Application of SMES Coordinated with Solid-State Phase Shifter to Load Frequency Control

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Abstract - **This paper proposes a sophisticated application of SMES to Load Frequency Control (LFC) in an interconnected power system. The SMES is coordinated with a solid-state phase shifter to enhance the LFC. The frequency control concept and control design of a SMES coordinated with a phase shifter are presented. Numerical results demonstrate the significant effects of LFC by the proposed control and the economical advantage of MJ capacity of SMES.**

I. Introduction

Various kinds of apparatus with a large and pulsive power consumption, for example a magnetic levitation transportation or a testing plant for nuclear fusion and so on, are expected to increase in the near future. Under these situations, the governor system may no longer be able to absorb the frequency fluctuations. In order to compensate for the sudden load changes, an active power source with fast response such as SMES is expected as the most effective countermeasure.

In the literature [1], a SMES is located in each area of two area system for LFC. As it has been expected, the frequency deviations of both areas are effectively suppressed. However, it may not be feasible to locate a SMES in every possible area of a multi-area interconnected system due to the economical reason. Therefore, it should be advantageous if a SMES with a large capacity located in an area, is available for the control of other interconnected areas. Series power flow controllers among FACTS [2] devices such as a solid-state phase shifter allow us to realize the control. Thus, this paper proposes a sophisticated control method using a SMES coordinated with a phase shifter for the LFC. Since the stored energy in a SMES is simultaneously used for the LFC of more than two areas, it is expected that the required MJ capacity is significantly reduced by the averaging effect of load variations.

First, the frequency control concept by a SMES with a phase shifter is described. A control design of a SMES and a phase shifter to enhance the inertia center mode as well as the inter-area oscillation mode is presented. The effect of LFC by the proposed control is investigated in a two area interconnected model system. The necessary MW and MJ capacities of SMES is also investigated in comparison with the control by two units of SMES.

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II. Concepts of Control Design

A. Frequency Control by SMES with Phase Shifter

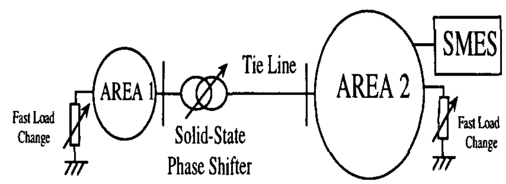


Fig. 1. SMES with Phase Shifter in Two Area System

A two area interconnected system, shown in Fig.1, is used to describe the concept of frequency control by SMES with phase shifter. It is assumed that a load with a large sudden change is installed in every area. As a result, the requirement of frequency controls of both areas are beyond their governors capabilities. A SMES located in area 2 operated as a main apparatus to absorb and supply the required active power to compensate for sudden load fluctuations in both areas. The load fluctuation in area 2 is controlled by the SMES, whereas it is difficult to compensate for the load fluctuation in area 1 by the SMES espectially in case that both areas are weakly interconnected through a long tie line. The phase shifter located in series with the tie line between two areas is capable of assisting the control of SMES. Thus, the required active power modulations necessary for the LFC of both areas are carried out by the phase shifter as well as the SMES, while the energy is commonly supplied by the SMES.

B. System Modeling for Control Design

The SMES and the phase shifter are superior to the governor system in terms of the response speed against the frequency fluctuations. Therefore, the operational tasks are assigned according to the response speed as follow. The SMES and the phase shifter are charged with suppressing the peak value of frequency deviations quickly against the sudden load change, subsequently the governor systems are charged with compensating for the steady state error of the frequency deviations. Figure 2 shows the model for the control design of SMES and phase shifter,

