Effect of SMES Unit on AGC Dynamics

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Abstract: In this paper, the influence of a Superconducting Magnetic Energy Storage (SMES) unit on the performance of the Automatic Generation Control (AGC) system is investigated. A comprehensive mathematical model of a two area interconnected power system is developed, taking into account boiler dynamics and nonlinearities such as governor dead band and generator rate constraints (GRC). The gain settings of the governor control system are obtained by using a least square criterion of the performance index. The results of the simulation studies on a typical test system are presented and discussed.

1 Introduction

Most published work on AGC studies adopt a simplified approach. Nonlinearities such as governor dead band, practical limits on the rate of increase of turbine output, delays associated with stored energy of steam in the boilers are often neglected. For a realistic study covering a long time frame, these have to be included in the model. Investigations have shown[1] that following a sudden change in power in an interconnected power system, the area frequencies and tie-line power undergo fluctuations which persists for a very long time, even though the governor integral controls are optimized. This phenomenon is attributed to the limit cycling caused by the nonlinearities of the system. These fluctuations are poorly damped and usually lie in the frequency range of 0.2 to 1 Hz. Since these oscillations are the result of imbalance of power, the SMES unit can be effectively used to eliminate this problem. The main advantage is that the SMES unit, once fully charged, can be utilized as a source or sink of power, and that this power transfer can be achieved very quickly and effectively, by proper design of its controller.

2. Model of the system with AGC and SMES unit

The block diagram of a two area interconnected power system with AGC is shown in Fig. 1. The SMES unit is located in area 1. The nonlinearity due to governor dead band is modeled using the Describing Function, and the approximate solution for representing backlash is [2]

$$DB_x = N_1 X + \frac{N_2}{w_0}\dot{X} \qquad (1)$$

where DB is the deadband. For this study, $N_1 = 0.8$ and $N_2 = -0.2$.

All data for the system are taken from reference [2].

The block diagram of the boiler system is shown in Fig. 2. The changes in generation are initiated by turbine control valves. Changes in steam flow and pressure are sensed and these control the combustion rate and hence the boiler output. An oil/gas fired boiler system has been assumed for this study, since such boilers have faster response compared to coal fired units. This will enable the improvement in AGC system to be more apparent.

In practical steam turbine systems, due to thermodynamic and mechanical constraints, there is a limit to the rate at which its output power (dP_g/dt) can be changed. This limit is referred to as generator rate constraint (GRC). A typical value of 0.1 p.u./min., applicable to most modern turbines, has been chosen for this study. Since the aim of this study is the investigation of the control strategy, an incremental model of the system is considered adequate.

The SMES system consists of a superconducting inductor, a 12-pulse cascaded bridge type AC/DC converter and a Y-Δ / Y-Y step down transformer as shown in Fig. 3. By suitable control of the firing angles (α) of the converter, the output voltage V_{sm} can be varied within a set range of positive and negative values [3]. Since the output current is unidirectional, this implies that the SMES can behave as a source or sink of energy. During the initial charging period, V_{sm} is held at a suitable positive value and once the current I_{sm} has reached its rated value, V_{sm} is now reduced to zero, and the SMES is now ready to be coupled to the power system. To prevent the possibility of discontinuous conduction, and to ensure that the maximum energy that can be extracted from the SMES is equal to the maximum energy that can be stored in it, limits are imposed on the value of I_{sm} [4] as follows:

