A Stabilization of Frequency Oscillations in an Interconnected Power System Using Static Synchronous Series Compensator

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Abstract

This paper proposes a new application of one of the sophisticated FACTS (Flexible AC Transmission Systems) devices, i.e. Static Synchronous Series Compensator (SSSC) to stabilize the frequency of oscillations in an interconnected power system. The SSSC located in series with the tie-line between any interconnected areas, is applicable to stabilize the area frequency of oscillations by high-speed control of tie-line power through the interconnections. The mathematical model of SSSC is derived from its characteristic of power flow control. The controller of SSSC is designed based on enhancing the damping of the inter-area oscillation mode. The state-feedback control scheme of SSSC using the techniques of overlapping decompositions and discrete eigenvalue assignment is systematically developed. Simulation study exhibits the significant effects of the proposed control.

1. Introduction

Nowadays, electric power systems are undergoing drastic deregulation. Under this situation, any power system controls such as frequency control etc. will be served as ancillary services. Especially, in the case that many Independent Power Producers (IPPs) which have insufficient abilities of frequency control, tend to increase significantly. In addition, various kinds of apparatus with large capacity and fast power consumption, such as a magnetic levitation transportation, testing plants for nuclear fusion, even an ordinary scale factory for steel manufacturing etc, increase significantly. When these loads are concentrated in a power system, they may cause a serious problem of system frequency oscillations. Under this situation, the conventional frequency control, i.e. governor system, may no longer be able to absorb the transient frequency oscillations. Therefore, it is very important to consider how the transient frequency oscillations should be rapidly stabilized.

Recently, the concept of utilizing power electronics devices for power system control has been proposed as FACTS (Flexible AC Transmission Systems) devices [1]. Among them, the Static Series Synchronous Compensator (SSSC) [2] has been highly anticipated to be an effective apparatus with the ability for dynamic control of power flow. This sophisticated characteristic of SSSC motivates many applications in power systems [2]. In this paper, a new application of SSSC to provide an active control facility for stabilization of frequency oscillations in an interconnected power system is proposed. An SSSC located in series with the tie-line between any interconnected areas, can be applied to stabilize the area frequency oscillations by high-speed control of tie-line power through the interconnections. In addition, the study results in this paper also show that the high-speed control of SSSC can be coordinated with the slow-speed control of governor systems for enhancing the stabilization of area frequency oscillations effectively.

The organizations of this paper are as follows. In part 2, the motivation of the proposed control are described. Part 3 focuses on the design of SSSC controller. Subsequently, the effects of the designed controller of SSSC are evaluated by a simulation study in part 4.

2. Motivation of Proposed SSSC Application

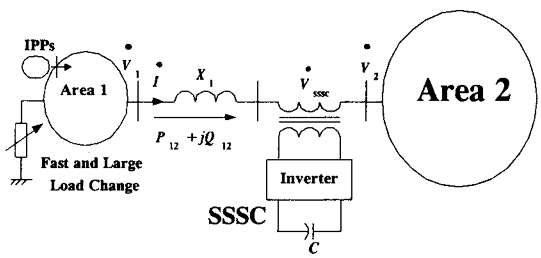

Figure 1. An SSSC in a Two Area Interconnected System

A two area interconnected power system as shown in Fig. 1 is used to explain the motivation of a proposed control. It is assumed that a large load with sudden change that has been installed in the area 1, causes a serious problem of frequency oscillations. In addition, many IPPs that have not sufficient abilities of frequency control, have been concentrated in the area 1. These imply that the capabilities of frequency control of governors in the area 1 are not enough. On the other hand, the area 2 has the control capability enough to spare for service of stabilization of frequency oscillations in the area 1. Therefore, the area 2 has installed an SSSC in series with the tie-line between both areas. In the event of frequency fluctuation in an area 1, the dynamic control of tie-line power by SSSC is applied to stabilize the transient frequency oscillations of area 1 by complementarily utilizing the control capability of area 2.