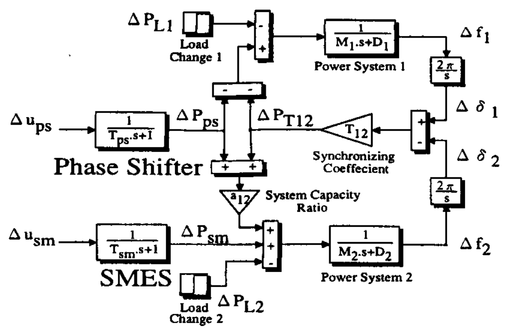


Fig. 2. Linearized Reduction Model for Control Design

where the dynamics of governor systems are eliminated by setting the mechanical inputs to be constant since the response of governor is much slower than that of SMES or phase shifter. The SMES is modeled as an active power source to area 2 with a time constant T_{sm}. The phase shifter is modeled as a tie line power flow controller with a time constant T_{ps}. The tie line power flowing into area 2 flows out from area 1. Therefore, the tie line power modulated by the phase shifter flows into both areas simultaneously with different signs (+ and -). Since the responses of power control by the SMES and by the phase shifter are sufficiently fast compared to the dynamics of the frequency deviations, the time constants T_{sm} and T_{ps} are regarded as 0 sec for the control design. Then the state equation of the system represented by Fig.2 becomes

$$\begin{bmatrix} \Delta\dot{f}_1 \\ \Delta\dot{P}_{T12} \\ \Delta\dot{f}_2 \end{bmatrix} = \begin{bmatrix} -\frac{D_1}{M_1} & -\frac{1}{M_1} & 0 \\ 2\pi T_{12} & 0 & -2\pi T_{12} \\ 0 & \frac{a_{12}}{M_2} & -\frac{D_2}{M_2} \end{bmatrix} \begin{bmatrix} \Delta f_1 \\ \Delta P_{T12} \\ \Delta f_2 \end{bmatrix} + \begin{bmatrix} -\frac{1}{M_1} & 0 \\ 0 & 0 \\ \frac{a_{12}}{M_2} & \frac{1}{M_2} \end{bmatrix} \begin{bmatrix} \Delta P_{ps} \\ \Delta P_{sm} \end{bmatrix} \quad (1)$$

where $\Delta f_i, i = 1,2$ is the frequency deviation of area i, ΔP_{T12} is the tie line power deviation, D_i is the damping coefficient of area i, M_i is the inertia constant of area i, T_{12} is the synchronizing power coefficient, a_{12} is the area capacity ratio between two areas, ΔP_{ps} is the actuating tie line power by the phase shifter and ΔP_{sm} is the power output of the SMES.

This system has three eigenvalues; one real eigenvalue corresponds to the inertia center mode and one conjugate pair of complex eigenvalues corresponds to the inter-area oscillation mode. Here, from the physical viewpoint it is noted that the phase shifter located between two areas is effective to stabilize the inter-area oscillation mode only, then the SMES which is capable of supplying the energy into the power system should be suitable for the control of the inertia mode. A coordinated control design based on the identified dynamical modes is derived in the following section.

III. Coordinated Control Design

A. Control Design of SMES

The design process starts from the reduction of two area system into one area which represents the inertia center mode of the overall system. The controller of SMES is designed in the equivalent one area system to reduce the frequency deviation of inertia center. The equivalent system is derived by assuming the synchronizing coefficient T_{12} to be large. From the state equation of ΔP_{T12} in (1),

$$\frac{\Delta\dot{P}_{T12}}{2\pi T_{12}} = \Delta f_1 - \Delta f_2 \quad (2)$$

setting the value of T_{12} in (2) to be infinity, yields $\Delta f_1 = \Delta f_2$. Next, by multiplying state equations of $\Delta\dot{f}_1$ and $\Delta\dot{f}_2$ in (1) by M_1 and M_2/a_{12} respectively, then

$$M_1\Delta\dot{f}_1 = -D_1\Delta f_1 - \Delta P_{T12} - \Delta P_{ps} \quad (3)$$

$$\frac{M_2}{a_{12}}\Delta\dot{f}_2 = -\frac{D_2}{a_{12}}\Delta f_2 + \Delta P_{T12} + \Delta P_{ps} + \frac{1}{a_{12}}\Delta P_{sm} \quad (4)$$