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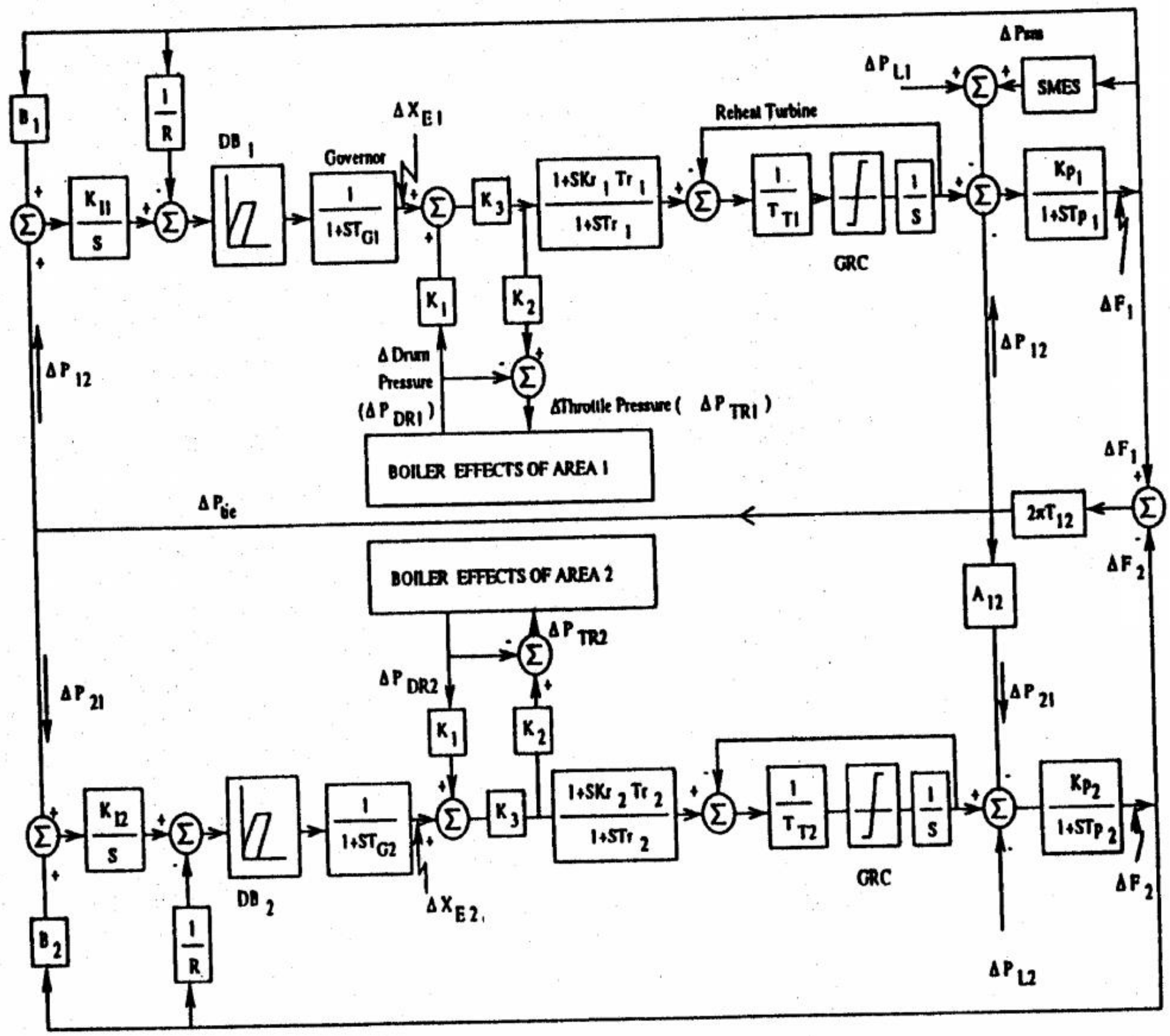

Fig. 1. Automatic Generation Control with SMES

$0.30 \le I_{sm} / I_{sm0} \le 1.38$

where I_{sm0} is the rated value of the inductor current

3. Control Strategy

For controlled two area systems, it is required that the steady-state frequency and tie line deviations, following a step load change, must be zero. This requirement guarantees that each area, in steady state, absorbs its own load. The individual Area Control Errors (ACE) can be expressed as [5]

$$ACE_1 = \Delta P_{tie\,1} + B_1\, \Delta f_1 \qquad (2)$$
$$ACE_2 = \Delta P_{tie\,2} + B_2\, \Delta f_2 \qquad (3)$$

The speed changer commands will thus be of the form

$$\Delta P_{c1} = -K_{I1} \int (\Delta P_{tie\,1} + B_1 \Delta f_1)dt \qquad (4)$$
$$\Delta P_{c2} = -K_{I2} \int (\Delta P_{tie\,2} + B_2 \Delta f_2)dt \qquad (5)$$

