IEEE Transactions on Energy Conversion, Vol. 11, No. 1, March 1996

CONTROL OF SUBSYNCHRONOUS RESONANT MODES IN A SERIES COMPENSATED SYSTEM THROUGH SUPERCONDUCTING MAGNETIC ENERGY STORAGE UNITS

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Abstract - **A simple and novel strategy for damping subsynchronous resonant oscillations through control of converter firing angles of a superconducting magnetic energy storage system (SMES) is proposed. The strategy is derived such that the current injected or drawn by the SMES compensates for any deviation in real and reactive power in the system. The proposed control has been tested on the IEEE second benchmark model for subsynchronous resonance studies. It has been found to eliminate the slowly growing transients resulting from the unstable modes very effectively. The control algorithm is simple and its realization will require very little hardware.**

Keywords: Damping Control, SSR, Series Capacitor Compensation, SMES.

I. INTRODUCTION

Series capacitor compensation has been used in power systems to raise the power limits of transmission lines. This, however, has brought about the phenomenon of subsynchronous resonance (SSR)[1]. A good amount of literature has been devoted to the study of SSR over the past 20 years. An exhaustive list of references is given by the IEEE Working Group bibliography on SSR[2,3]. Countermeasures proposed in the literature are excitation control, static var compensators, HVDC, static phase shifter, bypass filter and shunt reactors[4-8].

Superconducting magnetic energy storage (SMES) systems have the capability of storing energy in their low resistance coils. This energy can be supplied to the power system in case this is needed. The amount of energy supplied by the SMES or received by it can be controlled by controlling the firing angle of the converters in the SMES unit. A number of articles have been reported demonstrating the use of SMES for power system transient stability, dynamic stability, load frequency control and stabilizing transmission lines[9]. Application of SMES to damp SSR have been reported recently to the IEEE first and second benchmark models[8,10]. These articles used PID controls in the converter firing angle circuits and the parameters of the controllers were obtained by pole placement techniques. Linear control theory for the controller design were used and simulation tests were done on nonlinear system models.

This paper introduces a novel idea of injecting current to the power system from an SMES unit using a very simple control principle that in case of emergency, the SMES should supply (or absorb) real and reactive power in such a way that the net change in the system is zero. The algorithm has been derived considering all the nonlinearities of the dynamic system model and has been tested on the IEEE second benchmark model. The current injection strategy is found to be very effective in canceling the uncontrolled subsynchronous modes.

II. SYSTEM MODEL

The IEEE second benchmark model for SSR studies[11] as shown in Fig.1 is considered for this study. The system consists of a synchronous generator feeding an infinite bus over two parallel transmission lines , one of which is capacitor compensated. The mechanical part of the generating unit is a mass spring system containing four bodies shown in Fig.2 . The high pressure turbine (HP), the low pressure turbine (LP), the generator (GEN) , and the exciter (EX) are all coupled on the same shaft.

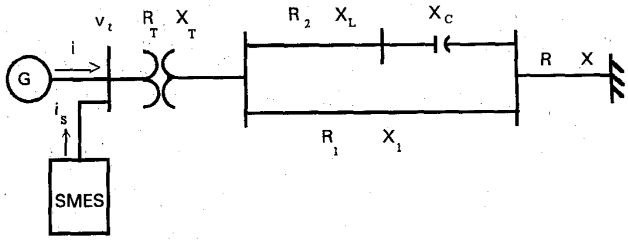

Fig.1. Configuration of the IEEE second bench mark model with SMES.

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95 SM 617-1 EC A paper recommended and approved by the IEEE Energy Development and Power Generation Committee of the IEEE Power Engineering Society for presentation at the 1995 IEEE/PES Summer Meeting, July 23-27, 1995, Portland, OR. Manuscript submitted December 16, 1994; made available for printing June 5, 1995.

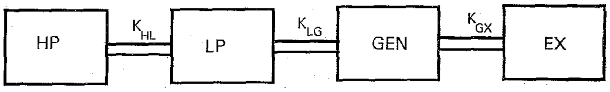

Fig.2. The generator turbine system.