3. Design of SSSC Controller

3.1 Mathematical Model of SSSC

In this paper, the mathematical model of SSSC for the stabilization of frequency oscillations is derived from the characteristic of power flow control of SSSC. As shown in Fig.1, by controlling the output voltage of SSSC, $\dot{V}_{SSSC}$, the tie-line power flow can be directly controlled. Because the SSSC fundamentally controls only the reactive power, then the injected voltage of SSSC, $\dot{V}_{SSSC}$ is perpendicular to the line current $\dot{I}$, which can be expressed as

$$\dot{V}_{SSSC} = jV_{SSSC}\left(\dot{I}/I\right) \qquad (1)$$

where $\dot{I}/I$ is a unit vector of line current. In Fig 1, the current $\dot{I}$ can be expressed as

$$\dot{I} = \left(\dot{V}_1 - \dot{V}_2 - jV_{sssc}\left(\dot{I}/I\right)\right)/jX_l \qquad (2)$$

where X_l is the reactance of tie-line, $\dot{V}_1$ and $\dot{V}_2$ are the voltages at buses 1 and 2, respectively. The active power and reactive power flow through bus $\dot{V}_1$ are

$$P_{12} + jQ_{12} = \dot{V}_1\bar{I} \qquad (3)$$

where $\bar{I}$ is a conjugate of $\dot{I}$. Substituting (2) into (3) yields

$$\begin{aligned} P_{12}+jQ_{12} &= (V_1V_2/X_l)\sin(\delta_1-\delta_2) - V_{sssc}\left(\dot{V}_1\bar{I}/X_lI\right) \\ &+ j\left(\left(V_1^2/X_l\right) - \left(\left(V_1V_2/X_l\right)\cos(\delta_1-\delta_2)\right)\right) \end{aligned} \qquad (4)$$

where $\dot{V}_1 = V_1e^{j\delta_1}$ and $\dot{V}_2 = V_2e^{j\delta_2}$. In (4), the second term of the right hand side $\dot{V}_1\bar{I}$ is $P_{12} + jQ_{12}$ (see (3)). Accordingly, the relation in the real part of (4) gives

$$P_{12} = \left(V_1V_2/X_l\right)\sin(\delta_1 - \delta_2) - \left(P_{12}/X_lI\right)V_{sssc} \qquad (5)$$

The second term of right hand side is the active power controlled by SSSC. Here, it is assumed that V_1 and V_2 are constant and the initial value of V_{sssc} is zero, i.e. $V_{sssc0} = 0$. By linearizing (5) about an operating point,

$$\Delta P_{12} = \frac{V_1 V_2 \cos(\delta_{10} - \delta_{20})}{X_l}(\Delta\delta_1 - \Delta\delta_2) - \frac{P_{120}}{X_l I_0}\Delta V_{sssc} \tag{6}$$

where the subscript 0 denotes the value at the operating point.

By varying the SSSC output voltage ΔV_{sssc}, the power output of SSSC can be controlled as $\Delta P_{sssc} = (P_{120}/X_l I_0)\Delta V_{sssc}$. Equation (6) therefore, implies that the SSSC is capable of controlling the active power independently. In this paper, the SSSC is represented by the power flow controller where the control effect of active power by SSSC is expressed by ΔP_{sssc} instead of $(P_{120}/X_l I_0)\Delta V_{sssc}$. As a result, (6) can be expressed as

$$\Delta P_{12} = \Delta P_{T12} - \Delta P_{sssc} \tag{7}$$

where

$$\Delta P_{T12} = (V_1 V_2 / X_l)\cos(\delta_{10} - \delta_{20})(\Delta\delta_1 - \Delta\delta_2) = T_{12}(\Delta\delta_1 - \Delta\delta_2) \tag{8}$$

and T_{12} is a synchronizing power coefficient.

3.2 Coordinated Control of SSSC and Governor

The SSSC is superior to the conventional frequency control system, i.e. governor, in terms of a high-speed performance. Based on this different speed performance, a coordinated control of SSSC and governor is explained as follows. When some sudden load disturbances occur in an area, SSSC quickly starts the control to suppress the peak value of transient frequency deviation. Subsequently, the governor responsibly eliminates the steady state error of the frequency deviation. In addition, there is another advantage in considering the different speed performance, that is the dynamic of the governor can be neglected in the control design of SSSC for simplicity.

