Use of superconducting magnetic energy storage device in a power system to permit delayed tripping

S.S.Ahmed, S.Bashar, A.K.Chatterjee, M.A.Salam and H.B.Ahmad

Abstract: Use of a superconducting magnetic energy storage (SMES) device in an electric power system can extend the time margin required for clearing a fault without any loss of stability of the synchronous generators in the system. Necessary mathematical model and computer simulation results have been presented. A wider time margin would be beneficial in many ways, such as precluding unwanted line tripping following temporary earth fault or transient swings, deferring costly replacement of the existing relays and breakers by the faster ones, and making a fair decision on tripping, taking into consideration a large volume of on-line data, constraints and complicated policies likely to be encountered in operating a power system under deregulation or a competitive market environment.

1 Introduction

Superconductivity is a property [1, 2] of certain metallic elements (e.g. zinc, mercury) or alloys (e.g. niobium titanium) or copper oxide base ceramics (e.g. yttrium-barium-copper oxide) by virtue of which their electrical resistivity drops from a finite value at normal room temperature to nearly zero when they are cooled to an extremely low temperature (termed transition or critical temperature) by means of a cryogenic medium (e.g. liquid helium or nitrogen). Continuous researches and advancements over the last two decades have turned the ceramics based high temperature superconductors (HTS) into an affordable reality. These use less expensive liquid nitrogen cooling and work for a critical temperature ranging from 77 to 160K. Consequently HTS devices are more compact, efficient, economic, reliable and compatible for higher magnetic field strength compared to alloy based low temperature superconductor (LTS) devices which use more expensive liquid helium cooling and work only for a critical temperature of 4K or less.

HTS coils are finding increasing applications in electrical power engineering, as for instance: (i) in the construction of various power apparatus like generators and motors [3], fault current limiters [4], transformers [5] and cables [6]; and (ii) as a lossless energy storage device in a power system for (a) load levelling [7], (b) back-up [8] supply to the loads (e.g. computers, chip manufacturing plants, etc.) sensitive to momentary voltage disturbances or power interruptions and (c) damping synchronous generators oscillations [9–14].

IEE Proceedings online no. 20000656

DOI: 10.1049/ip-gtd:20000656

Paper first received 16th November 1999 and in revised form 15th May 2000

S.S. Ahmed, S. Bashar and A.K. Chatterjee are with the Department of Electrical and Electronic Engineering, Bangladesh University of Engineering & Technology, Dhaka-1000, Bangladesh

M.A. Salam and H.B. Ahmad are with the Faculty of Electrical Engineering, Universiti Technologi Malaysia 81310, Skudai, Johor Bahru, Malaysia

S.S. Ahmed is currently with Universiti Technologi Malaysia

A superconducting coil (inductor) interfaced with a power system through a bidirectional AC/DC power electronic converter (rectifier/inverter) [15] is able to undergo fast charging of energy into or discharging energy from its magnetic field. This ability has so far been utilised for damping generator rotor speed oscillations to enhance transient stability [9, 10, 12, 14, 16] in the backdrop of a permanent fault or sudden loss of load/generation and for damping turbogenerator oscillations due to subsynchronous resonance (SSR) [11, 13] in a system with a series capacitor compensated transmission line. The present paper brings to focus a new application aspect that the fast charging and discharging capability of a superconducting coil can allow a longer time delay for tripping the faulty line/portion of a power system without losing transient stability.

The aforesaid time delay is favourable for avoiding unnecessary line tripping in case the generator oscillations result from momentary disturbance or temporary earth contact. Moreover, the complexities and operating strategies of the present day's power systems under deregulation or competition [17] pose conflicting requirements such as fair decision making through comprehensive analysis of a large volume of on-line data as against fast fault clearing. Extra time margin arising from the use of a superconducting magnetic energy storage (SMES) coil will enable correct decision making on occurrence of a fault in a system equipped with protective relays and breakers of normal speed.

The present paper also provides two suggestions: (i) control of the SMES converter's firing angle through an exponential relationship and (ii) turning off the SMES coil just after the generator rotor oscillations start settling. The first one is expected to avoid frequently reaching the maximum charging and minimum discharging current limits of the SMES coil and hence enable smoother control by SMES. The second one is expected to reduce the operating expenses of the SMES device.