A superconducting magnetic energy storage unit is connected to the generator bus. The SMES unit can supply energy to the power system or receive energy from it depending on the value of converter firing angle. The active and reactive power of the SMES unit can be controlled simultaneously by changing the firing angle of each bridge properly. By using GTO's instead of ordinary thyristors it is possible to get reactive power of not only lagging but also leading phase[12].

The IEEE Type 1 Exciter [5] is included to represent the excitation system of the second benchmark model.

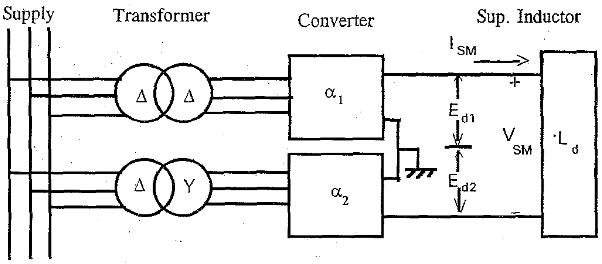

Fig.3 The SMES configuration.

The dynamic model of the system given in Fig.1 comprising of the electromechanical swing equation of the generator, the voltage-current-flux relationships of its various circuits, the excitation system, the transmission line containing the series capacitor, the mass-spring system on the generator shaft, and the SMES system can be written in the form

$$\dot{X} = f[X,u] \qquad (1)$$

where, the state vector X is

$$X = [X_1\ X_2\ X_3\ X_4\ X_5]^T \qquad (2)$$

and,

$$X_1=[\omega_H, \theta_H, \omega_L, \theta_L, \omega, \delta, \omega_E, \theta_E]$$

$$X_2=[i_d, i_f, i_D, i_q, i_Q, i_s]$$

$$X_3=[e_{cd}, e_{cq}, i_{cd}, i_{cq}]$$

$$X_4=[V_A, E_{fd}, V_s]$$

$$X_5=[\alpha, I_{SM}]$$

The control vector u contains the SMES currents and their derivatives along the direct and quadrature axes, given as

$$u = [i_{sd}, i_{sq}, pi_{sd}, pi_{sq}]^T \qquad (3)$$

III. MODAL ANALYSIS

For small perturbations of the states, the system of equations (1) can be linearized around the steady state equilibrium point and can be expressed as,

$$\Delta\dot{X} = A\,\Delta X + B\,u \qquad (4)$$

where, ΔX is the change of the state vector. The A matrix in the above equation depends on the degree of series capacitor compensation. The compensation factor, given as X_c/X_L, is normally expressed in percent. The real parts of the eigenvalues of the subsynchronous modes for various values of compensation factors are plotted in Fig. 4. The eigenvalue corresponding to the electromechanical swing is termed mode 0, while the other subsynchronous modes in ascending order are termed modes 1, 2, and 3. Fig. 4 shows that at lower values of compensation the electromechanical mode (mode 0) is unstable. This is expected for a weakly connected power system. With the increase in compensation, the real part of the electromechanical mode starts to decrease, while that of mode 1 starts to increase. At 56% capacitor compensation, mode 1 has the largest real part . The variations of the imaginary parts of the modes are not significant.

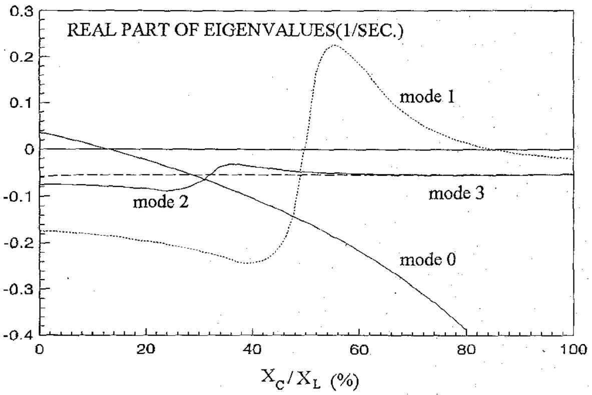

Fig. 4 . The real part of the eigenvalues of the subsynchronous modes for various degrees of compensation.