3.3 Control Design of SSSC

The linearized model of a two area interconnected system [3] including the dynamic of SSSC is delineated in Fig. 2 where the dynamics of governor systems in both areas are

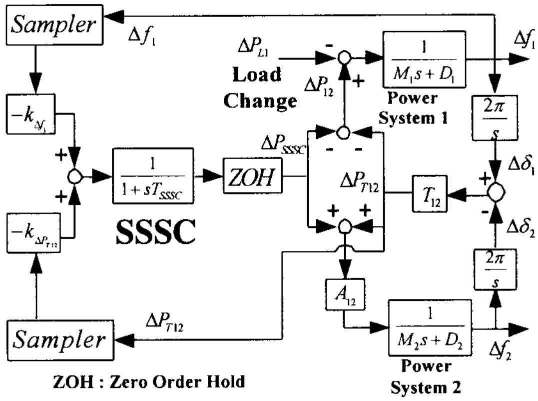

Figure 2. Linearized Model of Two Area System without Governor for Design of Digital Controller of SSSC

eliminated. The SSSC is modeled as a proportional controller of active power. It should be noted that the power flow control acting positively on an area reacts negatively on another area in an interconnected system. Power output of SSSC (ΔP_{sssc}), therefore, flows into both areas with different signs (+, -), simultaneously. This characteristic represents the physical meaning of (7). Here, the time constant T_{sssc} of proportional controller is set appropriately at 0.03 [sec]. To simplify a control design, the state equation of system in Fig.2 where the time constant T_{sssc} is ignored, can be expressed as

$$S: \begin{bmatrix} \Delta \dot{f}_1 \\ \Delta \dot{P}_{T12} \\ \Delta \dot{f}_2 \end{bmatrix} = \begin{bmatrix} -D_1/M_1 & -1/M_1 & 0 \\ 2\pi T_{12} & 0 & -2\pi T_{12} \\ 0 & A_{12}/M_2 & -D_2/M_2 \end{bmatrix} \begin{bmatrix} \Delta f_1 \\ \Delta P_{T12} \\ \Delta f_2 \end{bmatrix} + \begin{bmatrix} -1/M_1 \\ 0 \\ A_{12}/M_2 \end{bmatrix} \Delta P_{sssc} \tag{9}$$

Note that (9) is referred to as system "S". The variables and parameters in Fig.2 are defined as follows. Δf_1, Δf_2 are frequency deviations power deviation. ΔP_{T12} is a tie-line power deviation between areas 1 and 2 in case of no SSSC. ΔP_{12} is a tie-line power deviation in case of with SSSC. M_1, M_2 are inertia constants of areas 1 and 2. D_1, D_2 are damping coefficients of areas 1 and 2. A_{12} is an area capacity ratio between areas 1 and 2.

Here, the control scheme for power output deviation of SSSC (ΔP_{SSSC}) is designed by the eigenvalue assignment method, so that the dynamical aspect of the inter-area oscillation mode between areas 1 and 2 is specified. This mode can be explicitly represented after applying the variable transformation [4]

$$Y = WX \qquad (10)$$

where, W is a transformation matrix, Y is the transformed state vector, X is the state vector in (9). As a result, the transformed system can be expressed as

$$\begin{bmatrix}\Delta\dot{y}_1\\ \Delta\dot{y}_2\\ \Delta\dot{y}_3\end{bmatrix} = \begin{bmatrix}\alpha & \beta & 0\\ -\beta & \alpha & 0\\ 0 & 0 & \lambda\end{bmatrix}\begin{bmatrix}\Delta y_1\\ \Delta y_2\\ \Delta y_3\end{bmatrix} + \begin{bmatrix}\gamma_1\\ \gamma_2\\ 0\end{bmatrix}\Delta P_{SSSC} \qquad (11)$$

The transformed coefficient matrix of Y in (11) consists of two diagonal blocks with complex eigenvalues $\alpha \pm j\beta$ and real eigenvalue λ. The complex eigenvalues physically correspond to the inter-area oscillation mode. The real eigenvalue corresponds to the system inertia center mode. From the physical viewed point, it should be noticed that the SSSC located between two areas is effective to stabilize the inter-area mode only, then the input term of (11) corresponding to Δy_3 is zero. This means that the SSSC is uncontrollable for the system inertia center mode. In this paper, it is expected that the governor systems are responsible for suppressing the frequency deviation due to the inertia mode. Therefore, the controller of SSSC is designed based on the idea of stabilizing the inter-area mode by the discrete eigenvalue assignment method [5].

