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A NOVEL HIGH TEMPERATURE SUPER CONDUCTING MAGNETIC ENERGY STORAGE (HT-SMES) USING HYSTERISIS CONTROL

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ABSTRACT

This paper describes the design and implementation of a new High Temperature Superconducting Magnetic Energy Storage System (HTS-SMES) unit consisting of a high temperature superconducting coil as the energy storage device and two power converters to provide the power conditioning system capability (PCS). Two hysterisis controllers are used, one to control the ac supply current for active filtering and maximum demand control and the other to regulate the dc capacitor voltage to control the energy in and out of the superconducting coil. A strategy to provide fast charging to the superconducting coil after discharge is proposed. The operating principles of the proposed controllers are analyzed and the feasibility and performance of the proposed HTS-SMES under different operating modes are demonstrated through simulation and experimental results.

1. INTRODUCTION

Superconducting Magnetic Energy Systems (SMES) have been proposed for several power system applications such as power system load leveling [1], power system stabilizers [2,3] and voltage support for critical loads [4]. The load leveling is particularly important, since the industrial load is managed under the constraint imposed by utility for maximum demand (MD). The violation of maximum demand or power factor leads to penalty to the industries concerned. For this type of application, energy storage is usually required such as batteries or super-conducting coils [5]. With the availability of fast power electronics devices and fast DSP's, it is now possible to add power-conditioning capability to the traditional load leveling operation such that active filtering can be provided to ensure that the supply current is always sinusoidal even with distorted load waveform.

This paper describes the design and implementation of a new High Temperature Superconducting Magnetic Energy Storage System (HTS-SMES) unit consisting of a high temperature superconducting coil as the energy storage device and two power converters to provide the power conditioning system capability (PCS).

The high temperature superconducting coil is made using Ag-clad $(Bi,Pb)_2Sr_2Ca_2Cu_3O_{10+x}$ wire manufactured by the Australian Superconductors Ltd. using the oxide power-in-tube technique.

The paper initially discusses the operating principles of the proposed HTS-SMES, followed by an analysis of the effects of parameter variations on the performance of the proposed HTS-SMES. Based on the above analysis, a strategy is proposed to provide fast charging of the superconducting coil. To test the performance of the proposed HTS-SMES, a prototype is built in the laboratory and the results show that the proposed HTS-SMES can achieve its desired attributes, i.e. load leveling and improving the power quality of the supply system by providing inherent active filtering against distorted load. Fast charging of the superconducting coil after discharged can also be achieved.

2. PRINCIPLE OF OPERATION

The main components of the SMES system are a voltage source inverter (VSI), a μ-SMES coil and a dc current chopper for interfacing the super conductor magnet to the dc link of the VSI as shown in Figure 1.

Two hysteresis controllers are used. The first hysteresis controller ensures that as far as the power utility is concerned, the load (I_S) appears as a constant sinusoidal load both in magnitude, phase and waveform, irrespective whether load (I_L) is distorted or varying in nature. This controller, therefore, performs several tasks, such as active filtering and power control flow [6]. The load leveling at industrial loads around few hundreds of kW loads can be justified by considering the maximum demand criteria and pay back can be calculated with the penalty imposed for violation of Maximum Demand (MD) and power factor.

The chopper operates in order to keep the capacitor voltage (V_{DC}) maintained across the dc link. In actual operation, the Superconducting coil (SC) will have pulsated operation, which causes ac current losses in the coil. These losses must be taken into account while designing the SMES refrigeration system [9]. The proposed control relieves the stress on SC coil as well smoothes out the operation of charging and discharging so that the stress on the coil is minimised.

