Application of simultaneous active and reactive power modulation of SMES Unit under unequal α-mode for power system stabilization

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Abstract: A simple and novel control strategy for damping electromechanical oscillations through control of converter firing angles α_1 and α_2 of a Superconducting Magnetic Energy Storage (SMES) Unit is proposed. Both active and reactive power modulations are used under unequal α-mode of operation. The choice of unequal mode is discussed in detail. The gains of the proposed SMES controller are determined once off-line depending on the power system and the rating of the SMES unit. Simulation results show that the SMES unit can effectively suppress system oscillations by utilizing its active and reactive power modulation capabilities. The control algorithm is simple and its realization will require very little hardware.

Keywords: Damping control, SMES, P-Q modulation, unequal α-mode

I. INTRODUCTION

System disturbances such as load changes or faults are the main causes of power system oscillations. If no adequate damping is available, the oscillations may be sustained for minutes and grow to cause system separation [1]. Many countermeasures are suggested by researchers to increase damping. These include power system stabilizers [2], optimal control of the turbine governor system [3], and use of static phase shifters [4].

Since the successful commissioning test of the BPA 30 MJ unit [5], Superconductive Magnetic Energy Storage (SMES) systems have received much attention in power system applications. SMES systems have the capability of storing energy in their low resistance coils. This energy can be supplied to the power system when needed. The amount of energy to be supplied or received by the SMES unit can be controlled by controlling the firing angles α_1 and α_2 (Fig. 1) of the converters of the SMES unit. Also, the SMES unit should not consume any active or reactive power under normal operating conditions. A number of articles have been reported demonstrating the use of SMES unit for power system transient stability, load frequency control and damping subsynchronous oscillations [6-11]. However, when equal α-mode i.e. $\alpha_1 = \alpha_2 = \alpha$, is selected, the following problems are encountered:

a) Under normal operating condition, the SMES unit may act as an active load, reactive load or both.

b) During fault condition, there is an improper generation of firing angles which makes the SMES unit less effective.

The first problem has yet to be solved. As for the second, additional PID controllers have been proposed in references [6, 7].

In this paper, an attempt has been made to show that by selecting unequal α-mode to control the firing angles, not only the said problems can be alleviated, but also the necessity of incorporating extra controller can be eliminated. First, the description of the SMES unit and problems caused by the equal α-mode of control are presented. Then the proposed unequal α-mode of control is described in detail. The SMES system is applied to a test network and the simulation results are presented and discussed.

II. DESCRIPTION OF SMES SYSTEM

The SMES inductor-converter unit consists of a dc superconducting inductor, a 12-pulse cascaded bridge type AC/DC converter and a Y-Δ / Y-Y step down transformer(see Fig. 1). Control of the converter firing angle enables the dc voltage V_{sm} appearing across the inductor to be continuously varied between a wide range of positive and negative values.

Gate turn off thyristors (GTO) allow us to design such type of converter. The converter dc output current I_{sm} being unidirectional, the control for the direction of the inductor power flow P_{sm}, is achieved by continuously regulating the firing angle α.

For initial charging of the SMES unit, the bridge voltage V_{sm} is held constant at a suitable positive value. The inductor current I_{sm} rises exponentially and magnetic energy

PE-002-PWRS-0-07-1998 A paper recommended and approved by the IEEE Power System Dynamic Performance Committee of the IEEE Power Engineering Society for publication in the IEEE Transactions on Power Systems. Manuscript submitted September 23, 1997; made available for printing July 2, 1998.

W_{sm} is stored in the inductor. When the inductor current reaches its rated value I_{sm0}, it is maintained constant by lowering the voltage across the inductor to zero. The SMES unit is then ready to be coupled to the power system for the stabilization of electromechanical modes of oscillation.