IV. THE PROPOSED SMES CONTROL STRATEGY

Through the control of firing angles α_1 and α_2 of the cascaded converters in Fig.3, the real and reactive power outputs of the SMES can be adjusted simultaneously. For the sake of simplicity of analysis let us assume that converters are operating in equal firing angle mode, i.e. $\alpha_1 = \alpha_2 = \alpha$. The d.c. voltage output of the 12 pulse converter can then be written as

$$V_{SM} = E_{d1} + E_{d2} = 2\, V_{SMO} \cos\alpha \qquad (5)$$

Here, E_{d1} and E_{d2} denote the output d.c.voltage of each of the six pulse converter sets and V_{SMO} is the no load maximum d.c.voltage of each unit. The real and reactive powers transferred by the converters are

$$\begin{aligned} P_{SM} &= 2\, V_{SMO}\, I_{SM} \cos\alpha \\ Q_{SM} &= 2\, V_{SMO}\, I_{SM} \sin\alpha \end{aligned} \qquad (6)$$

Both P_{SM} and Q_{SM} can be controlled by controlling the firing angle α in the full range between 0 and 360 degrees[8].

In the dynamic model (1), the SMES currents are considered as inputs to the system. The real and reactive power injected or drawn by the SMES is equivalent to current injection (positive or negative) to the power system. The control strategy developed here is in terms of this injected current.

The fundamental idea behind the development of the current injection strategy is that when there is an unbalance in real and reactive power in the system, followed by any perturbation in it, the SMES should supply or absorb the differential power to offset the unbalance. The criteria can be written mathematically as

$$\begin{aligned} &P_{SM} + \beta_1\, \Delta P_e = 0 \\ \text{and,}\quad &Q_{SM} + \beta_2\, \Delta Q_e = 0 \end{aligned} \qquad (7)$$

where, ΔP_e and ΔQ_e are the changes in real and reactive powers in the system. β_1 and β_2 are real numbers which represent the extent of compensating power to be supplied by the SMES so that a satisfactory transition to normal operation is achieved. When the system returns to steady state ΔP_e and ΔQ_e are zero and the SMES will only supply the constant losses. Since the objective is to minimize changes in real as well as reactive power variations, both the electromechanical and electrical transients will be controlled.

If Δi_p and Δi_r represent the changes in the real and reactive components of current in the power system, we can write,

$$\begin{aligned} &P_{SM} + \beta_1\, v_t\, \Delta i_p = 0 \\ \text{and,}\quad &Q_{SM} + \beta_2\, v_t\, \Delta i_r = 0 \end{aligned} \qquad (8)$$

This gives,

$$\Delta i_p = -P_{SM} / \beta_1 v_t \;,\quad \Delta i_r = -Q_{SM} / \beta_2 v_t \qquad (9)$$

and we get,

$$\frac{\Delta i_r}{\Delta i_p} = \frac{\beta_1}{\beta_2}\, \frac{Q_{SM}}{P_{SM}} \qquad (10)$$

Combining (6) with (10), the expression for the converter firing angle α which satisfies conditions (7) is given as

$$\alpha = \tan^{-1} \left[\beta \frac{\Delta i_r}{\Delta i_p}\right] \qquad (11)$$

where, $\beta = \beta_1/\beta_2$

The block diagram in Fig. 5 shows the realization of (11). K_α and T_α represent the gain and delays, respectively of the firing angle control circuit.

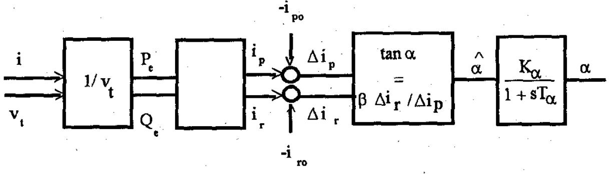

Fig.5 Block diagram showing realization of control α

From (11) it can be observed that determination of α requires real and reactive components of current which, in turn, can be obtained from measurement of terminal voltage, and real and reactive powers only. The optimum values of β_1 and β_2 can be obtained by trial from the system simulation studies.