Under load leveling condition, if I_S is kept constant then the SMES coil current must meet the load demand variation. To utilize the maximum power flow through the network, the source current is maintained at its maximum rated value without violating the thermal limit. The controller ensures that the energy balance is maintained between source, load and SMES. The stored energy is regulated in controlled manner through the inverter and chopper. The role of the capacitor energy storage is to facilitate the direct exchange of energy from coil to the load. The dc bus voltage is kept constant and the switching function modulates inverter voltage. The value of the capacitor voltage (Vdc), and the capacitance value are important in view of the inverter operation and the reactive power demand. While designing the controller, the most significant parameters of the system to be considered are the hysterisis band, source voltage source current (Is), SMES coil inductor (L), inverter front end interfacing inductor (Li) and source inductor (Ls).

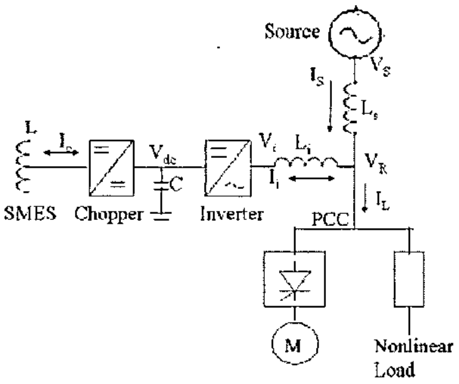


Figure 1: PCS System connected at PCC

3. HYSTERESIS CONTROL OF INVERTER AND CHOPPER

The basic concept in hysteresis control is to switch each phase leg to the opposite polarity whenever the measured current/voltage reaches above or below a given boundary. To keep the switching frequency relatively constant, adaptive hysteresis band controllers can be used [10]. There are alternative methods for variable band that utilises feed-forward and feedback technique to achieve the constant switching frequency with good dynamic response [11]. To reduce complexity, a simple hysteresis control strategy is adopted in the VSI system, with simple modification made in the dc chopper system. The operation of the two converters can be explained with the help of Figure 2.

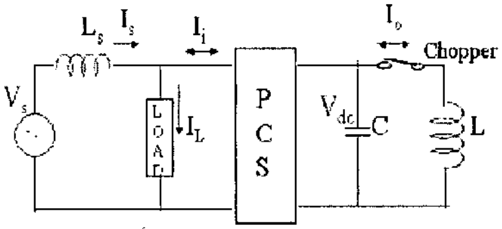


Figure 2: The Basic Circuit Configuration

To understand the operation of the system, the following assumptions have been taken in the following analysis:

a) there are no resistances in the system
b) the inverter and chopper are represented by ideal switches

The operation of the system with voltage tolerance +/- ΔV_{dc} on capacitor voltage V_{dc} and current tolerance +/- ΔI_s on the source current I_s is carried out. When the superconducting coil is being charged, the voltage across the capacitor will be reduced by:

$$V_{dc}(t+\Delta t) = V_{dc}(t) - (I_o(t)/C)\,\Delta t \tag{1}$$

where: V_{dc} = capacitor voltage (V)
C = capacitance (F)

and current in the inductor (I_O) increases to a value:

$$I_o(t+\Delta t) = I_o(t) + (V_{dc}(t)/L)\,\Delta t \tag{2}$$

When the coil discharges, the voltage across the capacitor builds up to:

$$Vdc(t+\Delta t) = Vdc(t) + (Io(t)/C)\,\Delta t \tag{3}$$

and current in the inductor decreases to a value:

$$Io(t+\Delta t) = Io(t) - (Vdc(t)/L)\,\Delta t \tag{4}$$

Similarly, in the inverter side, the effect of the hysteresis controller to regulate the value of ac source side current is to modify the effective value of capacitor voltage in the following manner:

During current build up, i.e. source current increasing towards the upper band value:

$$Is(t+\Delta t) = Is(t) + ((Vs - Vdc(t))/Ls)\,\Delta t \tag{5}$$

The capacitor voltage will be increased:

$$Vdc(t+\Delta t) = Vdc(t) + (Is(t)/C)\,\Delta t \tag{6}$$

Similarly when the upper band is reached, the current will start to reduce towards the lower band; the value of the source current becomes:

$$Is(t+\Delta t) = Is(t) + ((Vs + Vdc(t))/Ls)\,\Delta t \tag{7}$$

And capacitor voltage will be decreased:

$$Vdc(t+\Delta t) = Vdc(t) - (Is(t)/C)\,\Delta t \tag{8}$$

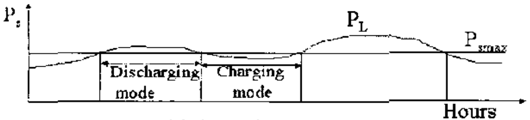
The power flow under load leveling is shown in Figure 3. The maximum demand that can be delivered by the supply can now be controlled and can be designated as Psmax. Defining the power coming from the inverter as Pinv, at any instant of time we would like to have:

$$Psmax = PL \pm Pinv \tag{9}$$

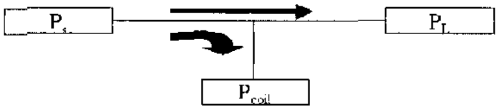
During the off-peak periods (PL < Psmax), SMES should be charged and during the peak load periods (PL > Psmax), the SMES can be discharged to provide power for part of the load.

4. SIMULATION RESULTS

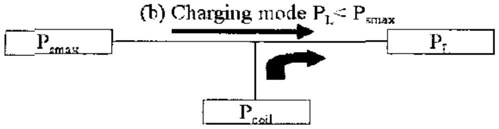
The performance of the HTS-SMES is obtained by simulation using MATLAB/C++. The basic inverter and chopper are considered as ideal converters using ideal switches. The electrical quantities are represented by their averaged values. The simplified model requires very low computational time and can be used to adjust the parameters of the system. The numerical simulation of equations 3-10 is carried out using Turbo C++. The system parameters used in the simulation are given in the Table- I. These parameters simulate the bench scale experiment in the laboratory.



(a) Operating mode



(b) Charging mode $P_L < P_{smax}$



(c) Discharging mode $P_L > P_{smax}$

Figure 3: PCS operation for load leveling

The effect of varying some of these parameters on the SMES current for a 40 ms (2 ac cycles) operation is presented in the following section.

A) The effect of varying the hysteresis tolerance band

The source current and dc bus voltage are controlled by the two hysteresis controllers. The effect of tolerances set in these hysteresis controllers are investigated. The tolerance band on set reference dc voltage and source current are presented as a percentage of its reference value. The dc bus reference voltage is set to 200 volts. The hysteresis tolerance on it is varied from ± 1 volts to ± 4 volts i.e. 0.5 % to 2%. Similarly the tolerance on the source current reference is varied from 0.5% to 2%. The dc bus voltage and SMES current are presented in Figure 4(a)-(d). The SMES current ripple is directly related to the dc bus tolerance set on the dc bus voltage, which is very much evident from the Figure 4(b) and 4 (d). It is observed from Figure 4 (b) and 4(d) that the increase or decrease in the dc bus voltage tolerance does not have significant effect on the magnitude of SMES coil current.

TABLE-I: PARAMETERS OF THE PCS

ac link inductance (L_s)	0.0001 H
dc link capacitor (C)	0.003 F
Dc link voltage (Vdc)	400 Volts
SMES current (I_0)	1000 Amps
SMES inductance (L_0)	0.008 H

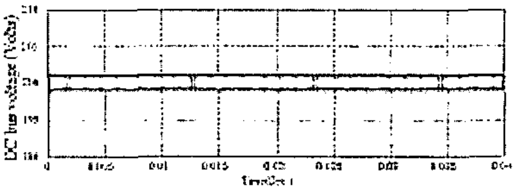


Figure 4(a): DC bus voltage under hysterisis control (tolerance band 200+/-1V)

Figure 4(b) DC bus voltage under hysterisis control (tolerance band 200+/-1 Volts)

