AGC of a Hydrothermal System with SMES Unit

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***Abstract* — In this paper, the AGC improvement of a two area interconnected hydrothermal system along with a Superconducting Magnetic Energy Storage is proposed. Generation Rate Constraints are also considered. Integral Squared Error technique is used to obtain the optimum values of the integral gain settings. Analysis reveals that the dynamic responses are considerably improved in the presence of the SMES unit. A comparison and analysis of the dynamic performances without and with SMES unit in the presence of GRC brings out the superior performance of the SMES unit in suppressing the frequency and inter-area tie-power deviations from their nominal values followed by a step load perturbation.**

***Index Terms* — AGC, ACE, Hydrothermal, ISE technique, Optimization.**

I. INTRODUCTION

Interconnected electric power systems consist of a number of control areas, which generate power to match the demanded power. To maintain the power system in its nominal state, at each instant, the generated power should exactly match the demanded power plus the associated system losses. However, the loads are random and unpredictable. Further, the ability of the generation to track the changing load is limited due to physical / technical considerations. Hence, the exact power generation – consumption equilibrium cannot be satisfied in practice. As the generation chases the load variations, the area frequencies and tie power deviate from their scheduled values resulting in accumulations of time error and inadvertent power interchanges between the control areas. Thus, the main objectives of Automatic Generation Control (AGC) are to maintain the area frequencies and the tie powers at their respective scheduled values as close as possible so that the steady state errors of these deviations are minimized and the quality of the power delivered is maintained.

With the growth in the interconnections of power systems, such frequency and inter area tie-line power oscillations arising out of small load perturbations has been a source of great concern and has attracted wide attention as revealed by the bulk of works reported in the literature [1]-[7]. The crux of AGC problem lies in the fact that the generator rotors are the only elements of a power system which can store rotational kinetic energy. Thus when a sudden load perturbation occurs, because of the huge inertia of the generator rotors, the additional power demand cannot be met instantaneously. In general, the strategies proposed for mitigating the AGC problem are concerned with adjusting the governor output in accordance to the load. But, most of the proposed approaches for AGC improvement could not be implemented practically because of the operational constraints and the severe costs associated with it.

Since fast-acting energy storage devices provide storage capacity, they can be considered for effectively suppressing such oscillations in the power system as and when required. A Superconducting Magnetic Energy Storage (SMES) is a device for storing and instantaneously discharging large quantities of power. It stores energy in the magnetic field created by the flow of DC in a coil of superconducting material that has been cryogenically cooled since direct current flows with almost zero losses in superconductors. SMES is very efficient with an energy efficiency of about 97% as there is no conversion of energy from one form to another, the cost per unit of stored energy decreases as storage capacity increases, the number of charge-discharge cycles obtainable can be huge which means longer life, has extremely short charge and discharge times which can be further accelerated to meet specific requirements depending on system capacity, has no moving parts (except in the refrigeration system), has high power density and has smaller size and reduced weight [8]-[10]. The only major losses (about 2%) during storage are the energy required to operate the refrigerator that maintains the superconducting coil below its critical temperature and the normal resistances associated with the silicon devices in the Power Conversion System (PCS).

As one go through the existing literature, one will find that the application of SMES in various capacities has been explored like as a means for diurnal storage needs, improvement of stability, damping and as a spinning reserve to transmission systems [11]-[12], as a tool for load-leveling and load-following purposes as well as for load-frequency stabilization and VAR compensation [13]-[15]. It may also be noted that the bulk of the work reported pertain to thermal systems. Practically no work has been reported concerning with the application of SMES for the AGC improvement of a hydrothermal power system.

Hence, this paper presents the analysis of (AGC) of a two-area interconnected hydrothermal system considering an SMES unit in the thermal area. Such an analysis seems to be important since, the operational performance of hydroelectric units is quite different from that of thermal units. The latter are inconvenient to start/stop and frequently adjust their output. On the contrary, the hydro units are suitable to do so.