The constants K_{I1} and K_{I2} are integrator gains, the constants B_1 and B_2 are the frequency bias parameters of each area. The minus sign must be included since each area should increase its generation if either its frequency error Δf_i or its tie line power increment ΔP_{tiei} , is negative. In the studied system, both area have equal capacity and they are related as

$$\Delta P_{tie\,1} = - \Delta P_{tie\,2} = - \Delta P_{tie}.$$

For this study it is assumed that

$$K_{I1} = K_{I2} = K_I \text{ and } B_1 = B_2 = B.$$

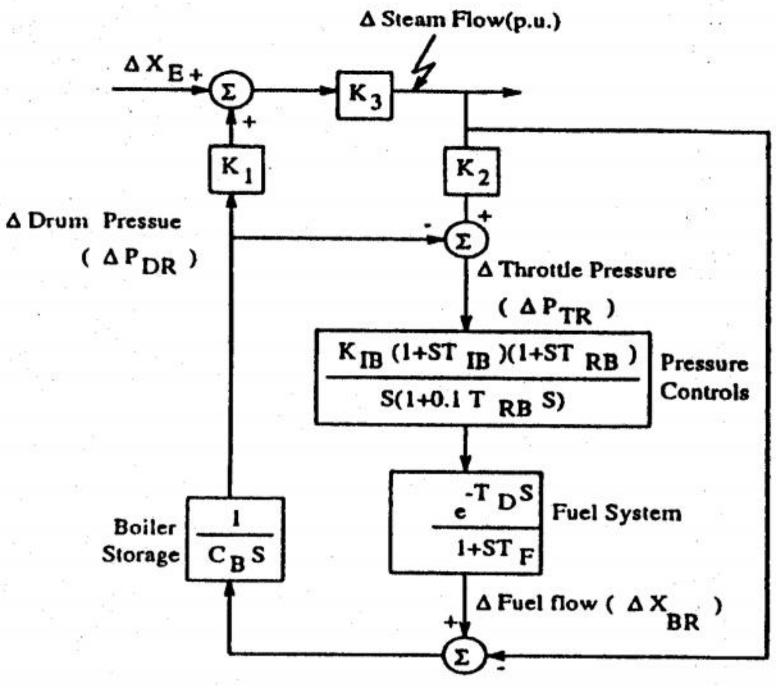

Fig. 2. The Boiler System

The optimal values of K_I and B are chosen, here, on the basis of a performance index (Eqn. 6). The performance-index (P. I.) curves are shown in Fig. 4.

$$P.\ I. = \int_0^{40} (\Delta P_{tie}^2 + w_1 \Delta f_1^2 + w_2 \Delta f_2^2)dt \qquad (6)$$

The weight factors w_1 and w_2 both are chosen as 0.25 for the system under consideration. It can be seen that the optimal integrator gain is 0.295 for B= 0.15.

The SMES control strategy is derived by utilizing the signals ΔP_{tie} and ΔI_{sm} instead of Δf_1 and Δf_2 (see Fig. 5). This has the advantage (i) that this technique works equally well for load change in either area and (ii) it does not depend whether the SMES unit is in area 1 or area 2. Furthermore this strategy ensures that both the tie line power and the SMES energy are restored to their predisturbance values. This negative feed back enables the SMES to regain its normal energy level.

The constants K_{tie} and K_{wsm} are optimized by keeping the optimized value vales of K_I and B. They are found as K_{tie} = 400 KV / unit ACE (area control error) and K_{Ism} = 2.4 KV/p.u. KA It is reported in the reference [4] and also found in the present study that the sensitivity of the system is reduced to changes in K_I for the power systems with energy storage units.