2 Operation of an SMES device in a power system

A simple and representative power system as shown in Fig. 1 has been considered in the present work. It comprises a synchronous generator connected to a large external system (representing an infinite bus) through a double circuit high voltage transmission line with a step-up and a step-down transformer, respectively, at the line's two ends. An SMES unit houses an HTS coil maintained through a cryogenic fluid at a temperature required for its becoming superconducting (resistance $R = 0$, inductance $L \neq 0$). It is interfaced with the generator side bus through a pair of bidirectional converters connected at the low-tension sides of two separate transformers. Each converter consists of a six-pulse bridge circuit [15] which employs semiconductor switches (thyristors/gate turn-off thyristors). The current I_d in the SMES coil is always DC and flows in a given direction being nonreversible, while the voltage E_d across the coil reverses its polarity depending on the firing angle α of the converter bridges. The SMES draws power from the AC grid to store it in its magnetic field in the charging mode, i.e. it acts as a rectifier (AC to DC) for $0° \leq \alpha < 90°$ while it delivers power to the grid, i.e. it acts as an inverter (DC to AC) for $90° < \alpha \leq 180°$. No power exchange takes place between the AC power system and the SMES when $\alpha = 90°$. The firing angle control strategy depends on the specific purpose (e.g. load levelling, momentary back-up, oscillation damping) the SMES coil is being used for.

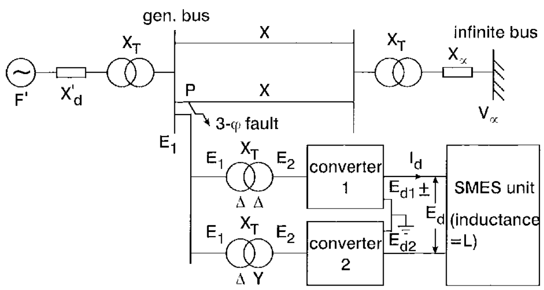

Fig. 1 *One-machine-to-infinite bus (OMIB) system with an SMES embedded in*

2.1 Mathematical formulations

The rotor angle δ of the synchronous generator shown in Fig. 1 is governed by the well known [18] swing equation which has been modified in the present work to take into account the presence of SMES as follows:

$$\frac{H}{\pi f_o}\frac{d^2\delta}{dt^2} = P_m - \frac{E'V_\infty}{X}\sin\delta - P_{SMES} \quad (1)$$

where H is the inertia constant of the generator in per unit of system base, f_o is the system frequency and P_m is the constant [18] prime mover power input at the generator shaft. The second term on the right side of eqn. 1 represents the electrical power output of the generator for transfer to the infinite bus when X is the total series reactance between generator constant EMF E' and infinite bus voltage V_∞. The power absorbed or released by the SMES coil is P_{SMES}, which will be positive for absorption from the grid and negative for release to the grid:

$$P_{SMES} = E_d I_d = 2E_{do}\cos\alpha I_d = 2\frac{3\sqrt{2}}{\pi}E_2 I_d \cos\alpha \quad (2)$$

where E_{do} is the maximum open circuit bridge voltage [15] of each six pulse converter at a firing angle of zero degrees ($\alpha = 0$) and E_2 is each converter transformer's secondary voltage.

The generator acceleration expressed by eqn. 1 is zero in the prefault condition because then its rotor angle is at such a value that the electrical power output is also P_m (neglecting losses in the generator). The SMES also does not exchange any power, i.e. $P_{SMES} = 0$ in the prefault condition. On occurrence of a fault at $t = 0$, the generator rotor angle δ undergoes oscillation about the synchronous position and its power output varies with δ. When it accelerates, the excess power is absorbed by its rotating mass as well as by the SMES. When it decelerates, both its rotating parts and the SMES release power. Without any SMES, only the rotor mass absorbs or releases energy due to inertia which, depending on the time of fault clearing (t_{fc}), may not be enough to damp the generator's oscillations and restore its synchronism.

