Applications of superconducting magnetic energy storage in electrical power systems

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Abstract. Fast-acting energy storage devices can effectively damp electromechanical oscillations in a power system, because they provide storage capacity in addition to the kinetic energy of the generator rotor, which can share the sudden changes in power requirement. The present paper explores the means of reducing the inductor size for this application so that the use of high-T_c superconducting materials becomes feasible.

Keywords. Magnetic energy storage; electrical power systems.

1. Introduction

Superconducting magnetic energy storage (SMES) system has numerous advantages in electrical power system applications over other conventional means of electrical energy storage, like pumped hydro energy storage, compressed air energy storage etc. Apart from being the most efficient, SMES has attracted the attention of power engineers in recent years because of its extremely fast response in switching over from charging mode to discharging mode and the high rate of energy discharge capability. The other means of electrical energy storage are inherently handicapped on these two counts.

Recognizing these advantages the Bonneville Power Administration of USA has already installed a 30 MJ SMES unit to stabilize the Pacific AC Intertie that connects the Northern and Southern power systems of that country (Rogers *et al* 1979, 1983; Boenig and Hauer 1985; Hassenzahl 1983). Detailed designs of massive SMES installations (of the order of 1 GWH) for load-levelling and peak shaving purposes have been evolved (Rogers *et al* 1979; Loyd 1986). However, the high cost of low temperature metallic superconductor technology has so far inhibited the wide-scale application of superconducting magnets in power systems.

With the discovery of high-T_c ceramic superconductors, the application of SMES in power system may acquire commercial viability in the near future. However, considerations of critical current density under high magnetic fields may restrict the energy storage capacity of such units.

This paper shows that SMES units with such small energy storage capacity can be used in load-frequency control of power systems. This problem occurs when there is a sudden change in load. The steam inlet to the turbine cannot change instantaneously and the additional load has to be met from the kinetic energy of the generator rotors. Consequently the rotor speed falls, the frequency drops, and normalcy can be restored only after a series of oscillations when the steam governor responds to the frequency deviation. These frequency oscillations are a persistent source of trouble in a power system and occasionally lead to instability and shut downs.

The LFC problem fundamentally being that of instantaneous mismatch between supply and demand of real power in a power system, a fast acting magnetic energy storage unit can improve the performance of a system by sharing the change in load till

the steam governor comes into action. Since the mismatch between demand and supply of power usually lasts for 5–10 seconds, the energy storage requirement is small for this application.

This work aims at presenting a strategy for controlling the SMES unit so that the energy storage requirement of the magnet can be further reduced for the same damping action. This opens up a new area of application of the emerging ceramic super-conductor technology in future.

2. Power modulation in SMES units

The SMES inductor-converter unit consists of a dc superconducting inductor, a 12-pulse cascaded bridge type ac/dc converter and a $Y-Y/\Delta$ step down transformer (figure 1). Control of the converter firing angle enables the dc voltage E_d appearing across the inductor to be continuously varied between a wide range of positive and negative values. The converter dc output current I_d being unidirectional, the control for the direction and magnitude of the inductor power flow P_d, is achieved by continuously regulating the firing angle α.

After initial charging of the inductor, the simplest control strategy can be to control the dc voltage E_d across the inductor depending on the sensed frequency deviation signal Δf (Peterson *et al* 1975). The incremental change in the inductor voltage ΔE_d is given by

$$\Delta E_d = [K_0/(1 + T_{dc} \cdot p)]\Delta f, \tag{1}$$

where K_0 is the gain of the control loop, T_{dc} the converter time delay and p the differential operator d/dt. When the system load increases the bus frequency falls. Consequently a negative voltage ΔE_d, shown in (1), is impressed across the inductor. The inductor current being unidirectional, application of a negative voltage across it results in withdrawal of energy.
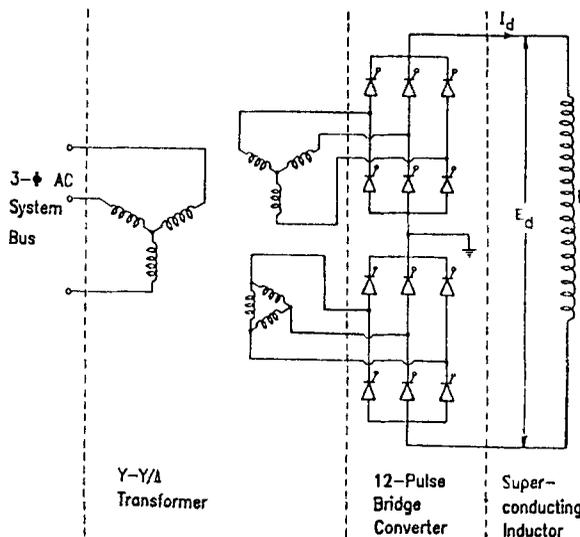
Figure 1. Schematic diagram of the magnetic energy storage unit.