V. COMPUTER SIMULATION OF THE SMES CONTROL

As mentioned, control α can be found when the real and reactive components of current are measured from an actual system. To simulate the control strategy on a digital computer and to study the behavior of the system, the set of equations (1) are to be solved subject to constraint (7). The following analysis is carried out to find i_{sd} , i_{sq} and their derivatives :

Differentiate (7) to get,

$$\begin{aligned} \dot{P}_{SM} + \beta_1\, \Delta\dot{P}_e &= 0 \\ \dot{Q}_{SM} + \beta_2\, \Delta\dot{Q}_e &= 0 \end{aligned} \qquad (12)$$

These are equivalent to

$$\dot{P}_{SM} + \beta_1 \dot{P}_e = 0$$
$$\dot{Q}_{SM} + \beta_2 \dot{Q}_e = 0 \qquad (13)$$

And since, $P_{SM} = v_t i_{sp}$ and $Q_{SM} = v_t i_{sr}$, we get,

$$\dot{P}_{SM} = v_t \dot{i}_{sp} + \dot{v}_t i_{sp} \qquad (14)$$
$$\dot{Q}_{SM} = v_t \dot{i}_{sr} + \dot{v}_t i_{sr}$$

In the above, i_{sp} and i_{sr} represent the real and reactive components of the SMES current i_s on the a.c. side. The derivatives of P_e and Q_e are obtained by differentiating the equations,

$$P_e = v_d i_d + v_q i_q \qquad (15)$$
$$Q_e = v_q i_d - v_d i_q$$

where, v_d and v_q are approximated, neglecting the transformer voltages, by

$$v_d = -r_a i_d - \omega \psi_q \qquad (16)$$
$$v_q = -r_a i_q + \omega \psi_d$$

The fluxes in the above equations given as,

$$\psi_d = -x_d i_d + x_{md} i_F + x_{md} i_D \qquad (17)$$
$$\psi_q = -x_q i_q + x_{mq} i_Q + x_{mq} i_S$$

Substituting (17) into (16), differentiating (15) and (16) and replacing the derivatives of currents from (1) , the derivatives of P_e and Q_e can be expressed as a function of the states as

$$\dot{P}_e = g_1(x), \text{ and } \dot{Q}_e = g_2(x) \qquad (18)$$

Similarly, we can write,

$$\dot{v}_t = (v_d \dot{v}_d + v_q \dot{v}_q)/v_t \qquad (19)$$
$$= g_3(x)$$

Substituting (14) and (18) into (13) results

$$\dot{i}_{sp} = -\beta_1 g_1(x)/v_t - i_{sp} g_3(x)/v_t \qquad (20)$$
$$\dot{i}_{sr} = -\beta_2(x) g_2(x)/v_t - i_{sr} g_3(x)/v_t$$

Breaking up i_{sp} and i_{sq} each into components along the d and q axes and adding the components of the respective axes, (20) can be expressed as

$$\dot{i}_{sd} = -\frac{\beta_1 g_1(x)}{v_t}\frac{v_d}{v_t} - \frac{\beta_2 g_2(x)}{v_t}\frac{v_d}{v_t} - i_{sd}\frac{g_3(x)}{v_t} \qquad (21)$$
$$\dot{i}_{sq} = -\frac{\beta_1 g_1(x)}{v_t}\frac{v_q}{v_t} - \frac{\beta_2 g_2(x)}{v_t}\frac{v_q}{v_t} - i_{sq}\frac{g_3(x)}{v_t}$$

The quantities $\dot{i}_{sd}$ and $\dot{i}_{sq}$ required in simulating (1) can be directly obtained from (21), while i_{sd} and i_{sq} are obtained from simultaneous solution of (1) and (21). The block diagram showing how α is obtained for numerical solution of (1) is shown in Fig. 6. The last block between $\hat{\alpha}$ and α is the same as in Fig. 5.