In order to extract the subsystem where the inter-area oscillation mode between areas 1 and 2 is preserved, from the system (9), the technique of overlapping decompositions [6] is applied. First, the state variables of the original system S are classified into three groups, i.e. $x_1 = [\Delta f_1]$, $x_2 = [\Delta P_{T12}]$ and $x_3 = [\Delta f_3]$. According to the process of overlapping decompositions, the system S can be expanded as

$$\tilde{S} : \begin{bmatrix}\dot{z}_1\\ \dot{z}_2\end{bmatrix} = \begin{bmatrix}a_{11} & a_{12} & 0 & a_{13}\\ a_{21} & a_{22} & 0 & a_{23}\\ a_{21} & 0 & a_{22} & a_{23}\\ a_{31} & 0 & a_{32} & a_{33}\end{bmatrix}\begin{bmatrix}z_1\\ z_2\end{bmatrix} + \begin{bmatrix}b_{11}\\ b_{21}\\ b_{21}\\ b_{31}\end{bmatrix}\Delta P_{SSSC} \qquad (12)$$

where $z_1 = \left[x_1^T, x_2^T\right]^T$ and $z_2 = \left[x_2^T, x_3^T\right]^T$. The element $a_{ij}, (i, j = 1,2,3)$ corresponds to each element in the coefficient matrix in (9). The system $\tilde{S}$ in (12) can be decomposed into two interconnected overlapping subsystems,

$$\tilde{S}_1 : \dot{z}_1 = \left(\begin{bmatrix}a_{11} & a_{12}\\ a_{21} & a_{22}\end{bmatrix} z_1 + \begin{bmatrix}b_{11}\\ b_{21}\end{bmatrix}\Delta P_{SSSC}\right) + \begin{bmatrix}0 & a_{13}\\ 0 & a_{23}\end{bmatrix} z_2 \qquad (13)$$

$$\tilde{S}_2 : \dot{z}_2 = \left(\begin{bmatrix}a_{22} & a_{23}\\ a_{32} & a_{33}\end{bmatrix} z_2\right) + \begin{bmatrix}a_{21} & 0\\ a_{31} & 0\end{bmatrix} z_1 + \begin{bmatrix}b_{21}\\ b_{31}\end{bmatrix}\Delta P_{SSSC} \qquad (14)$$

The state variable x_2, i.e. the tie-line power deviation between both areas, is repeatedly included in both subsystems, which implies " *Overlapping Decompositions* ".

For system stabilization, consider two interconnected subsystems $\tilde{S}_1$ and $\tilde{S}_2$. The terms in the right hand sides of (13) and (14) can be separated into the decoupled subsystems (as indicated in the parenthesis in (13) and (14) and the interconnection subsystems. As mentioned in [6], if each decoupled subsystem can be stabilized by its own input, the asymptotic stability of the interconnected overlapping subsystems $\tilde{S}_1$ and $\tilde{S}_2$ are maintained, moreover the asymptotic stability of the original system S is also guaranteed. Consequently, the interactions with the interconnection subsystems in (13) and (14) are regarded as perturbations and are neglected during control design. The decoupled subsystems of $\tilde{S}_1$ and $\tilde{S}_2$ can be expressed as

$$\tilde{S}_{D1} : \dot{z}_1 = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} z_1 + \begin{bmatrix} b_{11} \\ b_{21} \end{bmatrix} \Delta P_{SSSC} \quad (15)$$

$$\tilde{S}_{D2} : \dot{z}_2 = \left(\begin{bmatrix} a_{22} & a_{23} \\ a_{32} & a_{33} \end{bmatrix} z_2 \right) \quad (16)$$

