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Multi-Agent based Dynamic Stability Control for Low-Frequency Global Mode of Oscillations

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Abstract: This paper presents a multi-agent based dynamic stability control of electric power systems especially for low-frequency global mode of oscillations. Different types of intelligent agents are also proposed to realize the proposed wide area stability control system: monitoring agents for gathering required information to evaluate the dynamic stability of the study system, control agents which perform the actual control action, and a supervisor agent for the real time monitoring of eigenvalue based dynamic stability and the decision of the required dynamic stability control action to keep the pre-specified dynamic stability margin. The supervisor agent sends commands to a selected unit to keep the stability margin within the pre-specified range, whenever the stability margin is violated in the study system. To demonstrate the efficiency of the proposed multi-agent based dynamic stability control system, real time non-linear simulations have been performed on the Analog Power System Simulator at the Research Laboratory of Kyushu Electric Power Co.

1. INTRODUCTION

Owing to the increasing size and complexity of electric power systems, and also owing to the high rate of growth of electric power demand, electric power systems are being operated in a more stressed state and a lower stability margin.

Excitation control is well known as one of the effective means to enhance overall power system stability (Lasen et. al. 1981, Kundur et. al. 1989). In our previous studies (Hiyama et. al. 1993, 1994a, 1994b, 1994c, 1996a), we have proposed advanced fuzzy logic power system stabilizers (AFLPSS) to enhance the overall power system stability through the excitation control. For the further enhancement of power system stability, an integrated fuzzy logic generator controller for both the excitation and the governor systems has been proposed (Hiyama et.al. 1996b, c, 1997, 1998). In addition, the stabilization after detecting the instability of generators, an emergency control has been also proposed in our previous study (Hiyama et.al. 1999b). The controller consists of two blocks. The first block is a monitoring block of the dynamic stability (Hiyama. et. al. 1999a), where the stability of each generator is monitored in real time. The second one is the emergency control block to regulate the power output from the unstable generator. Whenever the instability of the generator is detected, the emergency controller sends the control signal to the speed governing control system for shifting the generator operating point to its new stable operating point in order to maintain the stability of the generator.

This paper presents a multi-agent based dynamic stability control (Hiyama et. al. 2003) to keep the stability margin specified by the real part of the dominant eigenvalue corresponding to the low-frequency global mode of oscillations in the study system within the pre-specified range. The proposed dynamic stability control system consists of three different types of intelligent agents: the monitoring agents for the distribution of required information through the computer network, the control agents for the actual control action on a selected unit, and the supervisor agent for the stability evaluation (Hiyama et. al. 2005a) in real time and the activation of the wide area dynamic stability control to keep the stability margin when the margin is violated. To demonstrate the efficiency of the proposed multi-agent based dynamic stability control, real time non-linear simulations have been performed on the Analog Power System Simulator at the Research Laboratory of the Kyushu Electric Power Co. (Hiyama et. al. 2005b).

2. MULTI-AGENT BASED DYNAMIC STABILITY CONTROL SYSTEM

Fig. 1 illustrates the concept of the proposed multi-agent based wide area dynamic stability control system.

The proposed multi-agent system has three different types of intelligent agents: the monitoring agents for the distribution of required information through the computer network, the control agents for the actual control action on a selected unit, and a supervisor agent for the real time dynamic stability evaluation of the target power system and the activation of dynamic stability control action to keep the stability margin within the pre-specified range when detecting the violation of the margin. The supervisor agent estimates the dominant eigenvalue in real time based on the scheme proposed in our previous study (Hiyama et. al. 2005a) after gathering the information sent from the monitoring agents through

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computer networks. In addition, the agent also evaluates the stability level of each generating unit based on the monitored speed deviation on each generating unit. Whenever the pre-specified stability margin is violated, the supervisor agent selects one of the generating unit as a target generating unit. After selecting the most fluctuating unit as the target unit, then the supervisor agent sends the control command to the control agent on the target unit through the computer networks in order to keep the stability margin within the pre-specified range. Finally, the control agent on the selected unit activates the stability control action to reduce its power output through the steam valve servo system in order to keep the stability margin.