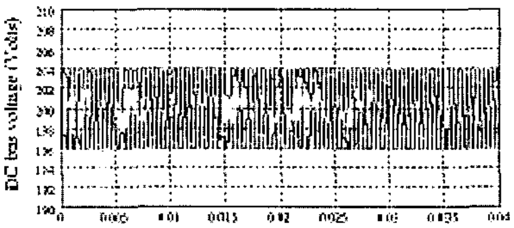


Figure 4 (c) DC bus voltage under hysteris control (tolerance band 200+/-4 Volts)

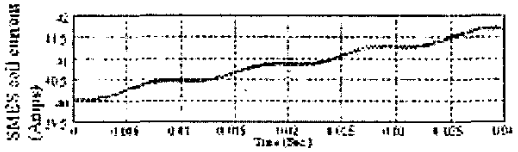


Figure 4(d) SMES coil current under hysterisis control (tolerance band 200+/-4 Volts)

The effect of hyteresis band tolerance variation on the source current is also observed. The increase in the tolerance of the source current increases the ripple content significantly as shown in the Figures 5 (a)-(c). The reference of the source current is set in phase with the source voltage so as to get the unity power factor. The waveform of the source current and source voltage are shown in the Figure 5(a).

B) The effect of varying the SMES coil inductance value:

The SMES coil inductance determines the total energy storage available. The variation in the coil current during the charging and discharging operation depends on the applied voltage and magnitude of the coil inductance. This current should be always lower than the critical current of the coil. The percentage increase in the SMES coil current from its initial value is obtained for different coil inductance values while keeping source inductance value constant. Initial values of coil currents (20/40A) are steady state operating coil current. It is observed that a small value of coil inductance will give a very high gain in the current.

This may lead to stress in the coil and unstable operation of the controller. If the initial current is high then the percentage change in coil current is small. The initial current level depends on the level of coil discharge. Typical percentage change in the current for various values of the coil inductance are presented in Figure 6 for 2 operating cycles of source current.

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Figure 6: Percentage variation in SMES coil current for different coil inductance values

C). The effect of varying source inductance

For a fixed value of the SMES coil inductance (Lo), the source side inductance (Ls) of the inverter is varied. It is observed that, for a particular range of Ls/Lo ratio only, the Io magnitude can be maintained in the coil. If this ratio is too small or too large, the hysteresis controller cannot build the proper ac source current (Is). This is observed from Equations 7 and 9, where the switching frequency depends on the inductance value. Too low or too high switching frequency makes it difficult for the source current to be controlled properly. The ratio (Ls/Lo) between 0.01 and 0.00001 is suitable for the parameters given in Table-1. This source side inductance of the inverter is an important parameter in the design of the PCS, as it represents the interfacing transformer at the PCC. Figure 7 indicates the almost constant gain in SMES current (Io) between these two limits.

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Figure 7: Percentage change in SMES current due to change in source side inductance Ls

D) The effect of varying the reference current in the ac system

If the reference Is current is increased in such a way that it is going from the source to the DC link, then SMES coil current is increased. Similarly if reference current is made to go from the DC link to the source, the SMES current is decreased. The charging and discharging operation is shown in Figure 8. The dc bus voltage is maintained constant during this operation. If the reference current is made 90° lagging or leading the source voltage, the SMES current can be maintained constant. This is consistent with our intuition that no energy is required to supply or absorb reactive power. This variation can be observed from Figure 9(a) and Figure 9(b). As the maximum value of Is is also an important criteria for inverter design, it is mainly dependent on the maximum value of available power from the source.

