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# IMPROVEMENT OF POWER SYSTEM DYNAMICS USING SUPERCONDUCTING MAGNETIC ENERGY STORAGE UNIT

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**Abstract:**

Fast acting energy storage unit 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. High temperature superconductor makes the SMES unit very attractive to the utility engineers. SMES systems have the capability of storing energy in periods of off-peak interval and supplies power during the peak-load.
In this paper a simple but novel control strategy is developed for Superconducting Magnetic Energy Storage (SMES) unit to improve the power system dynamics of a test system. The gain of the controller of SMES unit is determined depending on the power system and the capacity of the SMES unit. Two simple delayed functions are used to determine the desired active and reactive power from the SMES unit.

## Introduction:

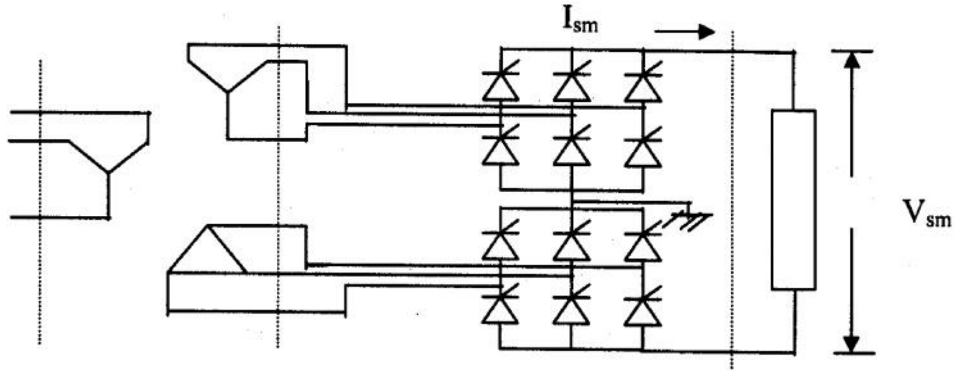
The stability problem is concerned with the behavior of the synchronous machines after they have been perturbed. The transients following the perturbation are oscillatory in nature. If the system is stable, these oscillations will be damped towards a new operating point. The perturbation could be a major disturbance such as the loss of generation or system fault or combination of such events [1]. Many countermeasures are suggested in the literature to increase the damping such as the use of power system stabilizer(PSS) [2], governor and turbine system[3] and static phase shifter[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 in case this is needed. The amount of energy to be supplied or received by the SMES unit can be controlled by controlling the firing angles of the converters of the SMES unit.

In this paper, different types of faults are considered to show the performance of the SMES unit. Small disturbances as well as large disturbances are considered to show the effectiveness of the SMES unit in power system application. The SMES system is applied to a test network and the simulation results are presented and discussed.

**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 (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.




Y-Y/Δ Transformer 12-pulse converter Inductor

Fig. 1 Schematic diagram of the SMES unit

Gate turn off thyristors (GTO) allow us to design such type of converter [8]. 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 $\alpha$.

For initial charging of the SMES unit, the bridge voltage $V_{sm}$ is held constant at a suitable positive value depending on the desired charging period. The inductor current $I_{sm}$ rises exponentially and magnetic energy $W_{sm}$ 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 with the power system.

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 the 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.

According to the circuit analysis of converter, the voltage $V_{sm}$ of the DC side of the 12-pulse converter is expressed by

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

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

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

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

$$P_{sm} = V_{sm} I_{sm} \quad (3)$$

The energy stored in the superconducting inductor is

$$W_{sm} = W_{sm0} + \int_{t_0}^{t} P_{sm} d\tau \quad (4)$$

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 current is chosen at $0.3I_{sm0}$, the upper inductor current based on the equal energy absorption/discharge criterion is set at $1.38I_{sm0}$. 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.

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:

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

Therefore, at any instant, for the particular SMES unit, the power $P_{sm}$ has the following limits:

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

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].

