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# Damping of Synchronous Generator using two FACTS Devices Based on Optimal Rating of the SMES Unit

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**Abstract**

The FACTS devices have recently received great attention in the damping of a power system. The super-conducting magnetic energy storage (SMES) systems have also received much attention in power system applications. However the cost of a practical SMES unit is more expensive than others power system stabilisers. In this paper, following an attempt to make it economical, the simultaneous application of TCSC and SMES is proposed to improve the power system dynamics. The results show that the proposed scheme can greatly reduce the rating of the super-conducting coil, without deteriorating the system dynamic performance.

**Keywords**
SMES, power system stabilisation, TCSC and P-Q modulation

## 1 INTRODUCTION

Power system oscillations will occur if there are system disturbances such as load changes and system faults. The damping of the system must be enough in order the system could return to steady state after the fault clearance. Different methods have been suggested to improve power system dynamics, the power system stabiliser (PSS) is a simple, effective and economical method. With the advent of FACTS [1], the potential of FACTS damping function in suppressing power system oscillation has attracted interests from both academia and industry [2-4]. Also due to the rapid development in the high temperature super-conducting material, the SMES unit was designed to store electric power. The SMES unit is able to absorb power from or deliver to the power system by controlling the firing angle of the converter switches. Therefore it will be able to damp power system oscillations [5-7]. In spite of the better performance of the SMES unit in improving the power system dynamics, the cost of a practical unit is high [8]. Although few SMES units with varying from 30MJ up to 250MJ have been used by BPA and other utilities in USA, the commercial devices are not available [7]. As the cost of a practical SMES unit is more expansive than other power system stabilisers, an attempt has been made in this paper to make it economic. To do so, the simultaneous application of SMES and TCSC is proposed to enhance power system stability using a lower rating of the super-conducting coil. A systematic approach is used to design the controller and its parameters are determined using modal control theory. The eigenvalue analysis and the simulation results show that the SMES unit under equal firing angle and PI controller can improve system dynamics, but when it is used in conjunction with TCSC, the required rating of the super-conducting coil is greatly reduced. If the unequal firing angle control of the SMES unit is employed, its rating can be further reduced. In this case the PI controller is no longer required [9].

## 2 SYSTEM DESCRIPTION AND MODELLING

In this study a single machine connected to an infinite bus through a transmission system with a shunt connected SMES and a series connected TCSC, as shown in Fig.1, is considered. The non-linear dynamic behaviour of the synchronous generator is described by two-axis model [10]. The generator is equipped with a static excitation control system and the governor and the reheat turbine system, which all are defined by a set of $10^{th}$ order non-linear differential equations [7]. The direct and quadrature current of generator are expressed by

$$I_{dg} = I_{td} + I_{sd} \qquad (1)$$

$$I_{qg} = I_{tq} + I_{sq} \qquad (2)$$

where $I_{td}$ and $I_{tq}$ are transmission line current, $I_{sd}$ and $I_{sq}$ provided by the SMES unit.

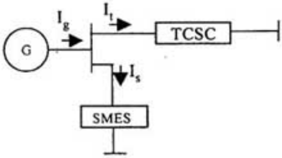


Figure 1: Single machine connected to infinite bus with SMES and TCSC

The SMES unit as shown in Fig.2 consists of a 12 pulse cascaded bridge type ac/dc converter, a Y–Δ/Y–Y step down transformer and a dc super-conducting inductor. The converter unit is forced commutated and $\alpha$ is the firing angle of switches. The power modulation can be achieved by controlling the firing angle control of converters. The current through super conducting coil and the voltage appeared across it are related by

$$I_{sm} = \frac{1}{L_{sm}} \int_{t_0}^{t} V_{sm} dt + I_{sm0} \qquad (3)$$

where $I_{sm0}$ is the initial current of inductor. The SMES powers are defined by [9]:

$$P_{sm} = 2V_{sm0} I_{sm} \cos\alpha \qquad (4)$$

$$Q_{sm} = 2V_{sm0} I_{sm} \sin\alpha \qquad (5)$$

The SMES voltage ($V_{sm}$) can be varied between positive and negative values by controlling the firing angle of converters, so the power delivered to or absorbed from the coil can be continuously varied. The operation of the SMES unit is possible in four quadrant modes using the GTO based converter [11]. In order to provide the power system dynamics during disturbances different methods can be used for SMES unit. In the simultaneous P and Q modulation approach the terminal voltage deviation and speed deviation related to the corresponding desired powers modulation are as follows [9 ]:

$$\widetilde{Q}_{sm} = \frac{K_{vs}}{1 + sT_{dc}} \Delta V_t + Q_{sm0} \qquad (6)$$

$$\widetilde{P}_{sm} = \frac{K_{ps}}{1 + sT_{dc}} \Delta\omega + P_{sm0} \qquad (7)$$

where $K_{vs}$ and $K_{ps}$ are the amplifier gains and $T_{dc}$ is the delay time of the converter. The equal firing angles are determined by

$$\alpha = \tan^{-1}(\widetilde{Q}_{sm} / \widetilde{P}_{sm}) \qquad (8)$$

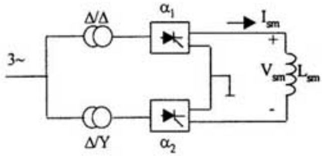


Figure 2: Diagram of SMES unit

The active and reactive powers of the SMES unit can be obtained from Equations (4) and (5). It has been shown that [12,13], this method can be effective in power system stabilisation only with the incorporation of an extra controller. The P modulation method can also be used to control the amount of $P_{sm}$ to make it equal to the desired $\widetilde{P}_{sm}$ regardless of the value of $Q_{sm}$. This control system using a PI controller is shown in Fig.3 and is successfully applied for power system stabilisation [7].

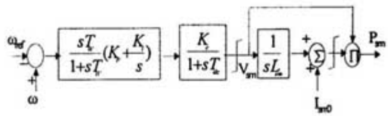


Figure 3: Control system of the SMES unit

In this approach the voltage $V_{sm}$ across the inductor is controlled on the measured speed deviation as follows:

$$\Delta V_{sm} = \frac{K_c}{1 + sT_{dc}} \Delta\omega \qquad (9)$$

where $K_c$ is the gain of control loop and $T_{dc}$ is the delay time of the control device. Because of constraints of hardware implementation, the SMES voltage and current have upper and lower limit [7], which have been considered in this study.

The simultaneous control of P and Q of the SMES unit under unequal firing angles of converters ($\alpha_1 \neq \alpha_2$) is proposed [9], in which there is no need for employing an extra controller. The control system based on

Equations (6) and (7) shown in Fig.4 which relates the speed and voltage deviations to the desired values of $\widetilde{P}_{sm}$ and $\widetilde{Q}_{sm}$ . In this case the $P_{sm}$ and $Q_{sm}$ of the SMES unit are described by the following equations:

$$P_{sm} = V_{sm0} I_{sm} (\cos\alpha_1 + \cos\alpha_2) \qquad (10)$$
$$Q_{sm} = V_{sm0} I_{sm} (\sin\alpha_1 + \sin\alpha_2) \qquad (11)$$

Knowing $P_{sm}$, Qsm and the present value of $I_{sm}$, the firing angles of the converters can be calculated by

$$\alpha_1 = \cos^{-1}\left(\frac{P_{sm}}{P_{sm}^2 + Q_{sm}^2}\right) + \cos^{-1}\left(\frac{P_{sm}^2 + Q_{sm}^2}{2V_{sm0} I_{sm}}\right) \quad (12)$$

$$\alpha_2 = \cos^{-1}\left(\frac{P_{sm}}{P_{sm}^2 + Q_{sm}^2}\right) - \cos^{-1}\left(\frac{P_{sm}^2 + Q_{sm}^2}{2V_{sm0} I_{sm}}\right) \quad (13)$$

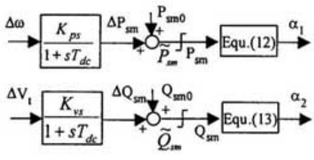


Figure 4: Unequal firing control of SMES

The main circuit of the TCSC consists of a capacitor bank and a thyristor controlled inductive branch connected in parallel as shown in Fig.5.

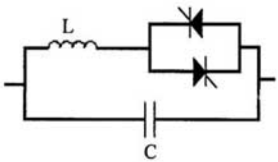


Figure 5: TCSC main circuit components

The characteristic of the TCSC depends on the relative reactance of the capacitor bank $XC = -1/\omega C$ and the thyristor branch $X_L = L\omega$. For power system damping a TCSC can be modelled as a variable reactance. The block diagram of the TCSC model is shown in Fig.6. Based on a control strategy a reference reactance $X_{ref}$ of TCSC is determined. This signal is passed through a delay block. The time constant T approximates the delay due to the main circuit characteristics and control system. The output of the model is restricted by two limits, i.e. static reactance limit and dynamic reactance limit.