II. The Two Area Hydrothermal Model

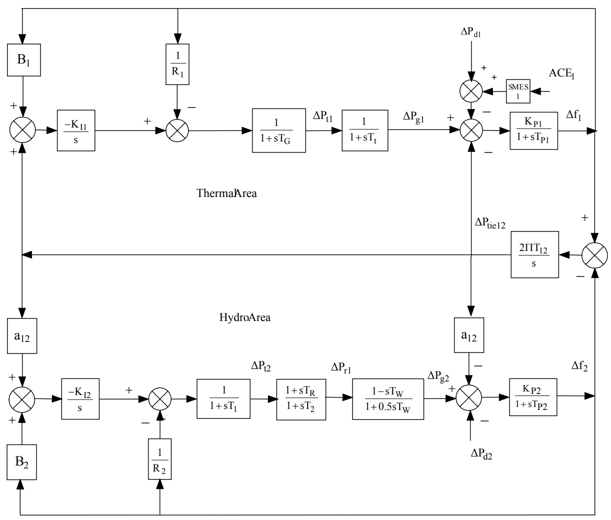

Fig. 1. Two Area Hydrothermal System with SMES unit

Area 1 consists of a nonreheat turbine and a Generation Rate Constraint (GRC) of 10% per minute is imposed on the turbine. Area 2 consists of a hydro unit and a GRC of 270% per min. for raising generation and 360% per min. for lowering generation are considered A step load perturbation of 1% of the nominal loading is considered in either of the areas. The nominal parameters of the system are given in the Appendix.

The transfer function block diagram model of the interconnected hydrothermal power system along with SMES unit in thermal area is illustrated in Fig. 1. The dynamic behavior of such a linearised system can be described by the state space model as

$$\dot{X} = AX + BU + \Gamma p \tag{1}$$

where X, U and p are the state, input and disturbance vectors and A, B and Γ are constant matrices of appropriate dimensions associated with them. The various state variables chosen are as shown in the power system model.

III. The SMES Unit

From circuit point of view, the primary components of a SMES unit are (a) an inductor coil manufactured using either high-temperature or low-temperature superconducting wire which is the heart of the system (b) a cryostat/refrigerator that maintains the superconducting materials at cryogenic temperatures. Typically, this is liquid helium (4.2 K) for low-temperature superconductors and liquid nitrogen (77 K) for high-temperature superconductors and (c) the Power Conversion System (PCS) consisting of a 12 pulse bridge converter as shown in Fig. (2).

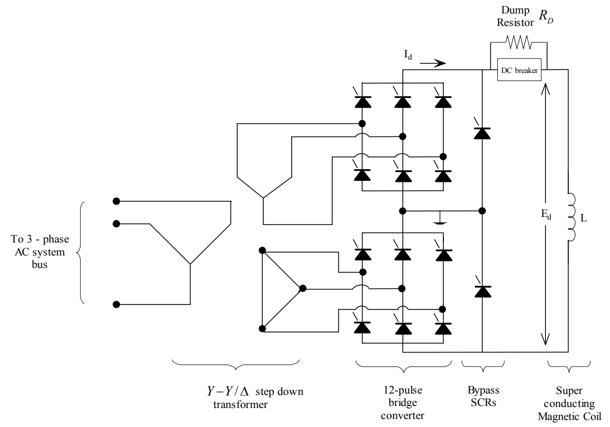

Fig. 2. SMES Circuit point of view

The bridges always maintain a unidirectional current so that a positive converter voltage V_d produces a positive power output, charging the coil and storing the energy. Similarly, for discharging, the PCS is made to appear as a load across the coil, thereby producing a negative voltage V_d causing the coil to discharge and release the energy. Though the maximum stored energy is determined by the coil geometry and the peak current (resulting in the maximum magnetic field), the maximum power is determined by the PCS power rating and the maximum coil withstand voltage. The bypass thyristors provide a path for current I_d in the event of a converter failure. A dc breaker allows I_d to be diverted into the energy dump resistor R_D if the converter fails followed by a cryogenic system failure.

By controlling the delay angle of commutation α, the bridge voltage E_d can be varied continuously throughout a wide range of positive and negative values. Assuming the losses to be negligible [16],

$$E_d = 2E_{d0}\cos\alpha - 2I_d R_D \tag{2}$$

When α = 0° in the rectifier mode, the superconducting coil gets "charged" at its maximum value with E_d at its maximum value. Once the rated current has built up in the coil, it is held constant by reducing the voltage ideally to zero which corresponds to α = 90° for the normal operating condition. The current I_d cannot reverse its direction and hence, can have only positive values. Since E_d is uniquely defined by α for positive and negative values of E_d, and I_d is not reversible, the power into the inductor, P_d is uniquely determined both in magnitude and direction. Thus, smooth and continuous reversibility as well as magnitude control of power flow can be achieved. Once the coil has attained its rated current, the SMES can be coupled with the power system and put into operation.

When there is a sudden load demand, the stored energy in SMES is immediately released to the power system. As the governor and other associated control mechanisms try to set the power system to the new equilibrium condition, the coil charges back to its initial current value. During sudden release of loads, similar is the effect. The coil immediately gets charged towards its full value, thereby absorbing some portion of the excess energy in the system. As the system returns to its steady state, the excess energy absorbed is released and the coil current attains its normal value.