2.2 Firing angle control

The absorption (charging) or release (discharging) of energy by the SMES coil is controlled by regulating the converter bridge firing angle. Among various strategies [9–14, 16] used for damping oscillation, the simplest but effective one is the proportional control with a time delay. In this scheme the change in firing angle, $\Delta\alpha$, is related to the postfault change in angular velocity of the generator, $\Delta\omega$, by the following transfer function:

$$\Delta\alpha(s) = -\frac{K}{1 + sT_{dc}}\Delta\omega(s) \quad (3)$$

where T_{dc} is the converter time delay constant and K is the control circuit gain parameter.

In the present work $\Delta\alpha$ is found in the time domain in a straightforward manner taking the inverse Laplace transform of eqn. 3 as follows:

$$\Delta\alpha(t) = -K[1 - e^{-(t/T_{dc})}]\Delta\omega(t) \quad (4)$$

At any time t the firing angle α is decided as follows:

$$\alpha(t) = \frac{\pi}{2} + \Delta\alpha(t);\ |\Delta\alpha| < \frac{\pi}{2},\ I_{d,\min} < I_d < I_{d,\max} \quad (5)$$

$$= 0;\ |\Delta\alpha| > \frac{\pi}{2}, \Delta\omega > 0,\ I_{d,\min} < I_d < I_{d,\max} \quad (6)$$

$$= \pi;\ |\Delta\alpha| > \frac{\pi}{2}, \Delta\omega < 0,\ I_{d,\min} < I_d < I_{d,\max} \quad (7)$$

$$= \frac{\pi}{2};\ I_d = I_{d,\min} \text{ or } I_{d,\max} \quad (8)$$

2.3 Algorithm for solving the swing equation

Eqn. 1 is solved for δ against t by the step-by-step method [18] at very short intervals of time Δt for discrete time $t = n\Delta t$, $n = 1, 2, \ldots$ up to the desired time limit as shown in the Appendix (Section 6.1). Eqns. 9–20 shown in the Appendix (Section 6.1) are used recursively with an initial value of δ_0 for the prefault swing angle and an initial value of I_{d0} for the SMES current.

3 Results from computer simulation

The mathematical model and algorithm described in Sections 2.1–2.3 were programmed using FORTRAN 77 and run on a PC for the system shown in Fig. 1 considering five cases of fault clearing and SMES operation. For each case a time step of $\Delta t = 0.01$s and a time span of 5.0s were considered.

A 3-phase fault was considered to occur at $t = 0$ on one of the two parallel circuits at a point P very close to the generator side bus of the system in Fig. 1. Prior to the fault the generator output for transfer to the infinite bus was 1.0 per unit (p.u.) equal to the prime mover input, P_m, at the generator's shaft neglecting losses. The fault was assumed to be cleared in each case by opening the breakers at both ends of the faulted circuit. The output obtained for each case was plotted in the form of a swing curve, i.e. rotor angle δ against time.

The parameters of the system shown in Fig. 1 have been considered on a 100 MVA base and presented in the Appendix (Section 6.2).

(i) *Case with SMES 'off'*

In this case the SMES was considered to be kept 'off' and the fault was cleared in 4.5 cycles, i.e. 0.075s (on a 60Hz basis) after the fault occurred. The obtained swing curve shown in Fig. 2 exhibits that the system is stable but with an oscillation having a peak > 90°.

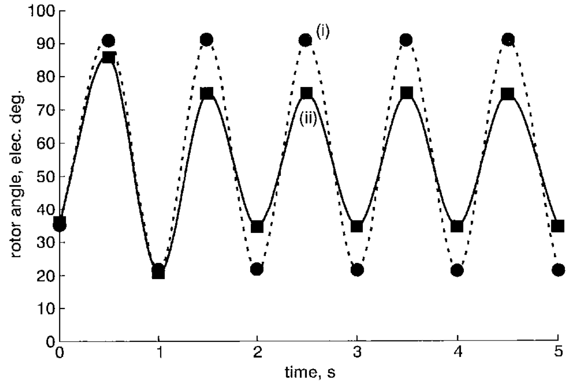

Fig. 2 *Swing curves for 3-phase fault duration of 4.5 cycles with SMES 'off' and 'on'*
(i) SMES 'off'; (ii) SMES 'on'

(ii) *Case with SMES 'on'*

In this case the SMES was considered to be kept 'on' and the fault was considered to be cleared in 4.5 cycles, i.e. 0.075s. The obtained swing curve (solid line) shown in Fig. 2 reveals that for the same fault clearing time the system is more stable with SMES than the case without SMES and undergoes diminished oscillations having a maximum peak of < 90°.