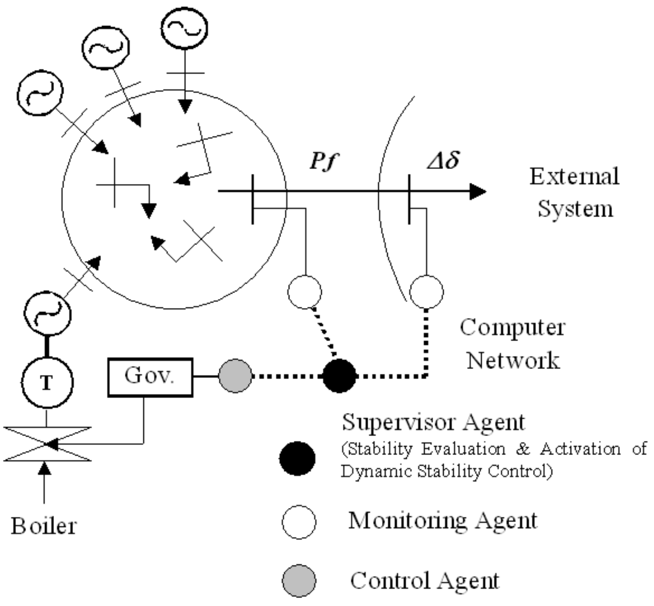


Fig. 1. Multi-Agent Based Wide Area Dynamic stability Control System

2.1 Selection of Target Unit for Stability Control

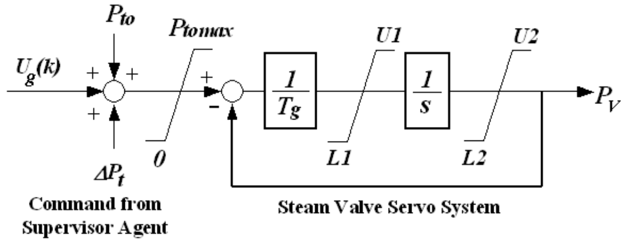
Whenever detecting the violation of the pre-specified stability margin, the most effective generating unit should be selected for the stability control. The following performance index J_i is evaluated at every 60 seconds for the selection of target unit. Whenever the stability violation is detected, the most fluctuating unit is selected as the target unit. Namely, the unit with the largest performance index is selected for the target of the stability control.

$$J_i = \sum \Delta\omega_i^2 \qquad (1)$$

where, $\Delta\omega$ is the speed deviation of the i-th unit.

2.2 Stability Control after Detecting Violation of Stability Margin

After detecting the violation of stability margin, the supervisor agent activates the dynamic stability control. Following the command sent from the supervisor agent, the control agent on the selected unit shifts its operating point by the modification of the real power output setting in the corresponding steam valve servo system shown in Fig. 2, where the term ΔP_t indicates the command from the supervisor agent.



$U_1 = 0.2$, $L_1 = -1000$, $U_2 = 1.5$, $L_2 = 0.0$

Fig. 2. Conventional Speed Governing System

3. REAL TIME STABILITY EVALUATION

Two monitored signals are utilized for the real time dynamic stability evaluation in the study system. From the sampled monitoring signals, a low order discrete time model parameters are identified at every sampling interval for the estimation of discrete time eigenvalues (Hiyama et. al. 2005). Through the monitoring of input signal $P_I(t)$, and the output signal $P_O(t)$, the parameters of the study system can be identified. Therefore, the stability of the study system can be evaluated from the eigenvalues of the identified study system. After monitoring the output $P_O(t)$ for an input signal $P_I(t)$, the relation between the input $P_I(t)$ and the output $P_O(t)$ can be expressed in a discrete manner as follows:

$$\begin{aligned} P_O(k) &= a_1P_O(k-1) + a_2P_O(k-2) + \cdots + a_nP_O(k-n) \\ &\quad + b_0P_I(k) + b_1P_I(k-1) + \cdots + b_nP_I(k-n) \end{aligned} \qquad (2)$$