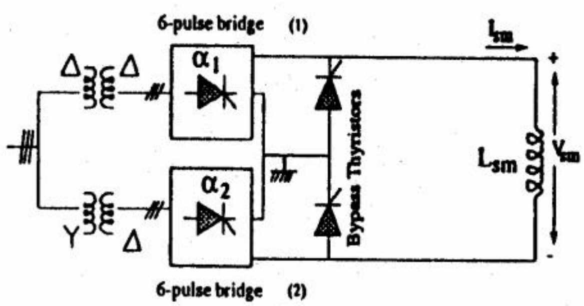

Fig. 3 Schematic diagram of SMES unit

4. Simulation Results and Discussion

The response of the two area interconnected power system of Fig. 1, to a step increase of demand of 0.01 p.u. (10 MW) was studied in detail. The time variation of frequency in each area, the tie line power, and the generator output rate (for the case without a SMES unit) are shown in Fig. 6. With no limit imposed on generator output rate (dP_g/dt), it reaches a value which is more than double the maximum value that can be practically feasible. With the output rate constrained to 0.1 p.u. /min., the response has become worse, as expected. In addition to the anticipated response of exponentially decaying modes associated with tuned integral controllers, there exists poorly damped oscillations of substantial magnitude, having a frequency of about 0.4 Hz, which persists even after 40 seconds. This confirms the fact that GRC and other nonlinearities have to be included in simulation studies to obtain realistic results.

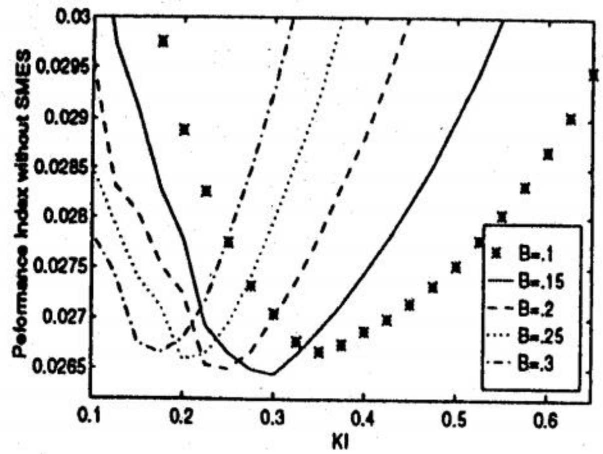

Fig. 4 The performance index versus K_I curves (without SMES)