**SMES control strategy:**

Let $\Delta V_t$ 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],

$$Q_{sm}^{*} = \frac{K_{vs}}{1 + sT_{dc}} \Delta V_t + Q_{sm0} \quad (5)$$

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

$$P^{*}_{sm} = \frac{K_{ps}}{1 + sT_{dc}} \Delta\omega + P_{sm0} \quad (6)$$

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

$$\alpha^{*}_{1} = \alpha^{*}_{2} = \alpha = \tan^{-1} (Q^{*}_{sm} / P^{*}_{sm}) \quad (7)$$

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

$$P_{sm} = 2\, V_{sm0}\, I_{sm} \cos\alpha \quad (8)$$
$$Q_{sm} = 2\, V_{sm0}\, I_{sm} \sin\alpha \quad (9)$$

## Determination of amplifier gains $K_{ps}$ and $K_{vs}$:

The disturbance in the system is made significantly large so that it is on the verge of instability. The maximum value of $\Delta V_t$ 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:

$$K_{ps} = \frac{V_{sm,max} I_{sm,max}}{\Delta\omega_{max}} \quad (10)$$

and

$$K_{vs} = \frac{V_{sm,max} I_{sm,max}}{\Delta V_{t,max}} \quad (11)$$

where $V_{sm,max}$ and $I_{sm,max.}$ are the maximum voltage and current limits for a particular SMES unit. Thus the value of $K_{ps}$ or $K_{vs}$ 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 68 and 1.38 respectively.

## Description of the system:

Fig. 2 shows the studied system consists of a synchronous generator connected to an infinite bus through a double transmission line and an SMES unit. Although the example system is simple one, it is sufficient to demonstrate the damping effect of SMES [10,11].The non-linear dynamic behavior of the synchronous generator is described by the two axis model [1].

$$\dot{\omega} = (P_m - D_g\omega - P_e) / M_g \quad (12)$$

$$\dot{\delta} = \omega_0 (\omega - 1) \quad (13)$$

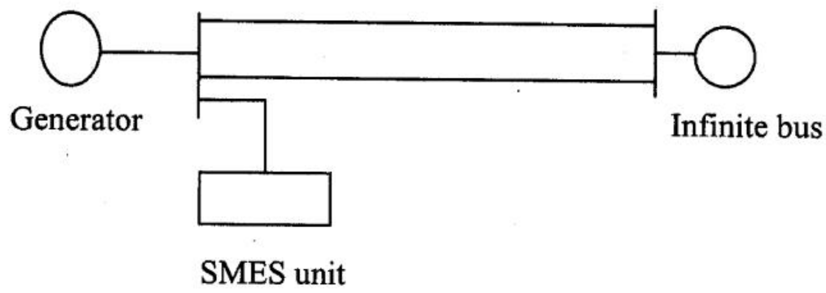



Fig. 2. The power system with SMES unit

The generator is equipped with a static excitation and governor systems[11].

**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 the non-linearities such as exciter ceiling voltage, SMES voltage limits, inductor current limits have been included. The system and SMES parameters used in the simulation are same as [11].

Fig. 3 shows the system responses when there is a 0.012 p.u. 100 ms load change. This is a small disturbance, and the speed oscillation plots certify the damping characteristics of the test system. Next the dynamic performance is examined for a large disturbance. A 100 ms three phase fault is occurred at the middle of the transmission line. The system responses are plotted for three different load conditions.

Fig. 4 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. 5 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. 6]. 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.