In (15) and (16), there is a control input ΔP_{SSSC} appearing only subsystem $\tilde{S}_{D1}$. Here, the decoupled subsystem $\tilde{S}_{D1}$ is regarded as the designed system, which can be expressed as

$$\begin{bmatrix} \Delta\dot{f}_1 \\ \Delta\dot{P}_{T12} \end{bmatrix} = \begin{bmatrix} -D_1/M_1 & -1/M_1 \\ 2\pi T_{12} & 0 \end{bmatrix} \begin{bmatrix} \Delta f_1 \\ \Delta P_{T12} \end{bmatrix} + \begin{bmatrix} -1/M_1 \\ 0 \end{bmatrix} \Delta P_{SSSC} \quad (17)$$

It can be verified that the eigenvalues of (17) are $\alpha \pm j\beta$, i.e. the inter-area oscillation mode in (9). It should be noticed that by virtue of overlapping decompositions, the physical characteristic of the original system S is still preserved after the process of model reduction.

Here, the control purpose of SSSC is to dampen the peak value of frequency deviation after the sudden load disturbance. Since the system (17) is the second-order oscillatory system, the percent overshoot M_p is available for the control specification [5]. When the value of M_p is given, the damping ratio ζ is calculated by

$$M_p = \exp(-\zeta\pi / \sqrt{1-\zeta^2}) \quad (18)$$

Next, to assign the new eigenvalues $\alpha_{new} \pm j\beta_{new}$, the new imaginary part (β_{new}) is specified at β. Thus, the undamped natural frequency ω_n can be determined by

$$\omega_n = \beta_{new} / \sqrt{1-\zeta^2} \quad (19)$$

As a result, the new real part α_{new} can be calculated by

$$\alpha_{new} = \zeta\omega_n \quad (20)$$

The new eigenvalue in S-plane can be transformed to Z-plane by

$$z = e^{sT} = e^{(-\alpha \pm j\beta)T} \quad (21)$$

where T is the sampling period. By representing (17) in a discrete form [5], the discrete feedback scheme of ΔP_{SSSC} can be expressed as

$$\Delta P_{SSSC} = -k_{\Delta f_1} \Delta f_1 - k_{\Delta P_{T12}} \Delta P_{T12} \quad (22)$$

As depicted in Fig.2, the feedback signals Δf_1 and ΔP_{T12} are sampled with the sampling period T which is set appropriately at 0.5 [sec]. The power output deviation of SSSC ΔP_{SSSC} is obtained through the Zero Order Hold (ZOH).

4. Control Design and Evaluation Effects

In this paper, a two area interconnected system (400 MW : 2,000 MW) with reheat steam turbine [3] is used to design and evaluate the effects of SSSC controller. The linearized model based on the load-frequency control (LFC) including the dynamics of turbines-governors is delineated in Fig.3.

Note that, since the time constants of an automatic voltage regulator (AVR), an excitation system, field and the damper windings of the generator are much smaller than those of turbines-governors in LFC loop, their transient responses decay much faster and do not affect the LFC loop [7]. Consequently, the dynamics of these components are not included in the linearized power system model.

The results of SSSC controller design are given in table 1.

Table 1. Control Design Results

Design Steps	Numerical Results
1. Inter-Area Mode (17)	$\lambda_{1,2} = \underline{-0.02} \pm j0.88$
2. Design Specification	$M_p = 10\%$
3. New Eigenvalues in S-Plane	$\lambda_{1,2} = \underline{-0.65} \pm j0.88$
4. New Eigenvalues in Z-Plane	$\lambda_{1,2} = 0.65 \pm j0.31$
5. Discrete State Feedback Scheme	$[k_{\Delta f_1}, k_{\Delta P_{T12}}] = [-0.2, -0.4]$