In actual practice, discontinuous conduction may occur in the presence of large disturbances. To avoid such possibilities, a lower limit is imposed upon the inductor current without allowing it to reach zero. To make the SMES unit equally effective during sudden increase or decrease of load, the rated inductor current I_{d0} is set such that the maximum allowable energy absorption equals the maximum allowable energy discharge. The power flow into the inductor coil at any time is

$$P_d = E_d . I_d \tag{3}$$

If E_{d0} and I_{d0} are the magnitudes of voltage and current prior to the load disturbance, then the initial power flow into the coil is

$$P_{d0} = E_{d0} . I_{d0} \tag{4}$$

On the occurrence of a small load disturbance ΔP_d, the incremental power change in the inductor is

$$\Delta P_d = (I_{d0} \Delta E_d + \Delta E_d \Delta I_d) \tag{5}$$

and in per unit,

$$\Delta P_d = (I_{d0} \Delta E_d + \Delta E_d \Delta I_d) / P_R \tag{6}$$

IV. SMES CONTROL STRATEGY

If the tie-line power deviations are available, then Area Control error (ACE) would be a suitable choice as the control signal to the SMES unit. For area 1, ACE is given by $ACE_1 = B_1 \Delta f_1 + \Delta P_{tie12}$ where Δf_1 is the change in frequency of area 1 and ΔP_{tie12} is the change in tie-line power flow out of area 1 to 2. Thus, the incremental change in the inductor voltage and inductor current can be expressed as

$$\Delta E_{d1} = \frac{K_{ACE1}}{1 + sT_{DC1}} ACE_1 \tag{7}$$

$$\Delta I_{d1} = \frac{\Delta E_{d1}}{sL_1} \tag{8}$$

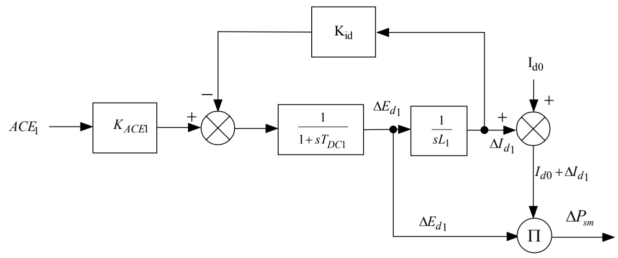

Fig. 3: SMES Block Diagram with Inductor Current Deviation Feedback

V. INDUCTOR CURRENT DEVIATION FEEDBACK

To overcome the slow current restoration process in the SMES unit and to enhance the rate of restoration, inductor current deviation feedback can be used in the SMES control loop. The inductor current deviation ΔI_d can be sensed and feedback negatively in the SMES control loops so that quick restoration of current is achieved. Then, with ACE as the control signal, deviation in inductor voltage is

$$\Delta E_{d1} = \frac{1}{1 + sT_{DC1}} [K_{ACE1} ACE_1 - K_{id} \Delta I_{d1}] \tag{9}$$

This control scheme has been represented in block diagram form in Fig. 3.

VI. PARAMETER OPTIMIZATION

Integral Squared Error (ISE) technique is used for obtaining the optimum gain settings of the integral controllers. A performance index chosen as

$$J = \int_0^t (\Delta f_1{}^2 + \Delta f_2{}^2 + \Delta P_{tie12}^2) dt \tag{10}$$

is minimized for 1% step load disturbance in either of the areas for obtaining the optimum values of the integral gain settings. Optimal values are those corresponding to the minimum of the performance index. As proposed in [17] that, the optimum value of the gain settings can be obtained on an individual basis by considering the other area uncontrolled. In the present work also, the optimum values of the integral gain settings of the investigated system is obtained by keeping the other area uncontrolled. It is found that, the optimum value of integral gain setting in the thermal area without SMES unit is $K_{I1} = K_{I1opt} = 0.1980$. Similarly for area 2, keeping the other area uncontrolled, the minimum of the above performance index is found which corresponds to the optimal value of the integral gain and the optimum value is found to be $K_{I2} = K_{I2opt} = 0.0470$. The above procedure is repeated with SMES in area 1 and ACE_1 as the input signal to the SMES unit. The optimal integral gain settings for each case are given in Table 1.

TABLE I
OPTIMAL INTEGRAL GAIN SETTINGS

Without SMES		With SMES in area 1	
K_{I1}	K_{I2}	K_{I1}	K_{I2}
0.1980	0.0470	0.5310	0.4700

It may be observed that the optimum values of the integral gain settings with the SMES unit in area 1 are higher than those without the SMES unit in area 1.