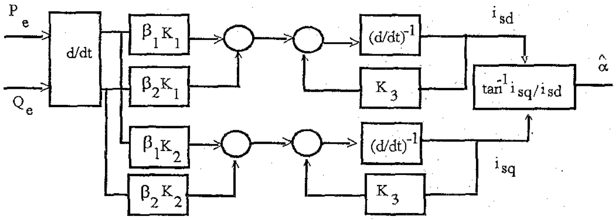

Fig.6 Realization of α for digital simulation. $K_1 = -v_d/v_t^2$, $K_2 = -v_q/v_t^2$, $K_3 = -g_3(x)/v_t$

VI. SIMULATION RESULTS

The IEEE second bench mark model for SSR studies with one generating unit and two parallel transmission lines and an SMES unit connected to the generator bus as shown in Fig. 1 was simulated. The data for the system are taken from references [10] and [11]. The system of equations (1) were solved with and without the proposed SMES current injection control scheme. 56% series capacitor compensation of one of the transmission lines which gives the largest real part of SSR mode 1 is considered. A torque pulse of 20% for a duration of 3 cycles was applied to the generator shaft. Figure 7 shows the response in the absence of any control. The response is slowly growing because of the presence of the unstable mode at this level of compensation. The torque on the shaft of the various sections of the turbine as well the generator are oscillatory and growing. Amongst the three torsional torques, viz., the HP-LP, LP-GEN, GEN-EX, the torque between the low pressure section of the turbine and the generator is the largest. The first part of Fig. 7 shows the variation of this torsional torque. The variations of angular frequency and the terminal voltage are also given in Fig. 7.

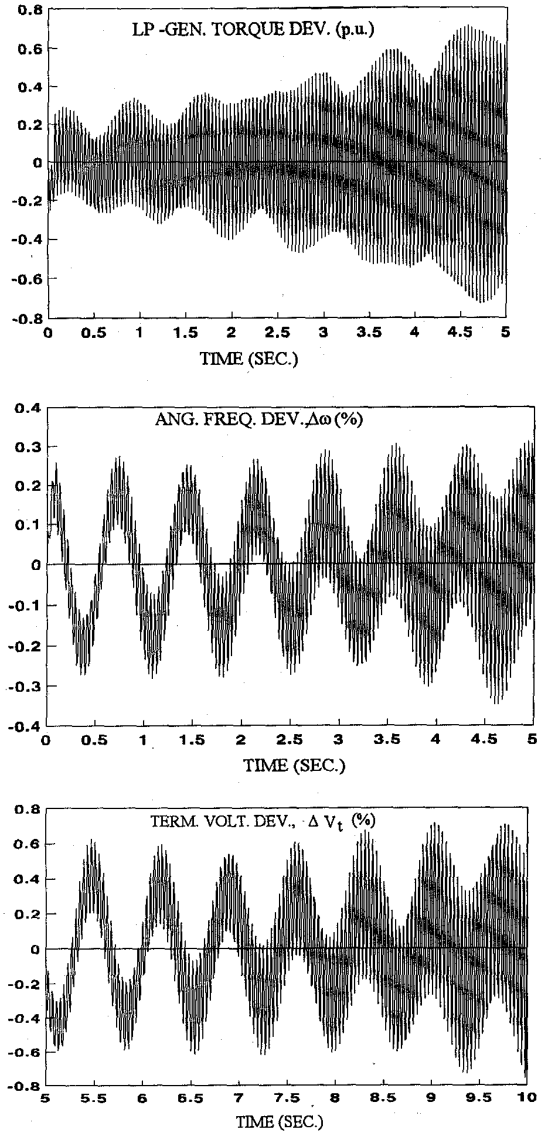

Fig. 7. Variation of LP - GEN torsional torque, angular frequency and terminal voltage of the generator following a 20% torque pulse on the generator shaft for a duration of 3 cycles without any stabilizing control.