By summing (3) with (4) and using the above relation $\Delta f_1 = \Delta f_2 = \Delta f$, then

$$\Delta\dot{f} = \frac{(-D_1 - \frac{D_2}{a_{12}})}{(M_1 + \frac{M_2}{a_{12}})}\Delta f + \frac{1}{a_{12}(M_1 + \frac{M_2}{a_{12}})}\Delta P_{sm} + C\Delta P_L \quad (5)$$

where the load change in this system (ΔP_L) is additionally considered. Here, the control $\Delta P_{sm} = -k_{sm}\Delta f$ is applied then

$$\Delta f = \frac{C}{s + A + k_{sm}B}\Delta P_L \quad (6)$$

where, $A = (-D_1 - D_2/a_{12})/(M_1 + M_2/a_{12})$, $B = 1/a_{12}(M_1 + M_2/a_{12})$. Since the control purpose of SMES is to suppress the deviation of Δf quickly against the sudden change of ΔP_L, the percent reduction of the final value after applying a step change of ΔP_L can be given as a control specification. In (6), the final values with $k_{sm} = 0$ and with $k_{sm} \neq 0$ are C/A and $C/(A + k_{sm}B)$, respectively. Therefore, the percent reduction is represented by

$$(C/(A + k_{sm}B))/(C/A) = R/100 \quad (7)$$

For a given R, the control gain of SMES is calculated as

$$k_{sm} = \frac{A}{BR}(100 - R) \quad (8)$$

B. Control Design of Phase Shifter

The controller for the phase shifter is designed to enhance the damping of the inter-area mode. In order to extract the inter-area mode from the system (1), the concept of overlapping decompositions [3] is applied. First, the state variables of the system (1) are classified into three groups, i.e., $x_1 = [\Delta f_1], x_2 = [\Delta P_{T12}], x_3 = [\Delta f_2]$. Next, the system (1) is decomposed into two decoupled subsystems, where the state variable ΔP_{T12} is duplicatedly included in both subsystems, which is the reason that this process is called "*Overlapping Decompositions*". Then, one subsystem which preserves the inter-area mode is represented by

$$\begin{bmatrix} \Delta\dot{f}_1 \\ \Delta\dot{P}_{T12} \end{bmatrix} = \begin{bmatrix} -\frac{D_1}{M_1} & -\frac{1}{M_1} \\ 2\pi T_{12} & 0 \end{bmatrix} \begin{bmatrix} \Delta f_1 \\ \Delta P_{T12} \end{bmatrix} + \begin{bmatrix} -\frac{1}{M_1} \\ 0 \end{bmatrix} \Delta P_{ps} \quad (9)$$

It has been proved that the stability of original system is guaranteed by stabilizing every subsystem [3]. Therefore, the control scheme of phase shifter is designed to enhance the stability of the system (9) by using the eigenvalue assignment method. Here let the conjugate eigenvalue pair of the system (9) be $\alpha \pm j\beta$, which corresponds to the inter-area mode. The control purpose of phase shifter is to damp the peak value of frequency deviation in area 1 after a sudden change in the load demand. Since the system (9) is the second order oscillation system, the percent overshoot $M_{P(new)}$ can be specified for the control design. $M_{P(new)}$ is given as a function of the damping ratio by

$$M_{P(new)} = e^{(-\zeta\pi/\sqrt{1-\zeta^2})} \quad (10)$$

The real and imaginary parts of eigenvalue after the control are expressed by

$$\alpha_s = \zeta\omega_n \quad (11)$$

$$\beta_s = \omega_n\sqrt{1-\zeta^2} \quad (12)$$

where ω_n is the undamped natural frequency. By specifying M_P and assuming $\beta_s = \beta$, the desired pair of eigenvalue is appointed. As a result, the eigenvalue assignment method derives the feedback scheme as

$$\Delta P_{ps} = -k_1\Delta f_1 - k_2\Delta P_{T12} \quad (13)$$

IV. Simulation Study

The effects of the proposed SMES coordinated with phase shifter on LFC are investigated in a two area interconnected system with reheat steam turbine generators [1], as shown in Fig.3. The time constants representing the dynamics of power control by the phase shifter and by the SMES are both set at $T_{sm} = T_{ps} = 0.03$ sec. This system consists of two 2,000 MW areas, which incorporates Generation Rate Constraint (GRC) and governor deadband. The GRC is represented by $-0.1/60 \leq \Delta\dot{P}_{ti} \leq 0.1/60$ p.u.MW/sec, i = 1, 2, which detracts from the effectiveness of LFC. In this system, it is assumed that the tie line between both areas is very long, so that the synchronizing coeffecient T_{12} is very small. Here, T_{12} is set at 0.02 MW/rad.