VII. DYNAMIC RESPONSES

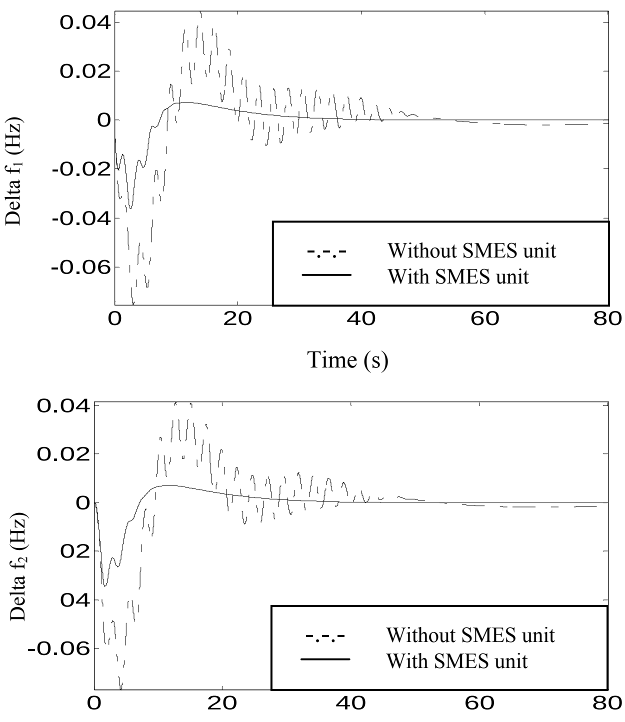

Fig.4: Dynamic responses for area frequencies following the 0.01 pu step load disturbance in area 1

The different dynamic responses without and with the SMES unit in area 1 and the 0.01 p.u. MW load disturbance in area 1 are shown in Figs. (4) and (5). Since the optimum gain settings are higher than those without the SMES unit, as expected, the dynamic responses have improved to a considerable extent. Fig. (4) depicts the area frequency deviations and it is evident that the settling time of the transient behavior has reduced to approximately 30 seconds in the presence of the SMES unit. Further, the amplitude of the oscillations has also reduced to a considerable extent. As shown in Fig. (5), the inter-area oscillations, with the SMES unit have drastically diminished and attains its zero steady state at about 30 seconds when compared with that without SMES unit wherein the settling time is more than 80 seconds.

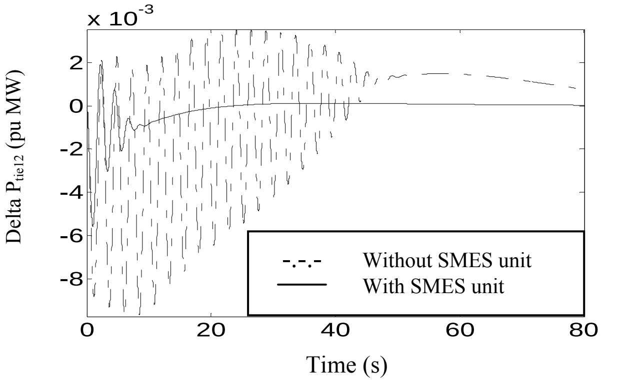

Fig.5: Dynamic response for the tie-power deviation following the 0.01 pu step load disturbance in area 1

Similarly, without and with the SMES unit in area 1, the deviations in area frequencies and inter-area tie-power oscillations when the step load disturbance is in area 2 are plotted in Figs. (6) and (7). It is evident from Fig. (6) that, without the SMES unit, the negative peak deviations of the area frequencies reach -0.08 Hz and with the SMES unit, the negative peak deviations have been reduced to a considerable extent.

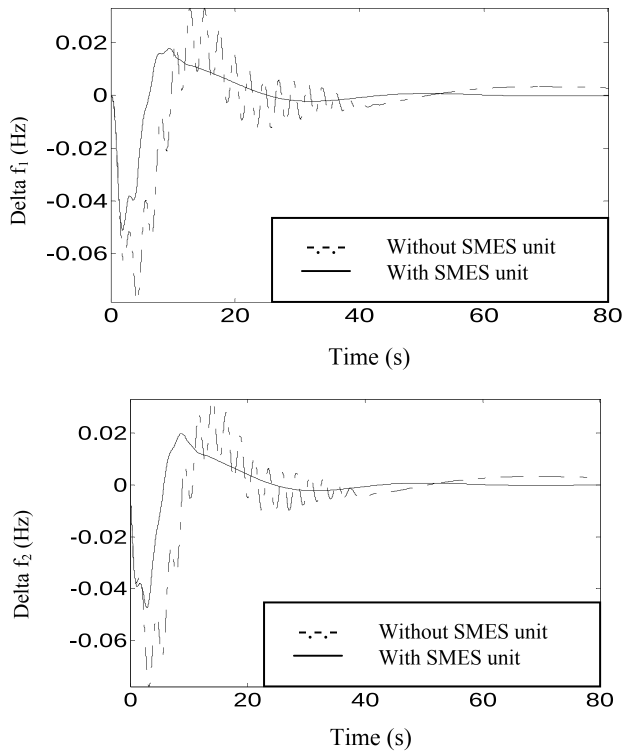

Fig.6: Dynamic responses for area frequencies following the 0.01 pu step load disturbance in area 2