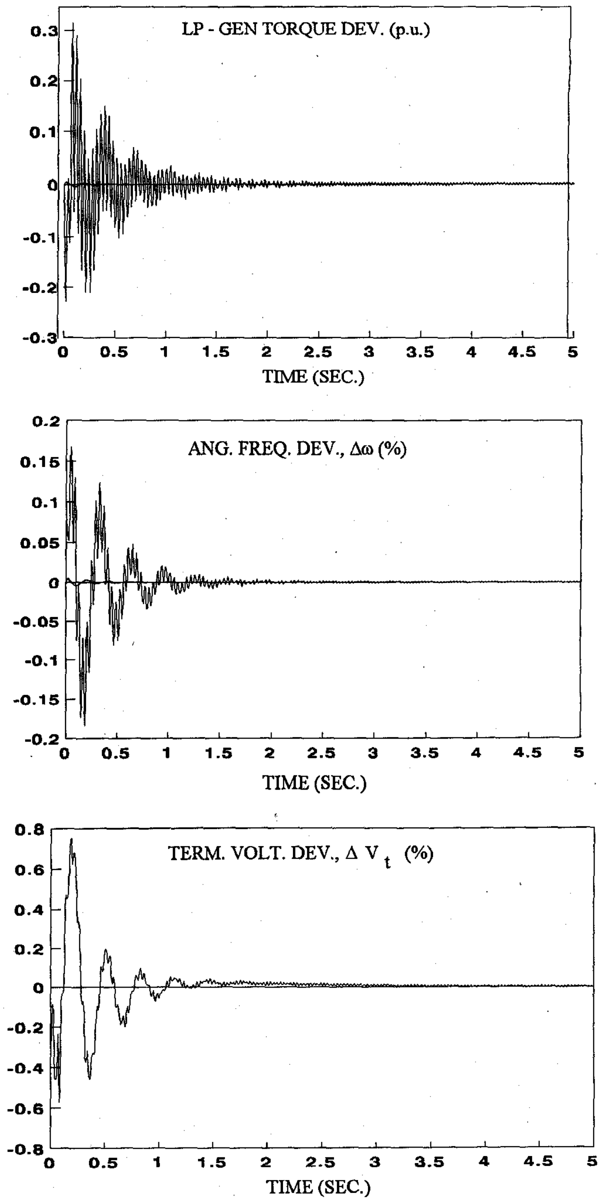

Fig. 8. Variation of LP-GEN torque, generator angular frequency and terminal voltage corresponding to Fig. 7 with current controller from the SMES.

Figure 8 shows the variation of the respective quantities when the proposed SMES control is applied. The converter angles are determined depending on the transient condition existing in the system as reflected in the variations of real and reactive power in the system. The SMES injects or draws current into or out of the system in such a way as to minimize any variation of electromechanical as well as the electrical transients . The response in Fig. 8 shows that the current injection controller stabilizes the system in about one second, returning the system states to normal operating levels. If the transient performance obtained in this study is compared with those obtained through excitation control[5], and PID control of SMES thyristor firing angles[9] , it can be seen that the proposed current injection strategy is superior in terms of transient control.

VII. CONCLUSION

A method of controlling the unstable modes arising from the subsynchronous resonance phenomenon through the control of currents injected from an SMES is presented. The control strategy is derived from a simple principle that the SMES should supply or receive power in such a manner that the net variation in the real and reactive power of the system is zero.

For digital simulation, the injected currents from the SMES and their derivatives which comprise of the input to the system model are obtained in terms of the system states. The unstable subsynchronous modes due to the series capacitor compensation are canceled by the appropriate injected currents as is evidenced by the results. Transient response recorded show that the subsynchronous frequency oscillations are removed in about a second. This indicates that long transmission links with series capacitor compensation can be reliably operated if equipped with proper SMES control circuitry.

In actual implementation, the control strategy proposed requires primarily the measurement of terminal voltage and variation of real and reactive power only. The proposed strategy is simple and would require very little hardware to implement.

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