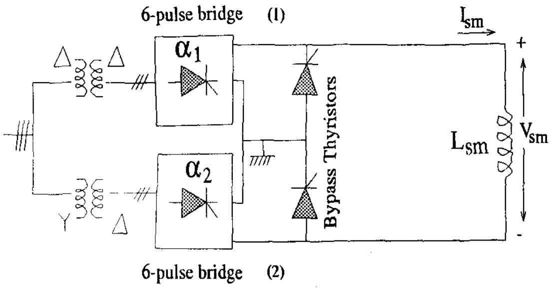

Fig. 1 Schematic diagram of the SMES unit

Due to sudden application or rejection of load, the generator speed fluctuates. When the system load increases, the speed falls at the first instant, but due to the governor action, the speed oscillates around a reference value. The converter works as an inverter ($90^\circ < |\alpha| < 180^\circ$) when the actual speed is less than the reference speed and energy is withdrawn from the SMES unit (P_{sm} negative). However the energy is recovered when the speed swings to the other side. The converter then works as a rectifier ($0^\circ < |\alpha| < 90^\circ$) and the power P_{sm} becomes positive.

The voltage V_{sm} of the DC side of the 12-pulse converter is expressed by

$$V_{sm} = V_{sm0}\,(\cos\alpha_1 + \cos\alpha_2) \tag{1}$$

where V_{sm0} is the ideal no-load maximum DC voltage of the 6-pulse bridges. The current and voltage of superconducting inductor are related as

$$I_{sm} = \frac{1}{L_{sm}}\int_{t_0}^{t} V_{sm}\,d\tau + I_{sm0} \tag{2}$$

where I_{sm0} is the initial current of the inductor. The real power absorbed or delivered by the SMES unit is

$$P_{sm} = V_{sm}\, I_{sm} \tag{3}$$

The energy stored in the superconducting inductor is

$$W_{sm} = W_{sm0} + \int_{t_0}^{t} P_{sm}\,d\tau \tag{4}$$

where $W_{sm0} = \frac{1}{2} L_{sm} I_{sm}^2$ is the initial energy in the inductor.

In actual practice the inductor current should not be allowed to reach zero to prevent the possibility of discontinuous conduction in the presence of the large disturbances. To avoid such problems, the lower limit of the inductor current is set at 30% of I_{sm0} [9]. It is desirable to set the rated inductor current I_{sm0} such that the maximum allowable energy absorption equals the maximum allowable energy discharge. This makes the SMES unit equally effective in damping swings caused by sudden increase as well as decrease in load. Thus, if the lower limit is chosen at $0.3I_{sm0}$, the upper limit based on the equal energy absorption/ discharge criterion is $1.38I_{sm0}$. When the inductor current reaches either of these limits, the dependence of P_{sm} on speed deviation is discontinued till the speed deviation swings to the other side.

The converter currents referred to the generator bus reference frame [6] under unequal α-mode are:

$$I_{sd} = 0.866\, I_{sm}\,(\sin\alpha_1 + \sin\alpha_2) \tag{5}$$
$$I_{sq} = 0.866\, I_{sm}\,(\cos\alpha_1 + \cos\alpha_2) \tag{6}$$

Because of constraints of hardware implementation, the voltage V_{sm} has also its upper and lower limits [11]. For the SMES unit modeled, the limits are:

$$-0.2532 \text{ p.u.} \le V_{sm} \le 0.2532 \text{ p.u.}$$

Thus for the particular SMES unit, the power P_{sm} has the following limits:

$$-0.2532\, I_{sm} \text{ p.u.} \le P_{sm} \le 0.2532\, I_{sm} \text{ p.u.}$$

In order to control the power balance of the synchronous generator effectively during dynamic period, the SMES unit is located at the generator bus [10,11].

III. PROBLEMS ASSOCIATED WITH EQUAL α-MODE OF CONTROL OF SMES UNIT

Under normal operating conditions, there should be no active and reactive power transfer between the SMES unit and the power system ($P_{sm} = 0$, $Q_{sm} = 0$). If the firing angles are selected as $\alpha_1 = \alpha_2 = \alpha$, then it is impossible to achieve this goal. Rather the following problems will arise:

i) SMES unit acts as an active load $\alpha_1 = \alpha_2 = 0^\circ$,
ii) SMES unit releases power $\alpha_1 = \alpha_2 = 180^\circ$,
iii) SMES unit acts as a reactive load $\alpha_1 = \alpha_2 = \pm 90^\circ$,
iv) SMES unit consumes both active and reactive load for any other value of α.