(iii) *Case with longer fault clearing time but SMES 'off'*

In this case the fault was cleared in 9.3 cycles, i.e. 0.155s while the SMES remained 'off' all along. The obtained swing curve plotted in Fig. 3 clearly indicates the system's instability as manifested through the rotor angle indefinitely increasing with time.

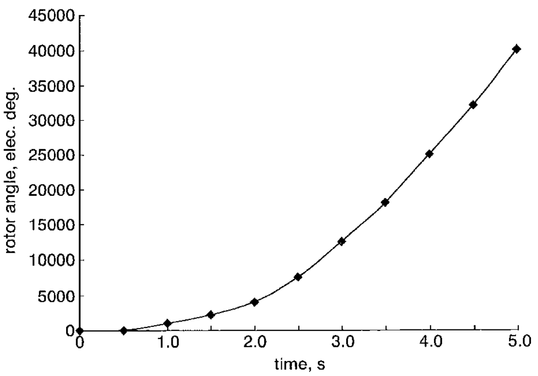

Fig. 3 *Swing curve for 3-phase fault duration of 9.3 cycles with SMES 'off'*

(iv) *Case with longer fault clearing time but SMES 'on'*

This case is the same as (iii) except that the SMES was kept 'on'. The obtained swing curve (solid line) of Fig. 4 exhibits that the system has been stable.

(v) *Case with longer fault clearing time but SMES 'on' for a shorter duration*

In this case the fault was cleared in 9.3 cycles, i.e. the same as in cases (iii) and (iv), but the SMES was kept 'on' for 3.0s. The obtained swing curve shown in the dotted line in Fig. 4 reveals that the system is not only stable but, compared to case (iv), the latter oscillations diminish in magnitude.

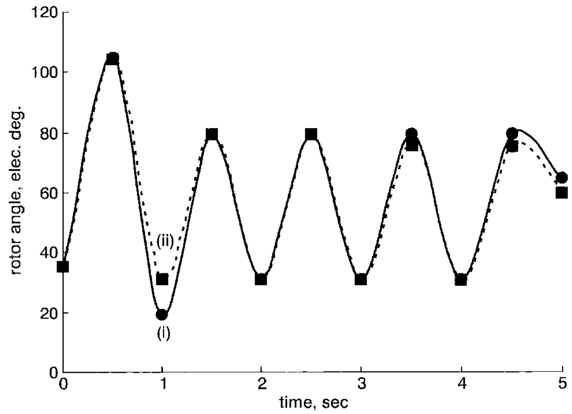

Fig. 4 *Swing curve for 3-phase fault duration of 9.3 cycles with SMES 'on' and with SMES turned 'off' after 3.0s*
(i) SMES 'on' continuously; (ii) SMES 'on' for 3s

3.1 Discussion

A comparison of cases (i) and (ii) shows that for the same fault clearing time a system with SMES is more stable than that without SMES. A comparison of cases (i), (iii) and (iv) proves that a system with SMES can sustain a fault without losing synchronism for a time almost double than that for a system having no SMES. It is noteworthy that case (i) involving no SMES device represents an almost marginal, i.e. critical, clearing case for the given system. On the other hand, case (iv) with the SMES device represents a case requiring a fault clearing time slightly less than the critical one. In fact, if an improved firing angle control strategy is employed, SMES may make the given system sustain a fault for > 9.3 cycles as the marginal case. So the existing relays and breakers, even though slower, may be continued for protection of a system with SMES, leading to a significant reduction in the protection cost.

A comparison of cases (iv) and (v) shows that once a system with SMES has regained postfault stability, the SMES need not be kept 'on' constantly, but turning it 'off' can reduce the generator rotor oscillations to some extent. This is because after attaining stability the kinetic energy stored in the rotating parts of the synchronous machine is enough to damp the oscillations and charging or discharging the SMES in this case proves to be unnecessary. Furthermore, just after attaining stability, i.e. on the onset of the steady state, dual control of oscillation by two elements (e.g. the rotating mass with stored kinetic energy as the primary control element and SMES as the secondary one) is likely to escalate the oscillations. However, the SMES will be automatically switched back whenever a case recurs, so that $\Delta\omega$ appreciably drifts away from its steady-state value or zero value. Moreover, on turning the SMES 'off', no energy exchange takes place between the SMES and the system to which it is interfaced. Then only the minimum current or energy is maintained in the SMES magnetic field. This reduces the SMES refrigeration, i.e. cryogenic medium, operating expenses.