After identifying the above model parameters by using the least square method, the discrete time transfer function $H(z^{-1})$ can be derived as follows:

$$H(z^{-1}) = \frac{b_0 + b_1z^{-1} + \cdots + b_nz^{-n}}{1 - a_1z^{-1} - a_2z^{-2} - \cdots - a_nz^{-n}} \qquad (3)$$

By solving the following characteristic equation, the stability of the discrete time system with the transfer function $H(z^{-1})$ can be evaluated.

$$1 - a_1z^{-1} - a_2z^{-2} - \cdots - a_nz^{-n} = 0 \qquad (4)$$

The discrete time eigenvalues can be easily converted to their corresponding continuous time eigenvalues as follow:

$$z_i = x_i + jy_i \qquad (5)$$

$$\alpha_i = \frac{\ln\left(\sqrt{x_i^{\,2} + y_i^{\,2}}\right)}{T} \qquad \beta_i = \frac{\tan^{-1}\left(\frac{y_i}{x_i}\right)}{T} \qquad (6)$$

The term α, which is the real part of the estimated eigenvalue, gives the damping coefficient and β gives the estimated frequency of the oscillation modes of the continuous time domain. Here, it must be noted that the system is stable when all the damping coefficients α have negative values. In addition, T denotes the sampling interval for the discrete time system. In the real time non-linear simulations shown later, the sampling interval T is set to 0.5s. Therefore, only the oscillation modes, related to the dominant low frequency global oscillation and inter-sectional oscillations, are maintained in the identified low order model.

4. CONFIGURATION OF SUPERVISOR AGENT

Fig. 3 illustrates the configuration of the supervisor agent for the stability evaluation and the activation of the dynamic stability control. In Fig.3, the term $Re(\lambda d)$ gives the real part α of the identified dominant eigenvalue and $\alpha margin$ is the pre-specified stability margin. When the real part α of the identified eigenvalue becomes greater than the setting of $\alpha margin$, the supervisor agent activates the dynamic stability control to bring the real part α within the stability margin, where α should be less than $\alpha margin$.

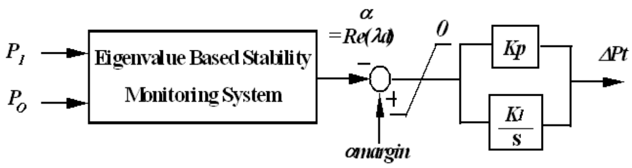


Fig. 3. Configuration of Supervisor Agent

The system instability occurs in the low frequency global mode of oscillation. Therefore, the sampling interval T is set to 0.5sec. for detecting the low frequency global oscillation mode under 1Hz in the non-linear real time simulations shown later.

5. STUDY SYSTEM

Non-linear real time simulations have been performed to demonstrate the efficiency of the proposed multi-agent based wide area dynamic stability control. The configuration of a longitudinal four-machine study system is shown in Fig. 4. Thermal plants are selected as the generators. Units 1 and 4 have self-excited excitation systems with the same configuration shown in Fig. 5. Units 2 and 3 have separately excited excitation systems. The configuration of the conventional PSS(CPSS) is illustrated in Fig. 6. The block diagram of the turbine system is also illustrated in Fig. 7.

The study system has two types of oscillation modes: local mode around 1Hz for each corresponding unit, and a low-frequency global mode around 0.3Hz. In the study system the instability is detected in the global mode.

The real time simulation tests have been performed after giving the command to increase the setting of power output Pto of Unit 1 in Fig. 3 from around 0.2pu to around 0.6pu. Whenever detecting the violation of the pre-specified stability margin during the real time stability evaluation on the supervisor agent, the supervisor agent locks the increase of the setting Pto and activates the dynamic stability control to keep the dynamic stability of the study power system within the pre-specified range given by the margin $\alpha margin$.