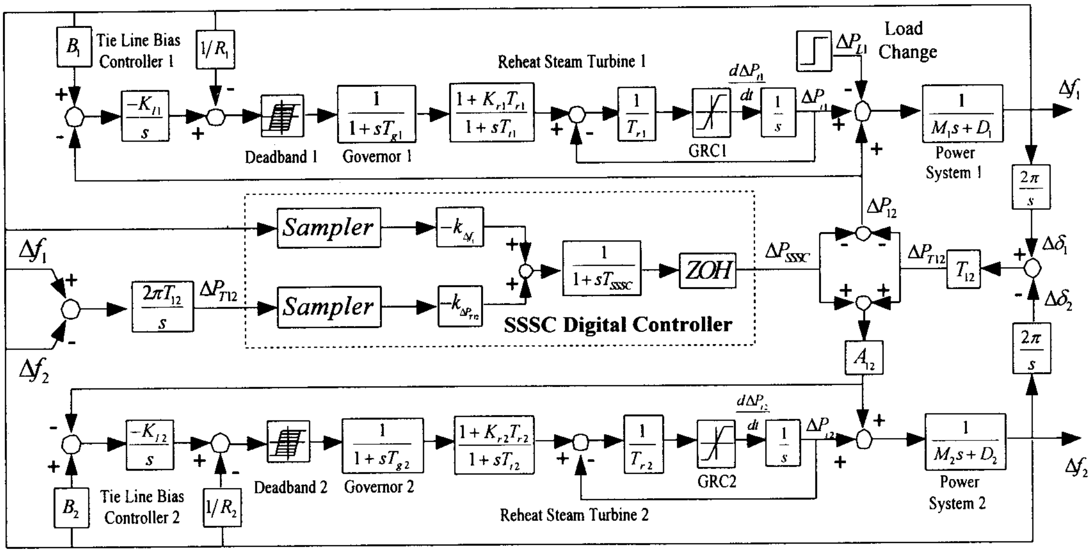

Figure 3. Digital Controller of SSSC in a Linearized Model of Two Area System including Governor

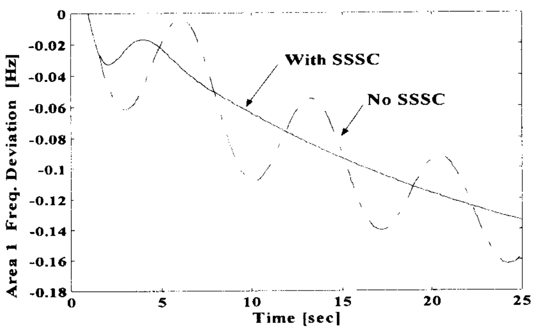

Figure 4. Frequency Deviation of Area 1 (No Governors)

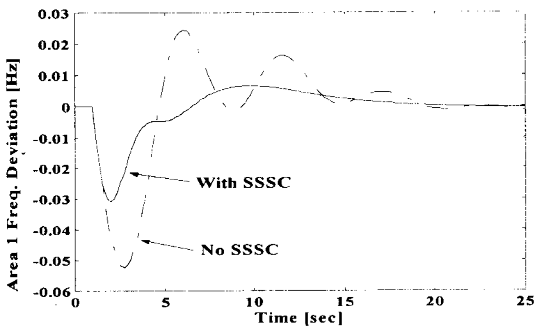

Figure 5. Frequency Deviation of Area 1 (With Governors)

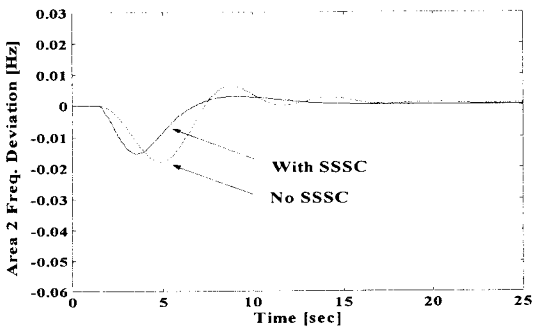

Figure 6. Frequency Deviation of Area 2 (With Governor)