The problems under the faulty conditions are further elaborated below:

Let ΔV_t be the voltage deviation at the terminal bus of the generator because of sudden change in load. Then the desired Q-modulation of the SMES unit can be derived as [10],

$$Q_{sm}^{*} = \frac{K_{vs}}{1 + sT_{dc}}\Delta V_t + Q_{sm0} \tag{7}$$

where K_{vs} is the amplifier gain and T_{dc} is the delay time of the converter. The corresponding active power modulation can be derived as

$$P^*_{sm} = \frac{K_{ps}}{1+sT_{dc}}\Delta\omega + P_{sm0} \qquad (8)$$

where K_{ps} is the gain of the amplifier. The firing angles are calculated as

$$\alpha^*_1 = \alpha^*_2 = \alpha = \tan^{-1}(Q^*_{sm} / P^*_{sm}) \qquad (9)$$

The active and reactive power consumed by the SMES unit are given by

$$P_{sm} = 2\, V_{sm0}\, I_{sm} \cos\alpha \qquad (10)$$
$$Q_{sm} = 2\, V_{sm0}\, I_{sm} \sin\alpha \qquad (11)$$

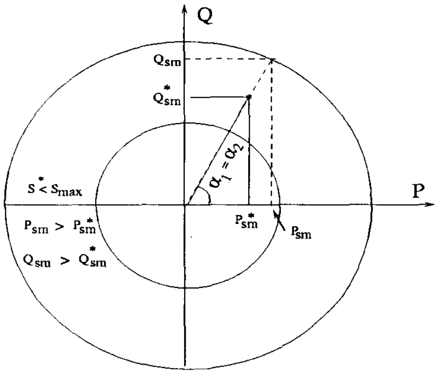

Fig. 2. P-Q modulation of SMES unit under equal α-mode of operation

The value of P_{sm} and Q_{sm} may or may not be equal to desired P^*_{sm} and Q^*_{sm} which can be viewed in Fig. 2. For a particular value of inductor current, the locus of P-Q modulation is a circle of radius $2V_{sm0} I_{sm}$. The commutating reactance has been neglected. If the variation of the inductor current is small, for large value SMES inductance, then one can write

$$2\, V_{sm0}\, I_{sm} = 2\, V_{sm0}\, I_{sm0} = S_{max} \qquad (12)$$

where S_{max} is the maximum MVA available in the SMES unit. Therefore, $P_{sm} = S_{max} \cos\alpha$ and $Q_{sm} = S_{max} \sin\alpha$. Defining $S^* = \sqrt{(P^{*2}_{sm} + Q^{*2}_{sm})}$,

If $S^* < S_{max}$, then $P_{sm} > P^*_{sm}$ and $Q_{sm} > Q^*_{sm}$.
If $S^* > S_{max}$, then $P_{sm} < P^*_{sm}$ and $Q_{sm} < Q^*_{sm}$.

It means that the active and reactive power consumption may not help in power system stabilization. It was demonstrated in references [7,8] that there is no improvement in the power system unless an extra controller is added. The problem becomes more serious when the system approaches the stable condition. In fact, the P-Q transfer under these conditions should be very small, but under equal α-mode, P_{sm} and Q_{sm} may reach very high values as is evident in Fig 2. This can be minimized if one can maintain P^*_{sm} equal to P_{sm} regardless of the value of Q_{sm} [11]. The firing angle can be calculated as

$$\alpha = \cos^{-1}(P_{sm} / 2V_{sm0}\, I_{sm}) \qquad (13)$$

The sign of α should be same as the sign of Q^*_{sm}. Then the corresponding value of Q_{sm} can be determined as

$$Q_{sm} = 2V_{sm0}\, I_{sm} \sin\alpha \qquad (14)$$

Though Q_{sm} is uncontrolled, the overall performance of the system can be improved with SMES unit [11].

