are shown that the direct load control with PMU measurement as an input has a great potential to enhance the oscillation damping.

Damping enhancement based on load control must be able to shed the load at the proper time, incorrect shed time can make the oscillation even bigger. Proposed controller performs very well and be able to damp the oscillation.

### REFERENCES

- [1] R. Witzmann, "Damping of Inter-area Oscillation in Large Interconnected Power Systems",
- [2] Kundur, P., Power System Stability and Control, McGraw-Hill, 1994.
- [3] IEEE / CIGRE Joint Task Force on Stability Terms and Definitions, "Definition and Classification of Power System Stability", IEEE Transactions on Power Systems, 2004
- [4] O. Samuelsson, B. Eliasson, G. Olson, "Power Oscillation Damping with Active Loads", Proc. Of the IEEE/KTH Stockholm Power Tech Conference, June 18-22, 1995, Vol III, pp 274-279
- [5] Stanton, S. E. and W. P. Dykas (1989), "Analysis of a Local Transient Control Action by Partial Energy Functions," IEEE T-PWRS, Vol. 4, No. 3, pp 996-1002
- [6] Olof Samuelsson, Magnus Akke, "On-Off Control of an Active Load for Power System Damping – Theory and Field Test", IEEE Transactions on Power Systems, 1999.
- [7] Singh, Satnam, "Application of Prony Analysis to Characterize Pulsed Corona Reactor Measurements", M.S., Department of Electrical and Computer Engineering, 2003
- [8] IEEE Power and Energy Society, "IEEE Std C37.118.1-2011 : IEEE Standard for Synchrophasor Measurements for Power Systems", IEEE Standard Association, 2011
- [9] IEEE Power and Energy Society, "IEEE Std C37.118.2-2011 : IEEE Standard for Synchrophasor Data Transfer for Power System", IEEE Standard Association, 2011
- [10] Digsilent Gmbh, "Digsilent Power Factory version 14.1 User Manual", Gomaringen Germany, 2011
- [11] I.A. Hiskens, J.V. Milanovic, "Locating Dynamic Loads which Significantly Influence Damping", IEEE Transactions on Power Systems, 1997, Vol. 12, No. 1, pp 255 – 261
- [12] O. Samuelsson, and B. Eliasson, "Damping of Electro-Mechanical Oscillation in a Multimachine System by Direct Load Control", IEEE Trans. On Power Systems, 1997, Vol. 12, No. 4, pp 1604-1609
- [13] O. Samuelsson, "Load Modulation at two Locations for Damping of Electro-Mechanical Oscillation in a Multimachine System", 2000, IEEE pp 1912 – 1917.
- [14] A. Kamwa, R. Grondin, D. Asber, J.P. Gingras, G. Trudel, "Large – Scale Active Load Modulation for Angle Stability Improvement", IEEE Transactions on Power Systems, 1999, Vol 14, No. 2, pp 582 – 590
- [15] B.B Monchusi, Y. Mitani, L.Changsong, and S. Dechanupaprittha, "PMU Based Power System Stability Analysis", IEEE,
- [16] Yuri V. Makarov, Zhao Yang Dong, David J Hill, "A General Method for Small Signal Stability Analysis", IEEE Transaction on Power Systems, 1998.