The power withdrawal and consequent deviation of inductor current are given by the following equations.

$$\Delta P_d = I_{d0} \cdot \Delta E_d + \Delta E_d \cdot \Delta I_d \tag{2}$$

$$\Delta I_d = \Delta E_d / p \cdot L \tag{3}$$

While following (1), the relationship between ΔE_d and Δf has to operate within two constraints: (a) the voltage E_d across the inductor should be within certain design limits and (b) the inductor current deviation ΔI_d during the disturbance should remain within specific upper and lower bounds.

3. Effects of SMES unit on LFC loop

In order to study the effects of SMES units in a power system, a two-area system of unequal capacities has been considered (see figure 2). Area 1 (of capacity 1000 MW) includes generators G_{11}, $G_{12}, \ldots G_{1m}$ connected to a common busbar while area 2 (of capacity 3000 MW) includes generators G_{21}, $G_{22}, \ldots G_{2n}$ connected to another common bus. Areas 1 and 2 are connected by a weak tie line. An SMES unit is connected to area 1 bus, as it is expected to experience larger load frequency disturbance due to its relatively low capacity. P_{L1} and P_{L2} are lumped initial system loads to areas 1 and 2 respectively and power system response to step load change $\Delta P_{L1} = 0.01$ p.u.MW is studied.

The investigation has been carried out by simulating the above power system on a digital computer by adding the state variable equations of the SMES unit to those of the power system (Elgerd 1983). The nominal parameters of the power system are as follows:

$$P_{R1} = 1000\,\text{MW}, \ P_{R2} = 3000\,\text{MW}, \ K_{p1} = K_{p2} = 100 \cdot 0\,\text{Hz/p.u.MW},$$

$$T_{p1} = T_{p2} = 20 \cdot 0\,\text{s}, \ T_{G1} = T_{G2} = 0 \cdot 08\,\text{s}, \ T_{T1} = T_{T2} = 0 \cdot 3\,\text{s},$$

$$K_{R1} = K_{R2} = 0 \cdot 5, \ T_{R1} = T_{R2} = 10 \cdot 0\,\text{s}, \ R_1 = R_2 = 2 \cdot 4\,\text{Hz/p.u.MW},$$

$$B_1 = B_2 = 0 \cdot 425, \ T^{\circ}_{12} = 0 \cdot 0866, \ a_{12} = -0 \cdot 333.$$

The parameters of the SMES unit are: $I_{d0} = 4 \cdot 0\,\text{KA}$, $L = 1 \cdot 0\,\text{H}$, $T_{dc} = 0 \cdot 026\,\text{s}$, and $K_0 = 100\,\text{kV/Hz}$ unless otherwise specified in the figures.
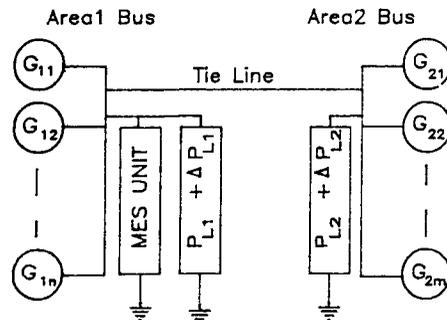

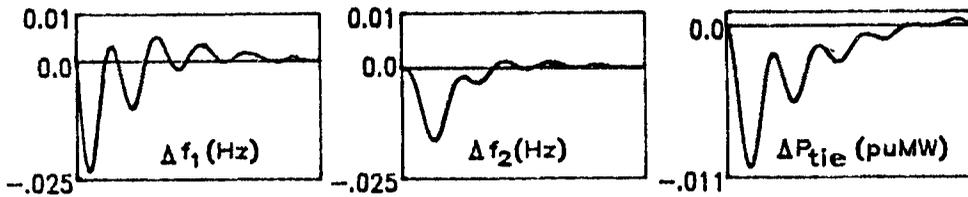**Figure 2.** Single line diagram of the two-area power system.