IV. PROPOSED CONTROL STRATEGY USING UNEQUAL α-MODE

A. Calculation of firing angles of the converters

Fig. 3 shows the proposed SMES controller for simultaneous control of P-Q modulation of the SMES unit. The control strategy use the two basic equations (7) and (8), which relate the speed deviations with desired P_{sm} and terminal voltage deviation with the desired Q_{sm}. Under unequal α-mode, the expressions for P_{sm} and Q_{sm} are modified as

$$P_{sm} = V_{sm0}\, I_{sm} (\cos\alpha_1 + \cos\alpha_2) \qquad (15)$$
$$Q_{sm} = V_{sm0}\, I_{sm} (\sin\alpha_1 + \sin\alpha_2) \qquad (16)$$

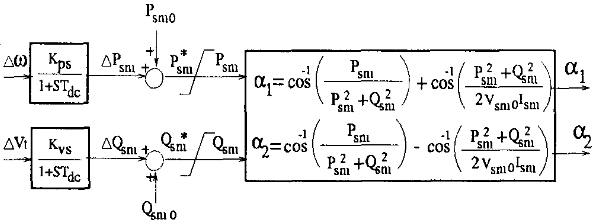

Fig. 3. SMES controller

Knowing P_{sm}, Q_{sm} and the present value of the inductor current I_{sm}, using (15) and (16), the firing angles of the converter under four quadrant operation can be calculated as [5].

$$\alpha_1 = \cos^{-1}(P_{sm} / S) + \cos^{-1}(S / S_{max}) \qquad (17)$$
$$\alpha_2 = \cos^{-1}(P_{sm} / S) - \cos^{-1}(S / S_{max}) \qquad (18)$$

The calculation of firing angles for typical values of P^*_{sm} and Q^*_{sm} are shown in the Fig. 4. Unlike the equal α-mode, if $S^* < S_{max}$, then $P_{sm} = P^*_{sm}$ and $Q_{sm} = Q^*_{sm}$. If $S^* > S_{max}$, then $P_{sm} = P^*_{sm}$, and the magnitude of Q_{sm} can be calculated as $Q_{sm} = \sqrt{(S^2 - P^{*2}_{sm})}$ and is always less than Q^*_{sm}. However the sign of Q_{sm} should be same as Q^*_{sm} .

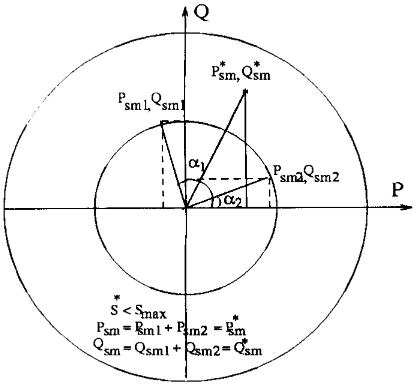

Fig. 4. P-Q modulation under unequal α-mode

B. Determination of amplifier gains K_{vs} and K_{ps}

The disturbance in the system is made significantly large so that it is on the verge of instability. The maximum value of ΔV_t and $\Delta\omega$ with SMES unit occurring in the post fault period are stored in the memory to obtain the constants K_{ps} and K_{vs} as follows:

$$K_{ps} = \frac{V_{sm,max} I_{sm,max}}{\Delta\omega_{t,max}} \tag{19}$$

and

$$K_{vs} = \frac{V_{sm,max} I_{sm,max}}{\Delta V_{t,max}} \tag{20}$$

where $V_{sm,max}$ and $I_{sm,max}$ are the maximum voltage and current limits for a particular SMES unit. Thus the value of K_{ps} and K_{vs} are varied depending on the type of power system and the rating of the SMES unit. For the studied system, K_{ps} and K_{vs} are found as 80 and 1.4 respectively.

V. DESCRIPTION OF THE SYSTEM

Fig. 5 shows the studied system, which consists of a synchronous generator connected to an infinite bus through a transmission line and an SMES unit. Although the system chosen is relatively simple, it is sufficient to demonstrate the damping eff-ect of SMES [10,11].The non-linear dynamic behavior of the synchronous generator is described by the two axis model [1]. The generator is equipped with a static excitation and governor systems[11]. The direct and quadrature axis current of the generator can be expressed as

$$I_d = I_{td} + I_{sd} \tag{21}$$

$$I_q = I_{tq} + I_{sq} \tag{22}$$

where I_{td} and I_{tq} represents transmission line d-axis and q-axis currents, and I_{sd} and I_{sq} come from the SMES unit.