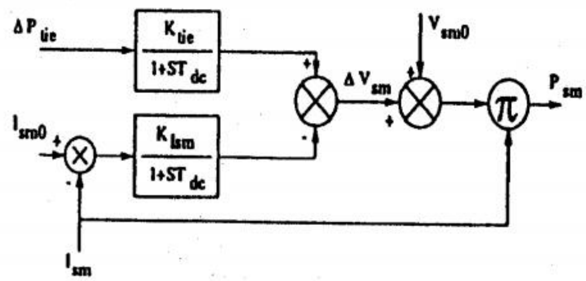

Fig. 5 SMES control strategy

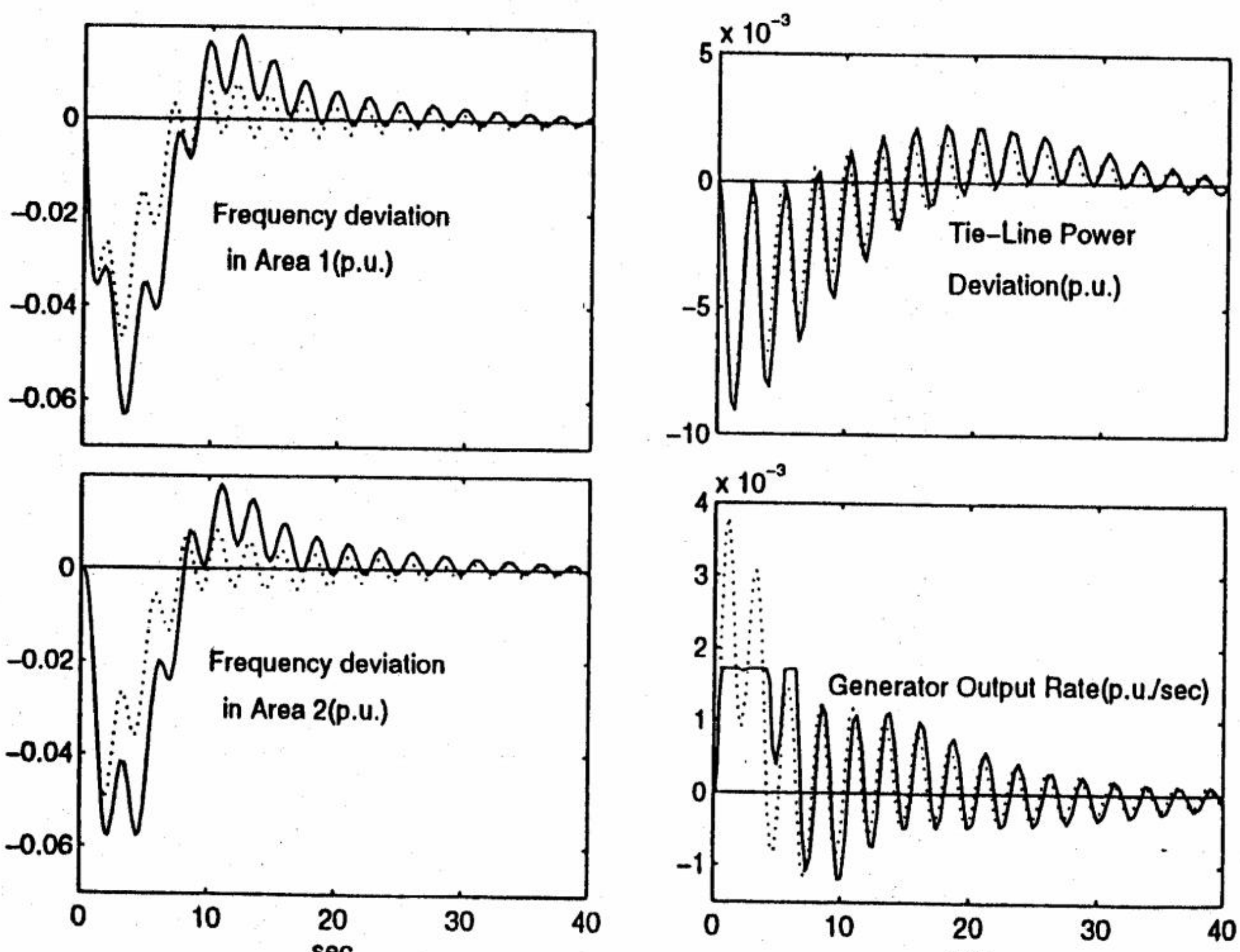

Fig. 6 System performances without SMES (......... without dP_g/dt limit, ____with dP_g/dt limit)