Both the CPSS and Fuzzy Logic PSS are tuned for a three-phase to ground fault at the location of A in the study system. The faulted line is isolated after four cycles. A quadratic performance index is utilized for the evaluation of control performance.

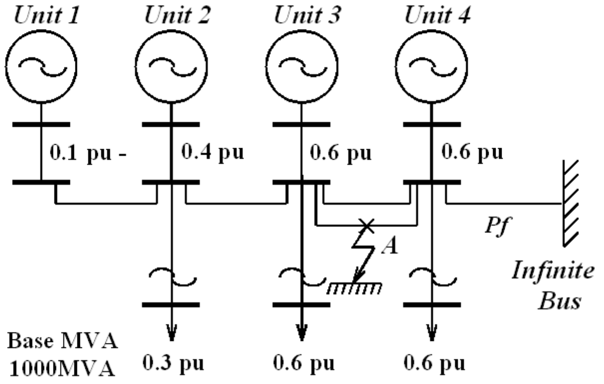
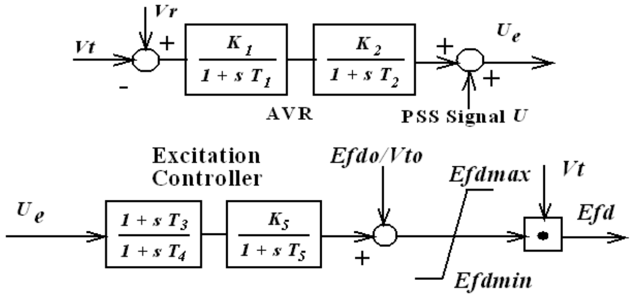
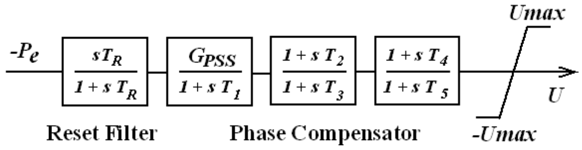


Fig. 4. Four Machine Infinite-Bus System



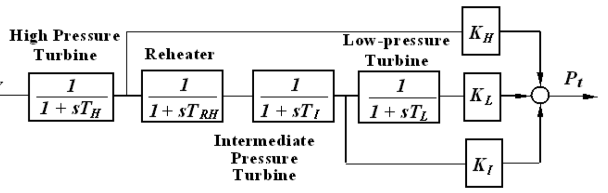
$K_1 = 1.0, T_1 = 0.013$ s, $K_2 = 10.0, T_2 = 0.013$ s,
$T_3 = 3.0$ s, $T_4 = 10.0$ s, $K_5 = 6.48, T_5 = 0.2$ s,
$Efdmax = 7.6, Efdmin = -5.2$

Fig. 5. Conventional Excitation System



$T_R = 4.0$ s, $Gpss = 10.0$, $T_1 = 0..025$ s, $Umax = 1.0$ pu

Fig. 6. Conventional PSS



$T_H = 0.44$ s, $T_{RH} = 10.0$ s, $T_I = 0.08$ s, $T_L = 0.58, K_H = 0.31$,
$K_I = 0.24, K_L = 0.45$

Fig. 7. Turbine System

6. REAL TIME SIMULATION RESULTS

Fig.8 shows the overview of the Analog Power System Simulator at the Research Laboratory of Kyushu Electyric Power Co. The study four machine system was set on the Analog Power System Simulator together with PC based multi-agent based dynamic stability control system.