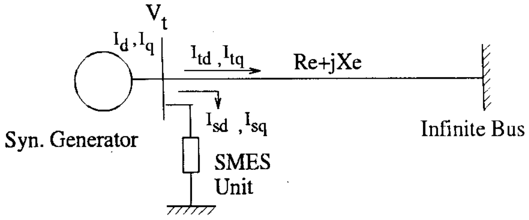

Fig. 5. The power system with SMES unit

VI. EIGEN VALUE SENSITIVITY

Table 1. System eigenvalues

Without SMES P_0=1.0 p.u	With SMES	Without SMES P_0=1.2 p.u.	With SMES
–217.80	–217.89	–217.89	–217.89
–41.55	–41.91	–41.70	–41.93
–19.45	–20.85	–19.47	–20.88
–.09±j10.2	**–15.9±j17.2**	**+.05±j10.4**	**–15.9±j17.0**
–11.63	–38.46	–11.59	–38.46
–4.32	–8.62±4.46	–4.30	–8.75±4.62
–2.25	–3.18	–2.35	–3.74
–1.51	–1.78±0.16	–1.50	–2.14
–.13	–.13	–.13	–1.62
			–.13

Electromechanical modes denoted in bold

Table 1 shows the system eigenvalues for two initial operating conditions. It is seen that for P_0 = 1.0 p.u., the real part of the oscillatory mode is very small. The system has positive real parts with P_0 = 1.2 unit. However, the overall performance is improved with the SMES unit. For both initial operating conditions, the real part of the electromechanical mode has been shifted significantly to a safe negative value when the SMES unit is added. In order to examine the control ability of the proposed controller at any other load conditions, the real part of the eigenvalues of the electromechanical mode is plotted in Fig. 6.The system is stable upto P_0 =1.128 p.u., without the SMES unit. With the SMES unit, the system is highly stable even at P_0 =1.7

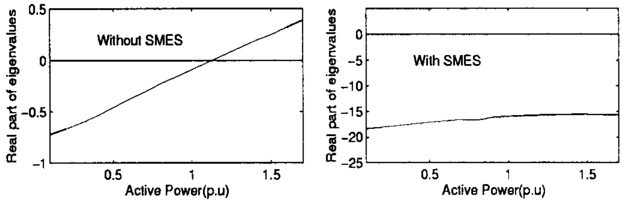

Fig. 6. Real part of electromechanical mode eigen value under various load condition

p.u.. The proposed controller has extended the stability margin considerably.

VII. DYNAMIC SIMULATION

In order to demonstrate the beneficial damping effect of the proposed SMES controller, computer simulations based on system non-linear differential equations are carried out at various load conditions. The differential equations are solved by using the 4th order Runge-Kutta method under MATLAB environment. All non-linearities such as exciter ceiling voltage, SMES voltage limits, inductor current limits have been included. The system and SMES parameters used are same as [11].

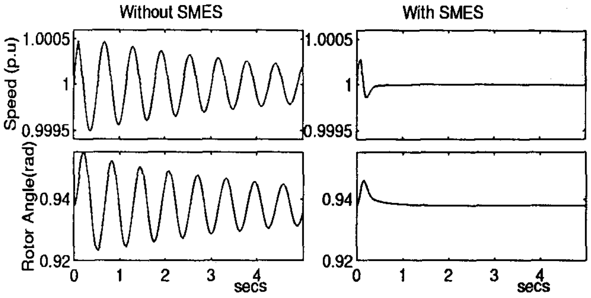

Fig. 7. System performance under small disturbance

Fig. 7 shows the system responses to a step change of 1.2% in load for a duration of 100ms. This is a small disturbance, and so the speed oscillation plots certify the damping characteristics of the electromechanical mode as given in Table 1. Next the dynamic performance is examined for a large disturbance. A 100 ms three phase fault is simulated at the middle of the transmission line. The system responses are plotted for three different load conditions.