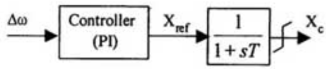


Figure 6: TCSC model as damping controller

## 3 CONTROL SYSTEM DESIGN AND EIGENVALUE ANALYSIS

In this study the two aforementioned models of SMES unit with and without TCSC have been applied to the same system of reference [7]. The system and the SMES parameters are found in this reference. When the equal control of SMES with PI controller is used the parameters of the controller are determined using the modal control theory. To do so, eigenvalue analysis has been carried out and the obtained results are shown in Table1. It is evident that system without SMES has two unstable electromechanical modes as shown in Table1. If the eigenvalues of these modes are assigned at:

$\lambda_1, \lambda_2 = -2.1 \pm j0.5$

Then the determined PI controller parameters are as follows:

$K_P = 25.01$
$K_I = 40$

The eigenvalues of system with PI SMES are also shown in Table1.

## 4 COMPUTER SIMULATION

To examine the damping effect of the SMES and TCSC, computer simulations based on the non-linear differential equations are carried out with 4[th] order Runge-Kutta method using MATLAB software. Since the firing angles control of the converter can have significant effect on the operation of the SMES, so its model under equal and unequal firing angle is considered.

Table1. System eigenvalues $P_0$=1.0 pf = 0.85

| Without PI SMES | With PI SMES |
|---|---|
| -217.83 | -217.83 |
| -42.07 | -42.07 |
| -20 | -20 |
| -9.95 | -10.03 |
| *0.025±j0.5 | -2.1±j0.5 |
| -2.5 | -2.64 |
| -1.3 | -3.21 |
| -5.66 | -0.194 |
| -0.13 | -0.138 |
| | -0.10 |
| | -24.4 |

*Electromechanical mode

In order to validate the effectiveness of SMES and TCSC simulation studies are carried out. A 4 cycles three-phase fault as a large disturbance and 10% increase in the turbine power for the same period as a small disturbance applied to the single machine power system.

Fig.7 and Fig.8 show the system performances under equal firing angle control ($\alpha_1$=$\alpha_2$) with and without TCSC respectively. It is evident that the system damping is satisfactory in both cases and the current and voltage of the SMES are within limits. While in the presence of TCSC the inductance of the super-conducting coil reduced from 0.18 H to 0.147 H. The predetermined limits for SMES unit in this case are:

$$-0.438 \le V_{sm} \le 0.438$$
$$0.2013 \le I_{sm} \le 0.8963$$

Fig.9 and Fig.10 show the similar simulation results when SMES unit is controlled under unequal firing angle ($\alpha_1 \neq \alpha_2$). The results show that in this case also satisfactory dynamic performance is provided with and without TCSC and the voltage and current of the SMES unit are also within predetermined limits. However in the presence of TCSC further reduction in the rating of the SMES coil observed. In this case the amount of inductance is reduced from 0.15 to 0.066 H. The predetermined limits for SMES unit are:

$$-0.2532 \le V_{sm} \le 0.2532$$
$$0.2400 \le I_{sm} \le 1.1040$$

Therefore a reduction of 18% up to 56% is possible depending on the control of the SMES unit. In all cases the parameters of PI controller for TCSC are:

$K_I$ = 60.5
$K_p$ = 7.5

which have been determined in this study such that satisfactory power system damping to be obtained.

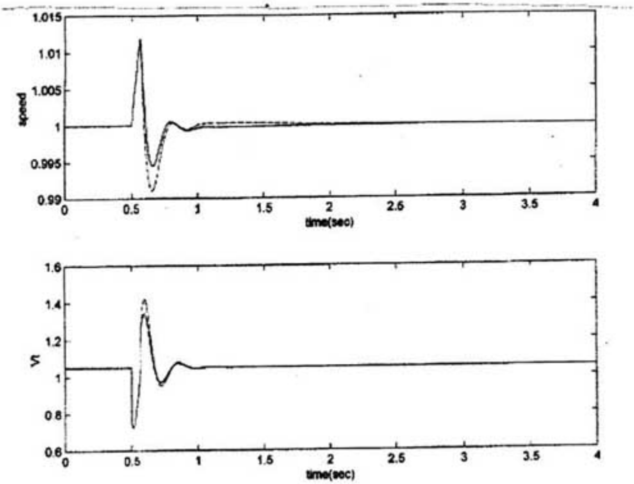


Figure 7: Variation of speed and terminal voltage under large disturbance for equal firing angle control of SMES $(\alpha_1 = \alpha_2)$ ---- With TCSC — Without TCSC