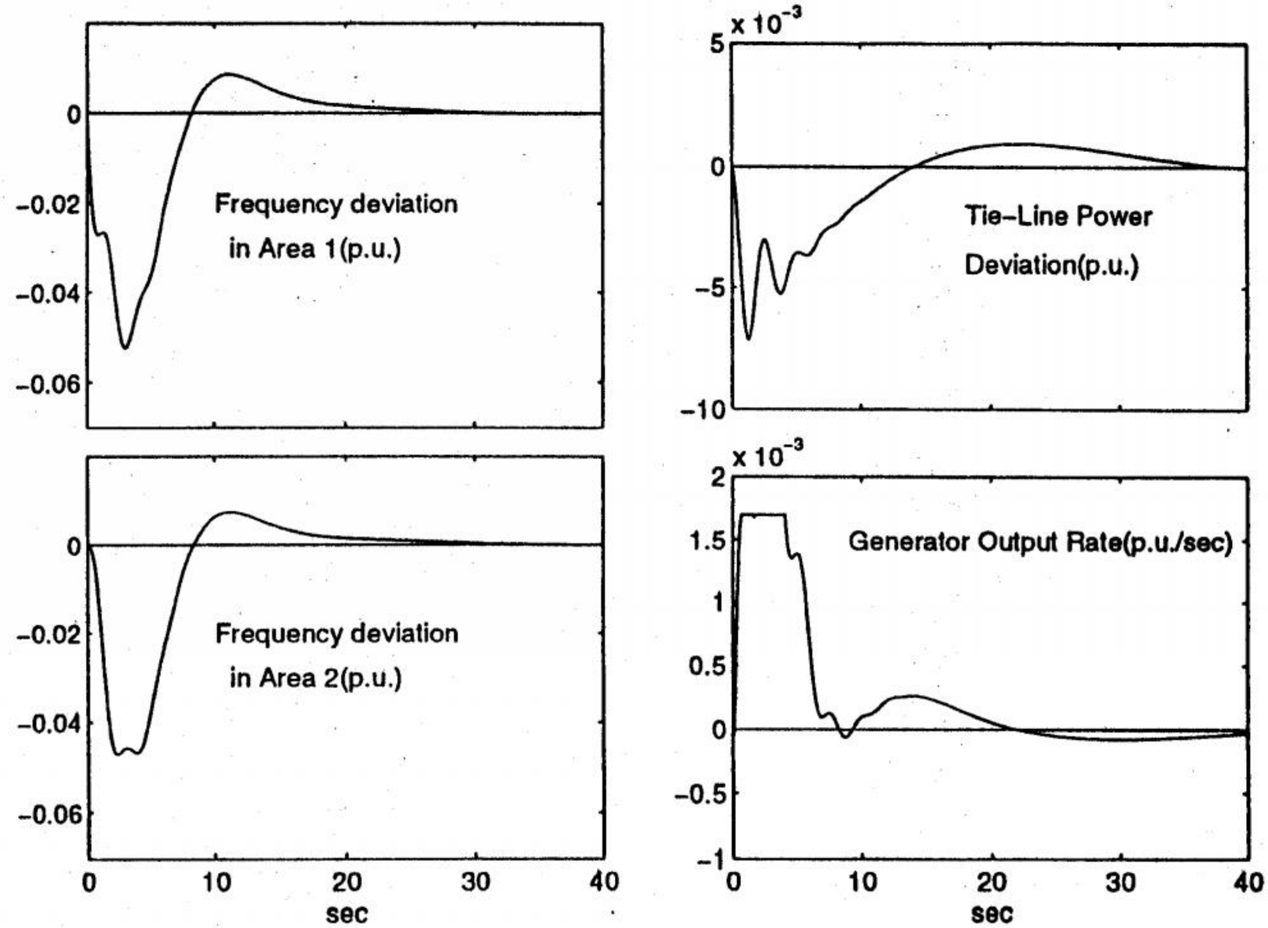

Fig. 7 Response of AGC with SMES

The response of the same disturbance when a SMES unit of reasonable size (6 MJ), is added to area 1, is shown in Fig. 7. The striking feature is that all the oscillatory components in tie lie power and area frequencies are virtually eliminated., even though the generator output rate is limited. As a consequence, the maximum deviations of the area frequencies and tie line power are also reduced significantly. The variation of inductor voltage, current, power and energy are shown in Fig. 8. A comparison of the tie line powers of Fig. 6, Fig. 7 and the SMES power of Fig. 8 show that almost all the oscillatory components of the power of Fig. 6 is taken up by the SMES unit, thereby demonstrating the effectiveness of the control strategy. A necessary implication is that, if the fluctuations in the tie line power is larger, then the SMES unit can not absorb/deliver more than its rating.

5. Conclusion:

It has been shown that the presence of the relatively small size SMES unit can improve the dynamic response of the AGC system of interconnected power systems. By using the tie line power and the inductor current as the control signals, the SMES unit is effective in damping out the oscillations that persists in the system following a disturbance. This study also confirms the fact that system nonlinearities such as ceiling limits on output rate, governor backlash, and boiler delays have to be included when dealing with simulation studies covering a long time frame.

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Appendix

System Data (2,3)

Area Capacity, $P_{R1} = P_{R2} = 1000$ MW
$f^{\circ} = 60$ Hz $K_{P1} = K_{P2} = 120$ Hz. /p.u. MW
$R_1 = R_2 = 2.4$ Hz / p.u. MW
$D_1 = D_2 = 0.00833$ Hz / p.u. MW
$T_{P1} = T_{P2} = 20$ s $T_{G1} = T_{G2} = 0.2$ s
$T_{T1} = T_{T2} = 0.3$ s $K_{R1} = K_{R2} = 0.3$
$T_{R1} = T_{R2} = 10$ s . $T^{\circ}_{12} = 0.0707$ p.u.MW/rad
$\Delta P_{L1} = 0.01$ p.u. MW $\Delta P_{L2} = 0$ $T_D = 0$ s
$T_F = 10$ s $K_{IB} = 0.03$ $T_{IB} = 26$ s $T_{RB} = 69$ s
$K_1 = 0.85$ $K_1 = 0.095$ $K_1 = 0.92$ $C_B = 200$