Fig. 8 shows the system performances with and without the SMES unit when $P_0 = 0.8$ p.u. The damping of the system is not satisfactory without the SMES unit. Fig. 9 shows the system performances with and without the SMES unit when $P_0 = 1.0$ p.u. The system becomes oscillatory without SMES unit. The system becomes unstable when $P_0 = 1.2$ p.u.[Fig. 10] as confirmed by the eigenvalue analysis. The corresponding rotor angle variations are also shown in each figure. It is observed that the addition of the SMES unit improves the system damping and the settling time decreases substantially. For the heavy load condition the system becomes stable with the SMES unit. It is observed in Fig. 8 through 10 that the use of unequal α -mode forces the SMES unit P-Q consumption to zero when the system approaches stable conditions. The firing angles starts with (90°, − 90°) and end with the same values. The results are compared with those obtained using the conventional equal α mode [6,7,8]. The method proposed does not require any additional/ supplementary control loops as proposed in [6,7] to obtain satisfactory damping. Also for the same fault level, the results obtained show measurable improvements when compared with the results obtained in our earlier work [8].

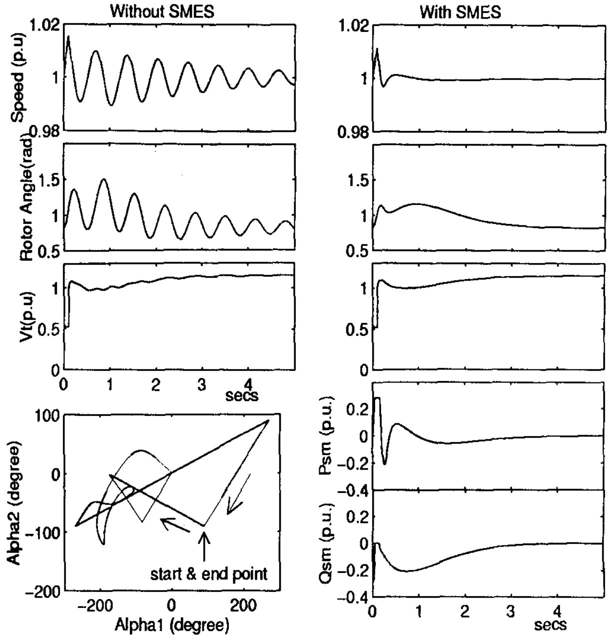

Fig. 8. System performance under large disturbance
P_0=0.8 p.u

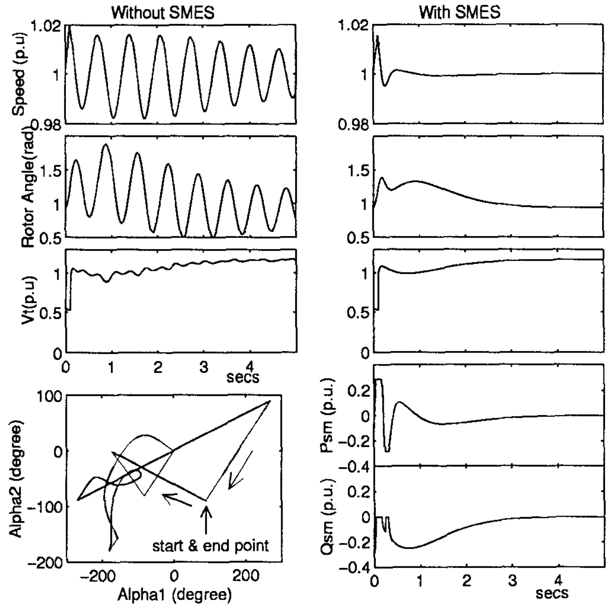

Fig. 9. System performance under large disturbance
$P_0 = 1.0$ p.u

In the unequal α-mode of control, the converter output consists of two pulse trains of different harmonic amplitudes, the lowest frequency being the sixth harmonic.

This will impose slightly higher duty on the associated filters and may also necsessitate a small derating of the inductor. Since this mode occurs only during transient conditions, the benefits derived from this mode of control outweights the above setbacks.