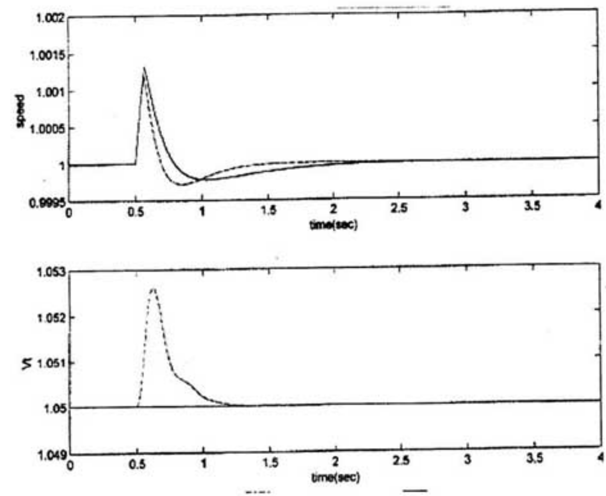


Figure 8: Variation of speed and terminal voltage under small disturbance for equal firing angle control of SMES $(\alpha_1 = \alpha_2)$ With TCSC Without TCSC

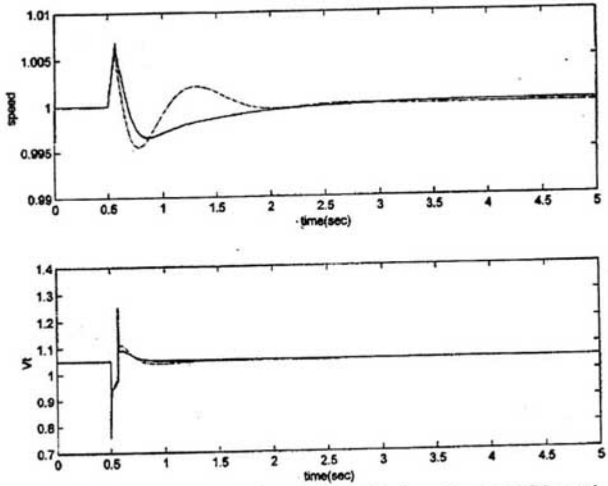


Figure 9: variation of speed and terminal voltage for under large disturbance for unequal firing angle control of SMES ($\alpha_1 \neq \alpha_2$) -·-·-·- with TCSC —— without TCSC

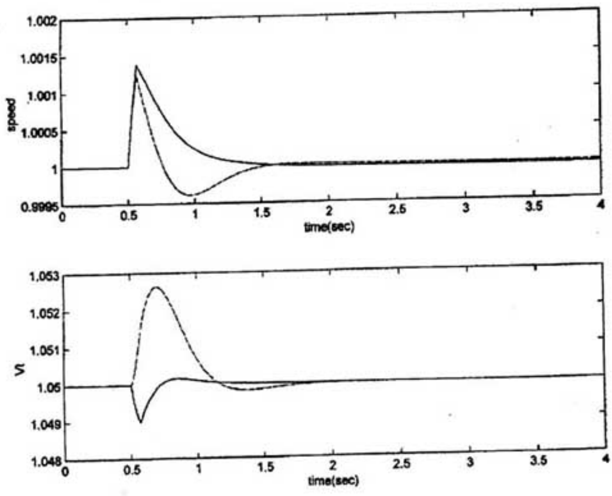


Figure10: variation of speed and terminal voltage for under large disturbance for unequal firing angle control of SMES ($\alpha_1 \neq \alpha_2$) ----- with TCSC —— without TCSC

## 5 CONCLUSION

In this paper attempt has been made to use the optimal rating of the SMES in power system damping. It has been shown that when the SMES unit is employed in conjunction with TCSC, the required rating of the super-conducting inductor is greatly reduced. It can be concluded that the SMES unit under unequal firing angle control with TCSC is technically effective and economically acceptable, so it can be used as a powerful tool to damp power oscillations.

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