Figure 3. Response of the power system without SMES unit for 15 s. Step disturbance $\Delta P_{L1} = 0.01$ p.u.
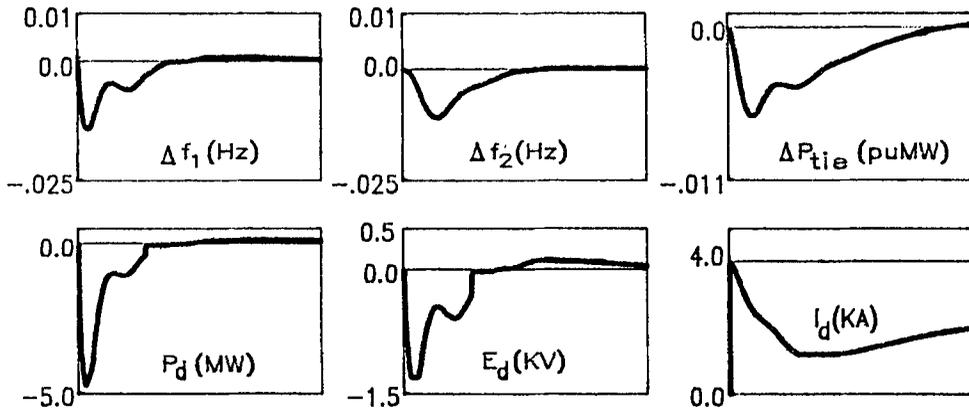

Figure 4. Response of the power system with SMES unit for 15 s. Step disturbance $\Delta P_{L1} = 0.01$ p.u., $K_0 = 100$ kV/Hz.

Figure 3 shows the deviations in frequencies Δf_1 and Δf_2 and tie-line power ΔP_{tie} without the energy storage unit in response to a step load change of 0.01 p.u. in area 1. The behaviour of the power system with the SMES unit under the same condition is shown in figure 4. It can be seen that the damping improves with the addition of the SMES unit and the maximum overshoots of Δf_1, Δf_2 and ΔP_{tie} reduce by approximately 40%, 30% and 35% respectively. Figure 4 also shows the plots of the voltage, current and power in the SMES unit.

4. Suggested control strategy

The first step in minimizing the inductor size is to reduce the current deviation in the inductor and quick restoration of the current to normal value following a load disturbance. It has been found that this can be achieved by using the inductor current deviation feedback in the control loop.

Secondly, in multiarea power systems it is desirable that each area carry its own load, least participating in the disturbances in the other areas. This reduces the inadvertent interchange of power between areas during frequency oscillations.

The present study has shown that in the SMES installations where the tie-line power deviation signals are available, this effect can be achieved by the use of area control error (ACE) in place of frequency deviation in the input of the SMES control logic.
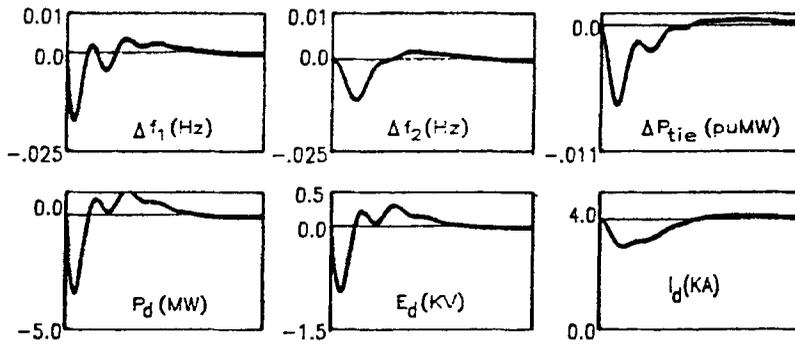
Figure 5. Response of the power system with optimized value of K_I for 15 s. $K_0 = 100$ kV/unit ACE, $K_{Id} = 0.5$ kV/KA, $K_I = 0.81$

Thus, with the ACE input and ΔI_d feedback the inductor voltage deviation can be expressed as

$$\Delta E_d = \frac{1}{T_{dc} \cdot p + 1}[K_0(\Delta P_{tie} + B \cdot \Delta f) - K_{Id} \cdot \Delta I_d], \qquad (4)$$

where K_{Id} is the gain for ΔI_d feedback, and B the frequency bias parameter.