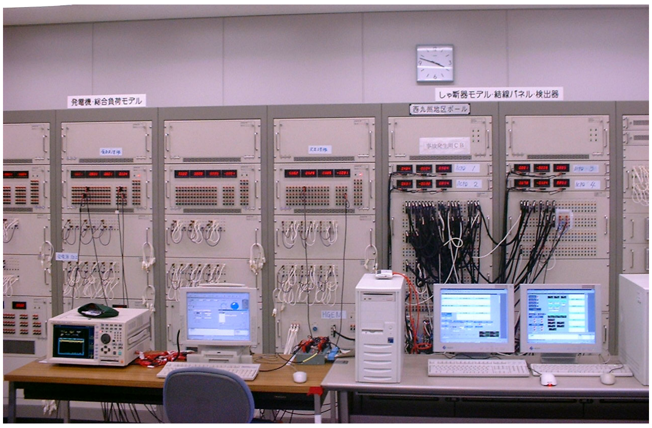


Fig. 8. Overview of Analog Power System Simulator

For the real time dynamic stability evaluation, the real power flow signal Pf on the trunk line to the infinite bus shown in Fig. 4 and the voltage phase variations $\Delta\delta$ of the infinite bus are monitored at every sampling interval of 0.5s as the output signal P_O and the input signal P_I for the study power system. Therefore, only the oscillation modes under 1 Hz are preserved in the identified low order model including the dominant low frequency global mode of oscillation. The required total computation time is less than 0.5s including the identification of low order model and the calculation of eigenvalues. The frequency of the dominant eigenvalue is around 0.3Hz for the low frequency oscillation mode. The real part α of the eigenvalue is utilized to activate the proposed dynamic stability control. During the process to increase the power output setting Pto on Unit1, if the stability margin is violated, the supervisor agent locks the increase of the output setting Pto on Unit 1 and activates the dynamic stability control on Unit 1, where Unit 1is the most fluctuating unit.

From Fig. 9 to Fig. 12, typical simulation results are illustrated to demonstrate the efficiency of the proposed multi-agent based dynamic stability control system.

In these figures, the real part α of the identified eigenvalue, the dynamic stability control signal ΔPt, the turbine output Pt, the electrical output Pe, the real power flow signal Pf on the trunk line to the infinite bus, and the voltage phase angle variation of the infinite bus are illustrated from the top to the bottom.

In Fig. 9, the conventional PSS(CPSS) is set on Unit 1 and there is no PSS on all the other units. The output setting of Unit 1 is linearly increased from 0.2 pu. The margin is specified to -0.15 for the real part of the estimated eigenvalue. Namely, $\alpha margin$ is set to -0.15. When the stability margin becomes small compared with the specified margin, the supervisor agent locks the increase of the output setting and activates the dynamic stability control to keep the margin to the pre-specified level as shown in Fig. 9. In Fig. 9, the stability control is activated at the time shown by A and the margin is recovered at the time B.

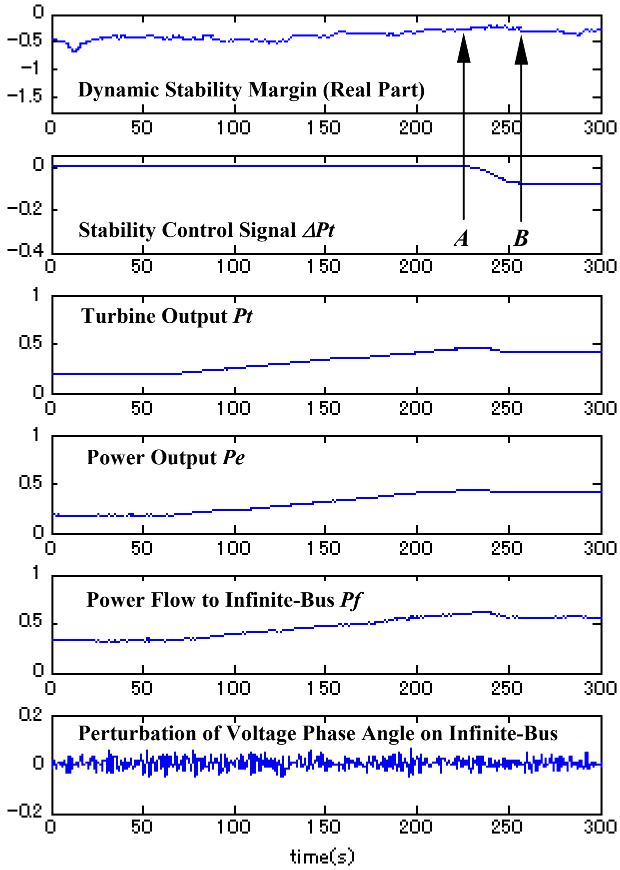


Fig. 9. Dynamic Stability Control (Unit1: CPSS)