The designed control parameters of SMES and phase shifter are shown in Table 1. It is assumed that a 20 MW (0.01 p.u.MW) step load disturbance occurs in area 1 at t = 1.0 sec. Simulation results are shown in Figs.4 and 5. The control results only by the phase shifter or only by the SMES in area 2 are not effective to suppress the first peak frequency deviation of area 1. On the other hand, in case

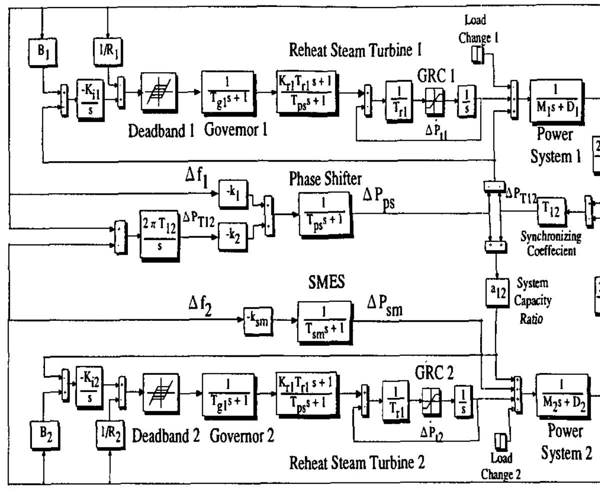


Fig. 3. SMES with Phase Shifter in Two Area Full Model System

TABLE I

SMES with Phase Shifter Control Design Results

SMES	1. Design Specification, $R = 12$ 2. SMES Gain by (7), $k_{sm} = 0.12$
Phase Shifter	1. Eigenvalue of System (9) $\lambda = -0.0250 \pm j0.868$ (Inter-area mode, $M_P = 91.35\%$) 2. Design Specification, $M_{P(new)} = 25\%$ 3. New Eigenvalue of System (9) $\lambda_{(new)} = -0.383 \pm j0.868$ 4. State Feedback Gain (13) $[k_1 \;\; k_2] = [-0.1193 \;\; -0.1938]$

of SMES with phase shifiter, the SMES in area 2 is not only effective to diminish the peak frequency deviation of area 2, but also capable of enhancing the frequency control effect of phase shifter for area 1. The system constants and the disturbance set here are the same in [1], where two units of SMES (one for each area) are installed. In comparison with the control results in [1], it can be said that the effects of the SMES coordinated with the phase shifter are the same with those of two units of SMES.

Here, the MW and MJ capacities required for the control are evaluated in comparison with the case of two units of SMES in [1]. The required MW capacities of SMES and phase shifter are evaluated from the peak value of power output of the SMES and the peak value of tie line power modulation by the phase shifter, respectively, which are shown in Fig.6. The MJ capacity is evaluated from the energy deviation of SMES ΔE_{sm} shown in Fig.7 as

$$\Delta E_{sm} = \int \Delta P_{sm} dt \quad (14)$$

$$SMES\ MJ\ Capacity = \Delta E_{sm(max)} - \Delta E_{sm(min)} \quad (15)$$

The results indicate that the MW capacities of SMES and phase shifter are 0.0042×2,000 = 8.4 MW and 0.005×2,000 = 10 MW, respectively. The MJ capacity

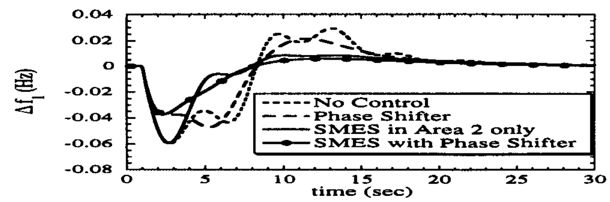


Fig. 4. Frequency Deviation of Area 1

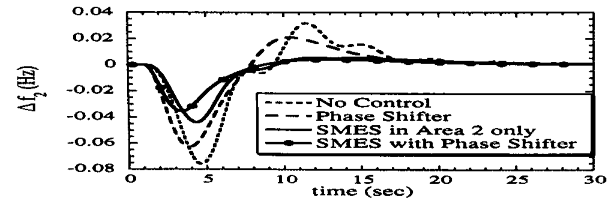
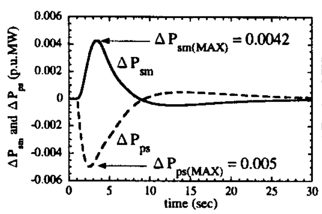