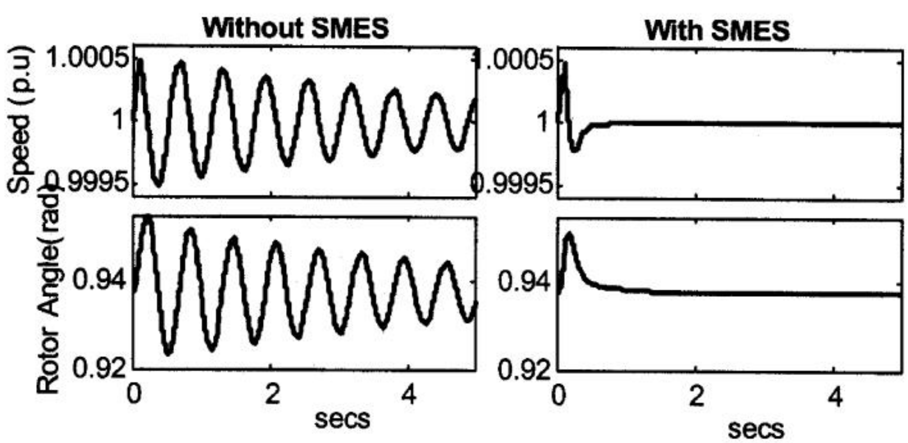



Fig. 3. System performance under small disturbance

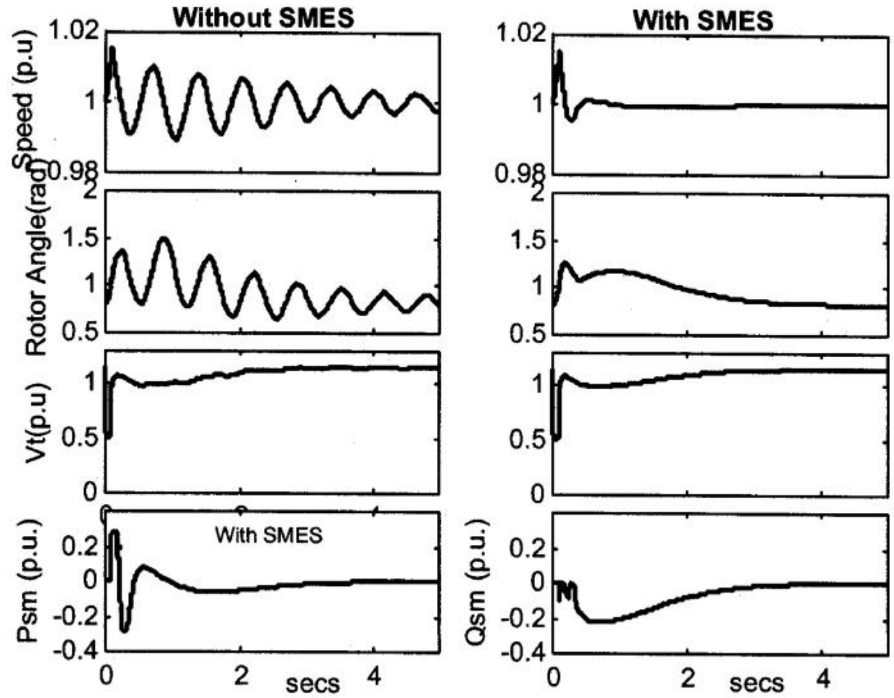



Fig. 4. System performance under large disturbance
$P_0$=0.8 p.u

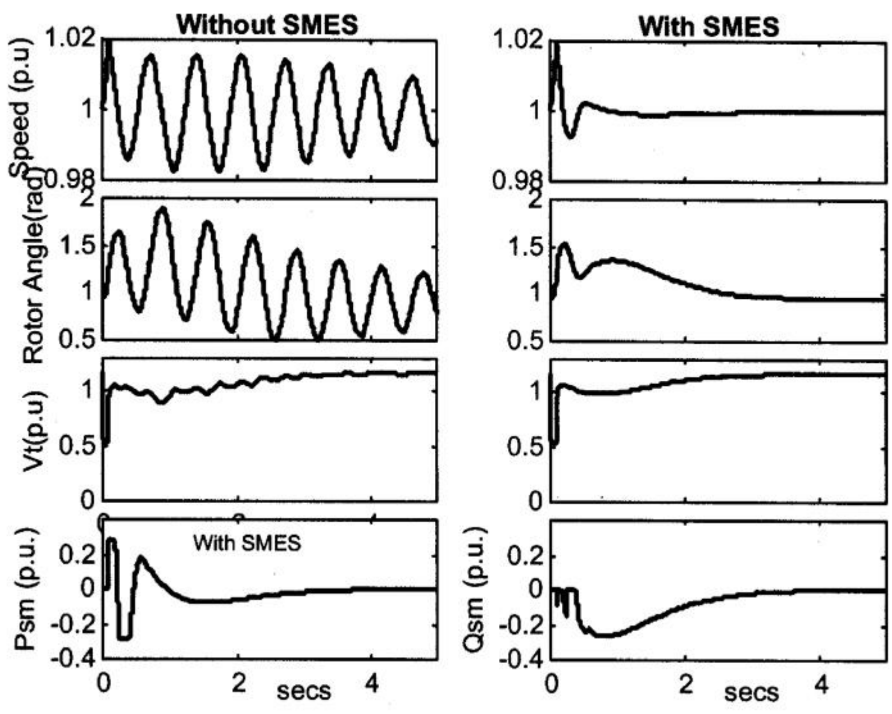



Fig. 5. System performance under large disturbance
$P_0$ = 1.0 p.u

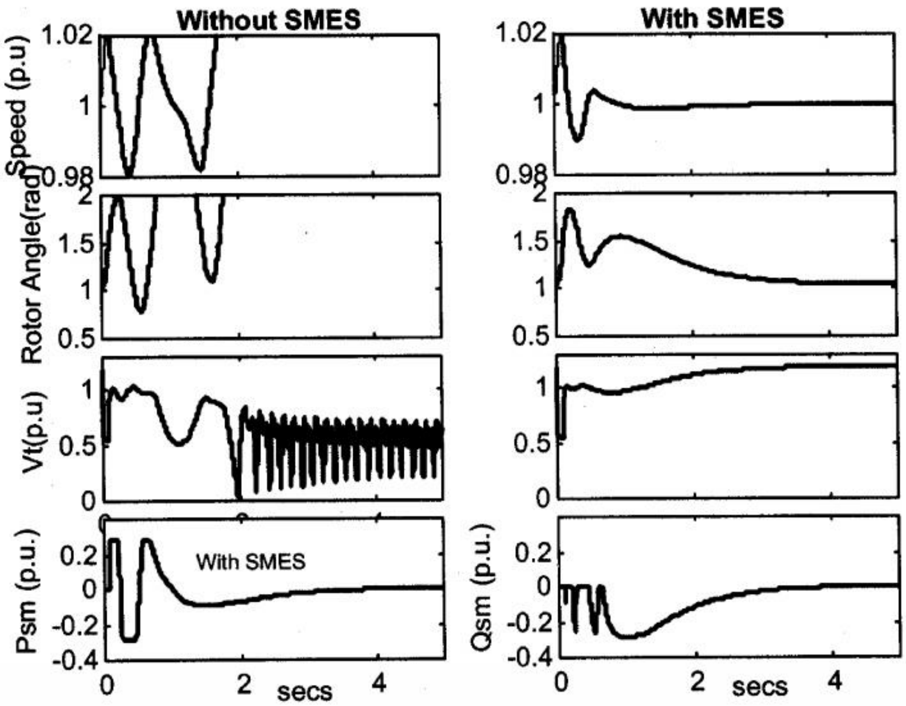



Fig. 6. System performance under large disturbance , $P_0 = 1.2$ p.u

It is found in the present research that the stability margin of the system with SMES can be extended considerably. All these results certify the effective use of the SMES power with the proposed mode of control.

**Conclusion:**

A method of improving the damping of synchronous generator through simultaneous control of active and reactive power modulation of the SMES unit under equal α-mode is presented. The control strategy is derived from a simple principle that the SMES unit should receive or deliver power according to the degree of disturbance. Also under normal condition, there should be no transfer of energy between the SMES and the power system. Different types of faults are considered to show the effectiveness of the power system. It has shown 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 of the converter. This controller would require very little hardware to implement.

System data and initial conditions [11]:
Generator and transmission line:
Base 160 MVA, 15 kV
Generator 160 MVA, 15 kV, 0.85 p.f.
Exciter 375 V, 926 A
$X_d' = 0.245$ p.u. $X_d = 1.70$ p.u. $X_q = 1.64$ Ra= 0.001096 Mg= 4.74 Dg=0
Ze=0.02+j.40 $T_{d0}' = 5.9$ sec $T_{q0}' = 0.075$ sec

SMES Unit: $I_{sm0} = 0.6495$ p.u. $V_{sm0} = 0$ p.u. $L_{sm} = 0.5$ H $W_{sm0} = 6$ MJ $T_{dc} = 0.26$ s.

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