SMES

$W_{sm0} = 6$ MJ $I_{sm0} = 4.5$ kA $V_{sm0} = 0$ kV
$T_{dc} = 0.026$ s $L = 0.5$ H
$K_{tie} = 400$ kV/ unit ACE $K_{ism} = 2.4$ kV / p.u. kA

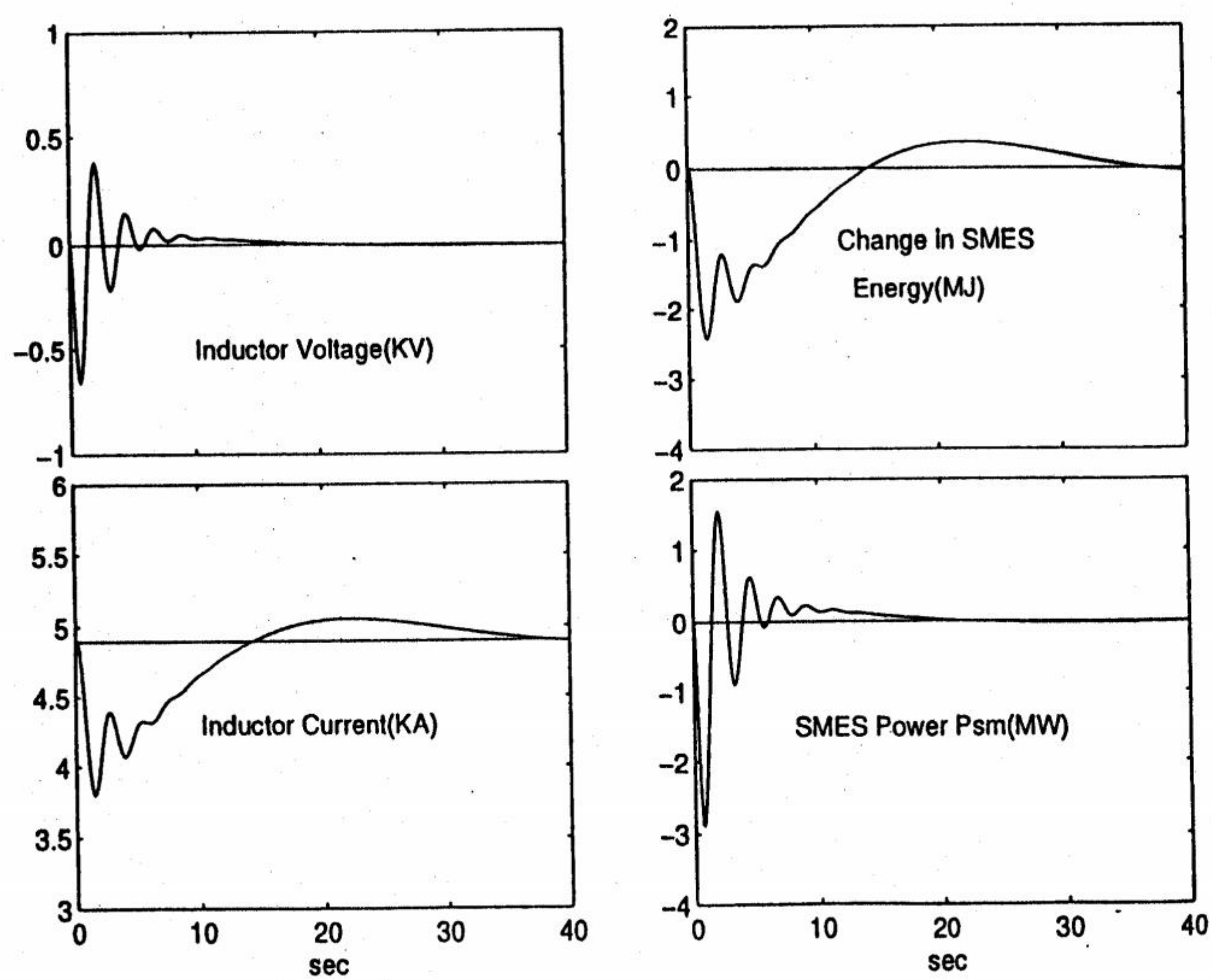

Fig. 8 SMES Voltage, Current, Power and Change in Energy