Fig. 5. Frequency Deviation of Area 2



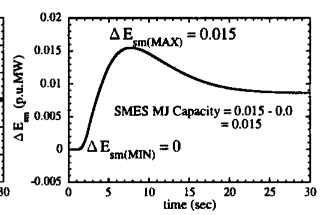
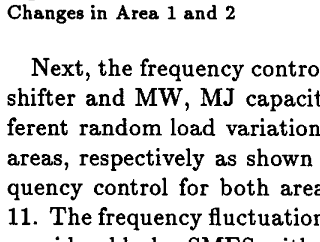


Fig. 6. Power Output of SMES and Phase Shifter

Fig. 7. Energy Deviation of SMES

of SMES is 0.015×2,000 = 30 MJ. In the case of two unit SMES in [1], the MW and MJ capacities are 10 MW and 30 MJ respectively, for each of them. This result implies that for the proposed SMES with phase shifter, the MJ capacity is reduced to half.



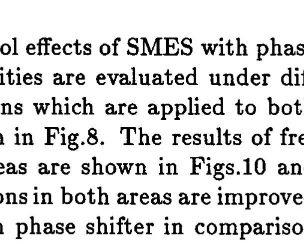


Fig. 8. Random Load Changes in Area 1 and 2

Fig. 9. MW and MJ Capacities

Next, the frequency control effects of SMES with phase shifter and MW, MJ capacities are evaluated under different random load variations which are applied to both areas, respectively as shown in Fig.8. The results of frequency control for both areas are shown in Figs.10 and 11. The frequency fluctuations in both areas are improved considerably by SMES with phase shifter in comparison with the case of no control. The results of evaluating the MW and MJ capacities are summarized in Fig.9, which are compared in the case of SMES and phase shifter with in the case of two unit SMES. The control scheme of two unit SMES is that each SMES uses the frequency devia-

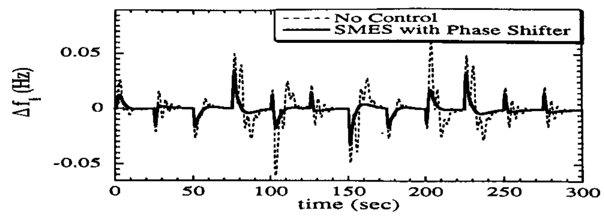


Fig. 10. Frequency Deviation of Area 1

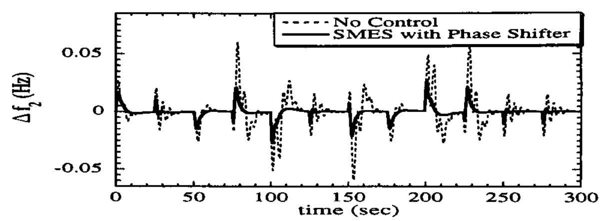


Fig. 11. Frequency Deviation of Area 2

tion of its located area as a feedback signal with a gain k_{sm} = 0.12. Note that both controls have almost same effectiveness on the frequency control. The results in Fig.9 demonstrates that the MW capacities are the same in both cases while total MJ capacities of SMES are drastically reduced in the case of SMES coordinated with phase shifter. The reason can be explained as follows. In the case of two unit SMES, each SMES independently operates to diminish the frequency deviation of its located area. On the contrary in the case of SMES coordinated with phase shifter, the control power to diminish the frequency deviation of area 1 is modulated by the phase shifter, which is supplied from area 2. As a result the load variations in areas 1 and 2 are averaged in area 2, which should be the control objective of the SMES.

V. Conclusions

In this paper, a sophisticated LFC by a SMES coordinated with a solid-state phase shifter is proposed. It has been demonstrated that by the design concept of damping the inertia mode and the inter-area mode, the coordinated control are effective to suppress the frequency deviations of two area system simultaneously. The LFC effect are almost the same with the control by two units of SMES, whereas the MJ capacity of SMES in the case of proposed control is drastically reduced due to the averaging effect of load variations in both areas.

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