It may be noted that when the power system demands the extra power during the first few seconds following the disturbance, it is supplied as required. The $(K_{Id} \cdot \Delta I_d)$ term in the above equation becomes effective only when the inductor current has deviated by a considerable amount. Consequently, this strategy leads to better utilization of the energy storage in the inductor.

It has been found in the present work that the energy storage unit partially counteracts the effects of the integral controller associated with automatic generation control. This implies that the optimal setting of the integrator gain K_I is altered with the addition of the SMES unit. The new optimal setting of K_I is computed using the integral square error criterion and it has been found that the optimal integrator gain setting is altered from 0.44 to 0.81 with the addition of the SMES unit. The advantage of a higher setting of the integrator gain is in the reduction of the settling time. This reduces the duration of power flow from the inductor and consequently further reduces the energy storage requirement.

The response of the optimized system for $K_0 = 100$ kV/unit ACE, $K_{Id} = 0.5$ kV/kA, and $K_I = 0.81$ has been shown in figure 5. It clearly shows the improvement in transient response (with a lesser settling time) in comparison with that in figure 4.

5. Reduction in inductor size

From the foregoing discussion it can be concluded that the application of inductor current deviation feedback and increase of integrator gain setting reduces the energy withdrawal from the SMES unit, thus allowing the use of an inductor of much smaller inductance. Figure 6 shows the response of the power system when the inductor size is reduced from 1.0 to 0.5 Henry. It shows that an SMES unit of energy storage capacity of 4 MJ suffices in reducing the maximum frequency and tie-line power deviations by
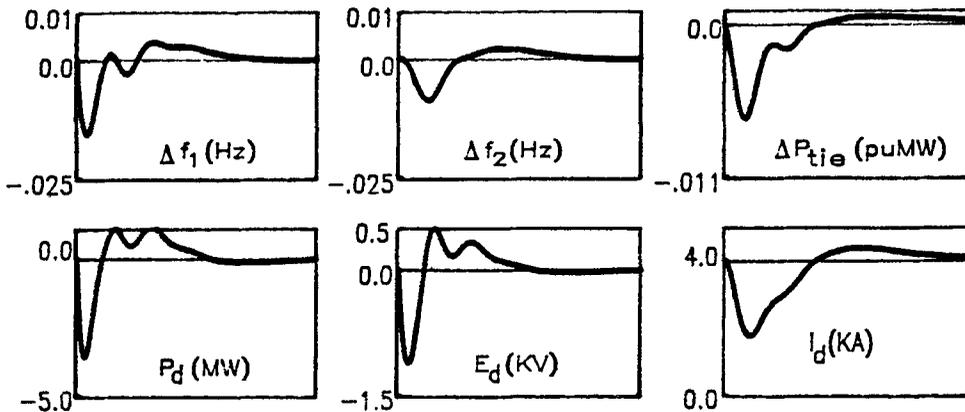
Figure 6. Response of the power system and the SMES unit when the inductance is reduced to 0·5 H. The other parameters remain the same.

approximately 40%. In the present work it has also been found that for an area of capacity 2000 MW, the required energy storage capacity is of the order of 6 MJ.

6. Conclusions

It has been shown in the present work that small-sized SMES units with suitable control can effectively reduce the frequency and tie-line power oscillations following sudden small load perturbations.

The control logic suggested for this purpose takes the area control error as its input and uses inductor current deviation feedback. In a power system with SMES unit, the optimal setting of the integrator gain is altered to a higher value. With the suggested control measure, an SMES unit of 4 MJ capacity can reduce the maximum deviations of frequency and tie-line power flow by approximately 40% in a 1000 MW power area.

For the above storage capacity, high-T_c superconducting inductors may be a viable option. However, further research effort is necessary to evolve suitable designs of such superconducting inductors in sizes required for LFC application.

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