In Fig. 10, CPSS is set on Unit 4 and there is no PSS on the other units. The output setting of Unit 1 is linearly increased from 0.1pu. The margin is specified to -0.25. Namely, αmargin is set to -0.25. When the stability margin becomes small compared with the specified nargin, the supervisor agent locks the increase of the output setting and activates the dynamic stability control to keep the margin to the pre-specified level. In this case the power output from Unit 1 is increased up to 0.4pu.

In Fig. 11, CPSSs are set both on Unit 4 and Unit 1. The output setting of Unit 1 is linearly increased from 0.1pu. The margin is specified to -0.4. Namely, αmargin is set to -0.4. When the stability margin becomes small compared with the specified margin, the supervisor agent locks the increase of the output setting and activates the dynamic stability control to keep the margin to the pre-specified level. In this case the power output from Unit 1 is increased up to 0.5pu.

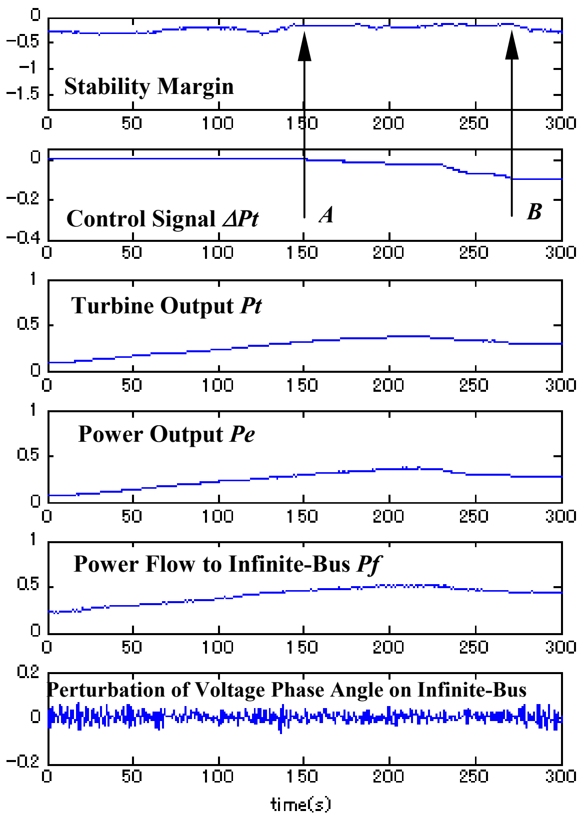


Fig. 10. Dynamic Stability Control (Unit 4:CPSS)