4 Conclusions

A computer modelling and study has been undertaken to investigate the effects of embedding an SMES in a power system on the system's response following a 3-phase fault at the sending end of a line, i.e. the worst fault case. It has been found that SMES actions can not only damp out the oscillations but also make the system sustain a fault of about double duration time without losing synchronism compared to a system having no SMES. It is expected that employing sophisticated firing angle control strategies for SMES would diminish the oscillations more and hence permit further delayed fault clearing without losing synchronism. Among other benefits, the delayed tripping makes it feasible to employ or continue comparatively slower but less costly relays and breakers for fault clearing. This would also lead to an optimum cost-benefit ratio for an SMES, which is also used in a power system for other purposes such as load levelling, back up against momentary power interruption and voltage sags, etc. Moreover, with continued research on superconducting materials and power conversion systems the cost of SMES device is decreasing continuously, so that incorporating this at the transmission level is expected to be a viable and cost-competitive option.

5 References

1 KITTEL, C.: 'Introduction to solid state physics' (John Wiley & Sons, Inc., New York, 1971)
2 MALOZEMOFF, A.P.: 'Superconducting wire gets hotter', *IEEE Spectrum*, 1993, **30**, (12), pp. 26–30
3 BLAUGHER, R.D.: 'Low-calorie, high-energy', *IEEE Spectrum*, 1997, **34**, (7), pp. 36–42
4 LEUNG, E.: 'Surge protection for power grids', *IEEE Spectrum*, 1997, **34**, (7), pp. 26–30
5 MEHTA, S.P., ARERSA, N., and WALKER, M.S.: 'Trasforming transformers', *IEEE Spectrum*, 1997, **34**, (7), pp. 43–49
6 RAHMAN, M.M., and NASSI, M.: 'High-capacity cable's role in once and future grids', *IEEE Spectrum*, 1997, **34**, (7), pp. 31–35
7 BOENIG, H.J., and HAUER, J.F.: 'Commissioning test of the Bonnevile power administration 30 MJ superconducting magnetic energy storage unit', *IEEE Trans. Power Appar. Syst.*, 1985, **104**, (2), pp. 302–312
8 DEWINKEL, C., and LAMOREE, J.D.: 'Storing power for critical loads', *IEEE Spectrum*, 1993, **30**, (6), pp. 38–42
9 EL-AMIN, I.M., and MUSHTAQ HUSSAIN, M.: 'Application of a superconducting coil for transient stability enhancement', *Electr. Power Syst. Res.*, 1989, **17**, (3), pp. 219–228
10 MITANI, Y., TSUJI, K., and MURAKAMI, Y.: 'Application of superconducting magnet energy storage to improve power system dynamic ferformance', *IEEE Trans. Power Syst.*, 1988, **3**, (4), pp. 1418–1425
11 WU, C.-J., and LEE, Y.-S.: 'Application of simultaneous active and reactive power modulation of superconducting magnetic energy storage unit to damp turbine-generator subsynchronous oscillations', *IEEE Trans. Energy Conv.*, 1993, **8**, (2), pp. 63–70
12 RAHIM, A.H.M.A., and MOHAMMAD, A.M.: 'Improvement of synchronous generator damping through superconducting magnetic energy storage systems', *IEEE Trans. Energy Conv.*, 1994, **9**, (4), pp. 736–742
13 WANG, L., LEE, S.-M., and HUANG, C.-L.: 'Damping subsynchronous resonance using superconducting magnetic energy storage unit', *IEEE Trans. Energy Conv.*, 1994, **9**, (4), pp. 770–777
14 RABBANI, M.G., DEVOTTA, J.B.X., and ELANGOVAN, S.: 'Application of simultaneouns active and reactive power modulation of SMES unit under unequal α-mode for power system stabilization', *IEEE Trans. Power Syst.*, 1999, **14**, (2), pp. 547–552
15 MOHAN, N., UNDELAND, T.M., and ROBBINS, W.P.: 'Power electronics : converters, applications and design' (John Wiley & Sons (SEA) Pte. Ltd., Singapore, 1995)
16 PAUL, B.C., COONICK, A.H., and CORY, B.J.: 'Robust damping of inter-area oscillations in power systems with superconducting magnetic energy storage devices', *IEE Proc., Gener. Transm. Distrib.*, 1999, **140**, (6), pp. 633–639
17 ILIC, M., GALIANA, F., and FINK, L.: 'Power systems restructuring: engineering and economics' (Kluwer Academic Publishers, MA, USA, 1998)
18 STEVENSON, W.D. Jr.: 'Elements of power system analysis' (McGraw-Hill Kogakusha, Ltd., Tokyo, Japan, 1975)