The inter area tie power oscillations following the step load disturbance of 0.01 pu MW in area 2, as seen from Fig. (7), also has improved in the presence of SMES. This establishes the ability and application of the SMES unit as far as AGC improvement is concerned since it effectively suppresses the inter area tie power oscillations as well as the deviations in the area frequencies followed by a small step load change.

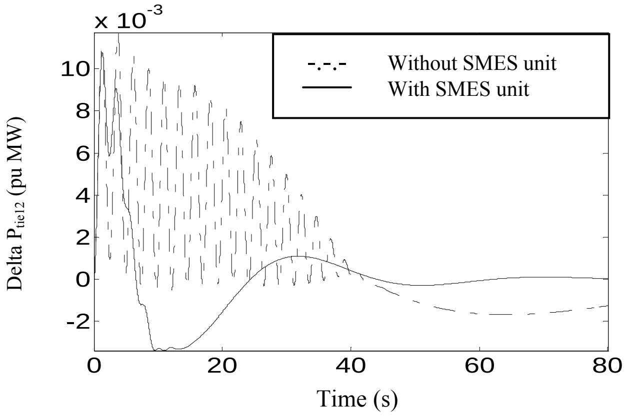

Fig.6: Dynamic responses for the tie-power deviation following the 0.01 pu step load disturbance in area 2

VIII. CONCLUSIONS

In this work, an attempt has been made to improve the AGC performance of an interconnected hydrothermal system with the use of a SMES unit in the thermal area. Area Control Error is used as the signal to the SMES control logic. The integral gain settings are obtained by minimizing a quadratic performance index using the Integral Squared Error technique. The application of SMES unit for improving the AGC of a hydrothermal interconnected system is very promising as revealed by the different dynamic responses. It is evident that, a fast acting energy storage device like SMES, is quite capable of taking up the momentary oscillations in the area frequencies and the inter area tie powers as they deviate from their respective scheduled values following a step load disturbance. Thus, an SMES unit may be recommended for AGC control especially in the futuristic power systems where frequency stabilizations are considered to be an ancillary service.

IX. APPENDIX

All notations carry the usual meanings.

(A) System Data

$P_{R1} = P_{R2} = 1200$ MW
$T_{p1} = T_{p2} = 20$ s
$K_{P1} = K_{P2} = 120$ Hz/p.u. MW
$T_{T1} = T_{T2} = T_{T3} = T_{T4} = 0.3$ s
$T_{12} = 0.0866$ s
$T_{G1} = T_{G2} = T_{G3} = T_{G4} = 0.08$ s
$R_1 = R_2 = R_3 = R_4 = 2.4$ Hz/p.u. MW
$D_1 = D_2 = 8.33 \times 10^{-3}$ p.u. MW/Hz
$B_1 = B_2 = 0.425$ p.u. MW/Hz
$p_1 = 0.01$ p.u. MW
$p_2 = 0.0$ p.u. MW

(B) Superconducting Magnetic Energy Storage Data

$L = 2.65$ H
$T_{DC} = 0.03$ s
$K_{ACE1} = 100$ kV/unit MW
$K_{id} = 0.2$ kV/kA
$I_{d0} = 4.5$ kA

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BIOGRAPHIES

Rajesh Joseph Abraham was born in Kerala, India, on October 10, 1976. He graduated in Electrical & Electronics Engineering from L. B. S College of Engineering, Kasaragod, Kerala, India in 1998, and post graduated in Guidance & Navigational Control from College of Engineering, Thiruvananthapuram, Kerala, India in 2002. Since July 2003, he is with the Department of Electrical Engineering, Indian Institute of Technology, Kharagpur, India working towards his Doctoral degree.

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Dr. Patra received the Young Engineer Award of the Indian National Academy of Engineering in 1996 and the Young Teachers' Career Award from the All India Council for Technical Education in 1995. He has been a Young Associate of the Indian Academy of Sciences during 1992-97. He is a member of IEEE (USA), Institution of Engineers (India) and a life member of the Systems Society of India.