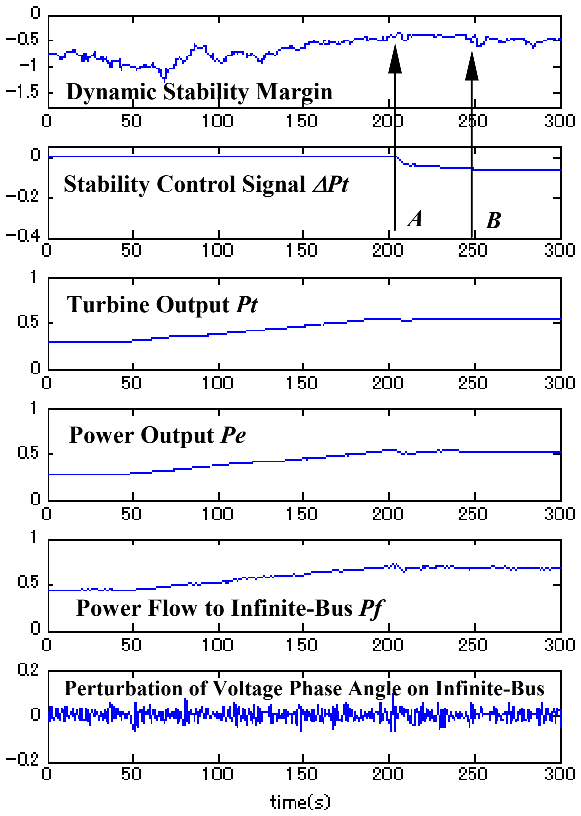


Fig 11. Dynamic Stability Control (Unit 1: CPSS, Unit 4: CPSS)

In Fig. 12, the Advanced Fuzzy Logic PSS(CPSS) is set on Unit 1 and the CPSS is set on Unit 4. The output setting of Unit 1 is linearly increased from 0.3pu. The margin is specified to -0.4 same as the setting in Fig. 9. Namely, αmargin is set to -0.4. When the stability margin becomes small compared with the specified nargin, the supervisor agent locks the increase of the output setting and activates the dynamic stability control to keep the margin to the pre-specified level. In this case the power output from Unit 1 is increased up to 0.6pu. compared with 0.52pu in the former case. This fact clearly indicates the improved dynamic stability of the study system after changing the PSS application. As shown in these figures, the proposed multi-agent based dynamic stability control is able to keep the dynamic stability margin to its pre-specified level by shifting the generator operating point automatically.

As shown in these real time simulation results, the proposed scheme can be applicable to actual large scale power systems in order to keep the dynamic stability level.to its pre-specified margin

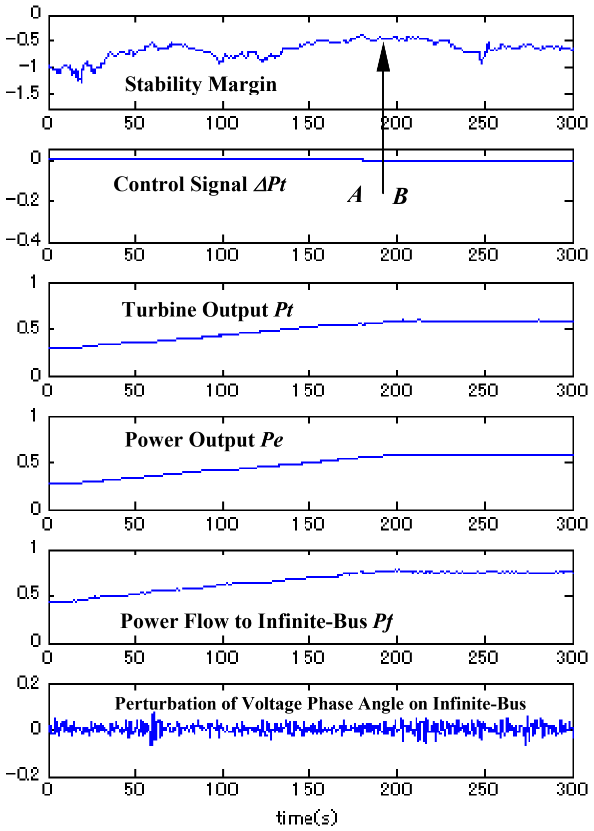


Fig. 12. Dynamic Stability Control (UNIT1: AFLPSS, Unit4: CPSS)

7. CONCLUSION

Through the non-linear real time simulations on the Analog Power System Simulator at the Research Laboratory of Kyushu Electric Power Co., the efficiency of the proposed multi-agent based dynamic stability control scheme has been demonstrated. In addition, the efficiency of the multi-agent based configuration of the proposed dynamic control system has been clarified.

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