6 Appendices

6.1 Algorithm for solving the swing equation

$$\Delta\omega(n) = \frac{d^2\delta}{dt^2}\Delta t = \frac{P_a(n-1)}{(H/\pi f_0)}\Delta t \tag{9}$$

$$\Delta\delta(n) = \Delta\delta(n-1) + \frac{P_a(n-1)}{(H/\pi f_0)}(\Delta t)^2 \tag{10}$$

$$\delta(n) = \delta(n-1) + \Delta\delta(n-1) \tag{11}$$

$$P_a(n-1) = P_m - P_{\max}\sin\delta(n-1) - P_{SMES}(n-1) \tag{12}$$

$$P_{\max} = \frac{E'V_\infty}{X} \tag{13}$$

when

$X = X_{pf}, t = 0^-$ (prefault condition)

$X = X_{df}, 0 \le t \le t_{fc}$ (during fault, i.e. up to fault clearing)

$X = X_{af}, t > t_{fc}$ (after fault clearing)

$$P_{SMES}(n-1) = E_d(n-1)I_d(n-1) \tag{14}$$

$$\alpha(n-1) = \frac{\pi}{2} + \Delta\alpha(n-1) \tag{15}$$

or as in eqns. 6–8 depending on $\Delta\alpha(n-1)$, $I_d(n-1)$, $\Delta\omega(n-1)$

$$\Delta\alpha(n-1) = -K[1-e^{-(n-1)\Delta t/T_{dc}}]\Delta\omega(n-1) \tag{16}$$

$$I_d(n-1) = I_d(n-2) + \frac{1}{L}\int_{(n-2)\Delta t}^{(n-1)\Delta t} E_d dt \tag{17}$$

Using the trapezoidal rule of integration,

$$I_d(n-1) = I_d(n-2) + \frac{1}{L}\left[\frac{E_d(n-2)+E_d(n-1)}{2}\right]\Delta t \tag{18}$$

$$E_d(n-1) = 2\frac{3\sqrt{2}}{\pi}E_2\cos\alpha(n-1) \tag{19}$$

$$E_d(n-2) = 2\frac{3\sqrt{2}}{\pi}E_2\cos\alpha(n-2) \tag{20}$$

6.2 System parameters

Generator:

E' = EMF behind transient reactance = 1.25p.u.

P_m = constant prime mover input at generator shaft = 1.0p.u.

x'_d = direct axis transient reactance = 0.20p.u.

H = generator inertia constant = 3.0p.u.

f_0 = system operating (base) frequency = 60Hz

Transformer:

x_T = each transformer reactance = 0.08p.u.

Transmission line:

x = each parallel line's (circuit) series reactance = 0.56p.u.

Infinite bus:

V_∞ = infinite bus voltage = 1.0p.u.

x_∞ = reactance in series with infinite bus = 0.08p.u.

SMES:

T_{dc} = converter time delay constant = 0.03s

L = coil inductance = 0.6627p.u. (0.5H)

K = firing angle control circuit gain = 5.0

E_2 = each converter transformer's secondary voltage set through tap = 0.44p.u.

$I_{d,0}$ = initial value of the current in SMES coil = 0.2p.u.

$I_{d,\max}$ = maximum value of current in SMES coil = 2.5p.u.

$I_{d,\min}$ = minimum value of current in SMES coil = 0.06p.u.