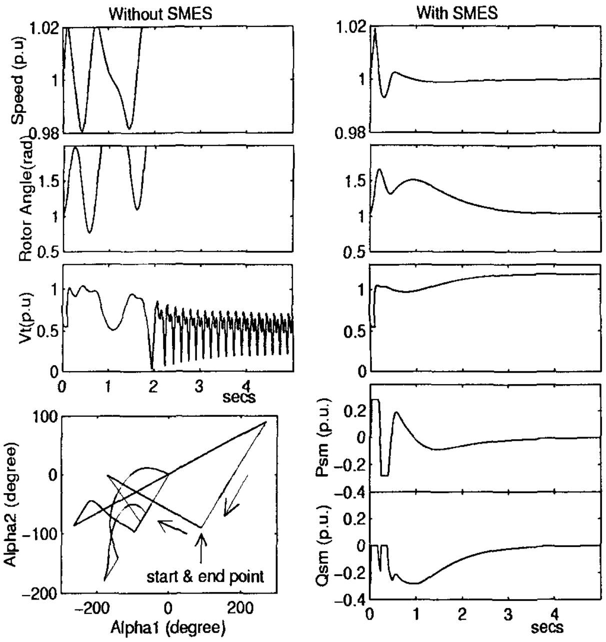

Fig. 10. System performance under large disturbance $P_0 = 1.2$ p.u

VII. CONCLUSION

A method of improving the damping of synchronous generator by simultaneous control of active and reactive power modulation of the SMES unit under unequal α-mode is presented. The control strategy is based on the principle that the SMES unit should receive or deliver power according to the degree of disturbance. Also under normal conditions, the SMES energy transfer should be zero. It has been shown that the additional degree of freedom provided under unequal α-mode of control, significantly improves the system performance. This indicates that the power system can be stabilized reliably if equipped with proper SMES control circuitry. The proposed controller is very simple and does not require additional controller for the correction of desired firing angles. This controller would require very little hardware to implement.

VIII. REFERENCES

[1] P.M. Anderson and A. A. Fouad, *Power System Control and Stability*, Iowa State University press, Ames, Iowa, 1977.

[2] E. V. Larsen and D. A. Swann, Applying power system stabilizers, *IEEE Trans. Power Appar. and Syst.*, vol. PAS-100, 1981, pp. 3017-3046.

[3] S. C. Tripathy, T. S. Bhatti, and C. S.Tha, et. al., Sampled data automatic generation control analysis with reheat steam turbines and governor dead-band effect, *IEEE Trans. on Power Appar. Syst.*, vol. PAS-13, 1984, pp. 1045-1051.

[4] H. Stemmeler and G. Guth, The thyristor controlled static phase-shifter a new tool for power flow control in ac power system, *Brown Boveri Review*, vol. 69,1982, pp.73-78.

[5] H. J. Boening and J. F. Hauer, Commissioning test of the bonneville 30 MJ superconductive magnetic energy storage unit, *IEEE Trans. on Power Appar. Syst.*, vol. PAS - 104, no. 2, February 1985, pp. 302-312.

[6] C. J .Wu and Y. S. Lee, "Application of Simultaneous Active and Reactive Power Modulation of Superconducting Magnetic Energy Storage Unit to damp Turbine-Generator Subsynchronous Oscillations", IEEE Trans. on Energy Conversion, vol. 8, no. 1, March 1993, pp. 63-70.

[7] L. Wang, S. Lee and C. Huang, "Damping Subsynchronous Resonance Using Superconducting Magnetic Energy storage Unit", IEEE Trans on Energy Conversion, vol. 9, no. 4, December 1994, pp. 770-777.

[8] M.G. Rabbani, J.B.X. Devotta and S. Elangovan, "A fuzzy set theory based control of superconducting magnetic storage (SMES) unit to improve power system dynamic performance", International Journal of Power Systems Research, Vol. 40, 1997, pp. 107-114..

[9] S. Banerjee, J. K. Chatterjee, and S. C. Tripathy, Application of magnetic energy storage unit as load frequency stabilizer, *IEEE Trans. on Energy Conversion*, vol. 5, no. 1, March 1990, pp. 46-51.

[10] Y. Mitani , K. Tsuji, and Y. Murakami, Application of superconducting magnetic energy storage to improve power system dynamic performance, *IEEE Trans. Power Syst.*, vol. 3, no. 4, November 1988, pp. 1418-1425.

[11] C. J. Wu and Y.S. Lee, "Application of Superconducting Magnetic Energy Storage Unit to improve damping of Synchronous Generator", IEEE Trans. on Energy Conversion, vol. 6, no. 4, December 1991, pp. 573-578.

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