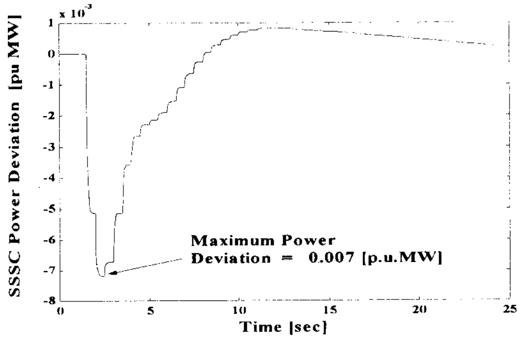

Figure 7. Power Output Deviation of SSSC

In the area 1, in addition to a large load with fast change, the Generation Rate Constraint (GRC) is also equipped with the turbine of area 1 as shown in Fig.3. The rate of change in turbine power output with respect to time ($d(\Delta P_{t1})/dt$) is restricted as $-0.1/60 \leq d(\Delta P_{t1})/dt \leq 0.1/60$ [pu MW/sec]. As mentioned in [8], the turbine equipped with GRC experiences large overshoot of frequency oscillations with a long settling time due to the inadequate generation of power during the occurrence of abrupt load change. This situation may emerge in a deregulated power system such a case that many IPPs with insufficient frequency control capabilities have been concentrated in the area 1. Here, it is assumed that a 4 MW (0.01 [pu MW]) step load occurs in an area 1 at t = 1.0 [sec]. Figure 4 indicates that in case of no governors, the frequency oscillations which are composed of the inter-area mode and the inertia center mode are very large and undamped. After applying an SSSC, the first overshoot of frequency deviation is suppressed as expected by the design specifications. At the same time, the oscillatory part due to the inter-area mode is also stabilized completely. Although, the frequency deviation due to the influence of inertia center mode continuously increases because of the difference between generation power and load power, the governors are expected to solve this problem. As shown in Figs. 5 and 6, after the suppression of peak frequency deviations of both areas by SSSC, governor systems continue to eliminate the steady state error of frequency deviations slowly, as expected. The required MW capacity of SSSC is evaluated from the peak value of power output deviation of SSSC, (ΔP_{SSSC}). As depicted in Fig.7, the necessary MW capacity of SSSC is about 0.007 [pu MW], which is less than the size of load change.

5. Conclusions

In this paper, a new application of Static Series Synchronous Compensator (SSSC) to stabilization of frequency oscillation in an interconnected power system is proposed. The interconnections between two areas are utilized as the control channels of tie-line power flow of SSSC for frequency stabilization. The design method of digital controller via the technique of overlapping decompositions and discrete eigenvalue assignment is presented. The digital controller of SSSC is constructed by a simple state-feedback scheme which is easy to implement in practical power system. Simulation study explicitly confirmed the significant effects of the proposed controller.

In this study, the dynamics of AVR loop, excitation system, damper and field windings are neglected in the power system model. However, these components may cause some interactions with the high-speed control of SSSC. This problem will be carefully investigated in the future study.

The proposed SSSC application can be expected to be a new method of interconnection of the future AC power system against the HVDC (High Voltage Direct Current) transmission system. Moreover, it is also expected to be a new ancillary service for stabilization of frequency oscillations in the next century of deregulated power system.

6. References

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Appendix

System Data [3]

- Inertia Constant

  $M_1 = 0.2,\ M_2 = 0.167$ [p.u.MW.s/Hz]

- Damping Coefficient

  $D_1 = D_2 = 0.00833$ [pu MW/Hz]

- Turbine Gain

  $K_{r1} = K_{r2} = 0.333$

- Reheat Turbine Time Constant

  $T_{r1} = T_{r2} = 0.3$ [sec]

- Turbine Time Constant

  $T_{t1} = T_{t2} = 0.3$ [sec]

- Governor Time Constant

  $T_{g1} = T_{g2} = 0.2$ [sec]

- Regulation Ratio

  $R_1 = R_2 = 2.4$ [Hz/pu MW]

- Bias Coefficient

  $B_1 = B_2 = 0.2$ [pu MW/Hz]

- Integral Controller Gain

  $K_{I1} = K_{I2} = 0.4$ [1/sec]

- Synchronizing Power Coefficient

  $T_{12} = 0.02$ [pu MW/rad]

- Area Capacity Ratio

  $A_{12} = 0.2$