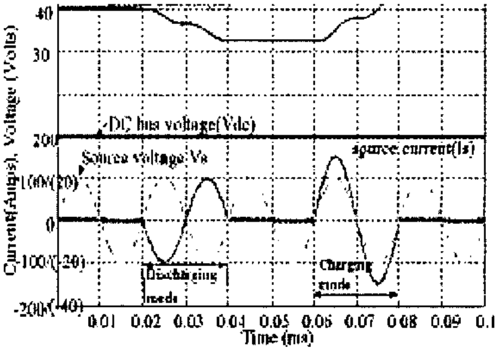

Figure 8:
Variation of SMES current under charging and discharging mode

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Figure 9(a): Source voltage and current with reactive load compensation

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Figure 9(b): SMES current under reactive loading

5. THE PROPOSED CONTROL SCHEME

The simulation results above indicate the sensitivity of SMES current change with the variation in reference source current (I_s). When the reference source current is increased more than the load demand, the coil current increases and the superconducting coil is being charged, and when the source current is below the load demand, the superconducting coil discharges its stored energy to supply part of the load. A two-quadrant dc chopper performs this operation. The chopper keeps the dc bus voltage constant under the SMES operation. SMES coil charging current varies as the source current varies and it solely depends on the magnitude of the source current. The opportunity of regaining back the energy in the super-conducting coil in the shortest time is not feasible under this control operation.

Many schemes proposed in the past are based on this type of control strategy [6]. This leads us to the new proposal to modify the control strategy so that the recovery of lost energy can be regained in shortest possible time, by quickly changing the controller from voltage-mode control to current-mode control once the charging process is started. The proposed control system is shown in Figure 10.

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Figure 10: Chopper with current and voltage controllers

6. EXPERIMENTAL RESULTS

To verify the proposed scheme, a 2 kW three-phase inverter was designed and implemented in the laboratory as a bi-directional self-commutated voltage source converter and was used to interface the 380V three phase supply system with the DC link capacitor. The power electronics switching devices used in the inverter employ the third-generation insulated gate bipolar transistors (IGBTs), each rated at 600V, 50A and connected in parallel with a reverse diode to give the converter the capability of handling power flow in reverse directions. The IGBT devices chosen have very fast switching speed and lower conduction and switching losses. A DC chopper was also designed and implemented to interface the high temperature super-conducting coil with the DC link capacitor.
The controllers are implemented using DSP TMS320C31. The test results are shown in Figure 11(a) and (b). The coil voltage and current are shown in expanded view in Figure 11 (a)-1 and 2 respectively. The SMES coil current during charging and discharging is shown in the Figure 11(b). The coil energy available to support the load (resistive and inductive) is very small in this experiment. Figure 12 shows the source, load and inverter current along with the source voltage demonstrating the active filtering performance. The source current is in phase with the source voltage, while inductive load is supported. Further performance tests will be carried out with higher capacity SMES.

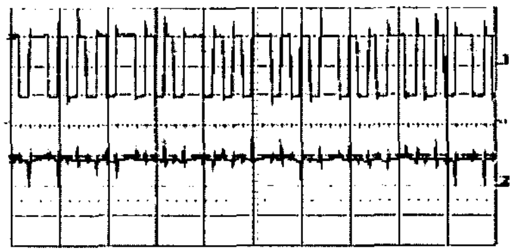

Figure 11(a): 1.Voltage across the SMES coil (200V/div), 2. SMES coil current (10 A/div) x-axis 0.5 msec/div

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Figure 11(b)
1. Voltage across the SMES coil (400V/div)
2.SMES coil current during charging and discharging mode
(5 A/div), x-axis (0.2sec/div)

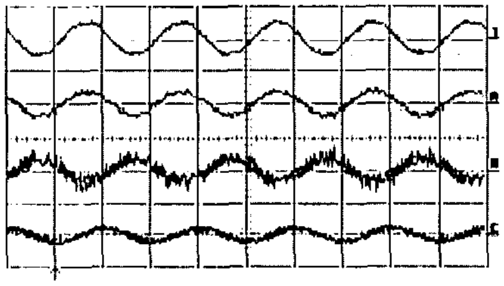

Figure 12: Active Filter Action during charging: 1. Source voltage (200V/div), A: Source Current (10A/div), B. Inverter current (10A/div), C. Load current (10A/div), x-axis- 10 ms div

7. CONCLUSION

A modified hysteresis band controller for a power conditioning system using super-conducting magnetic storage has been analyzed in this paper. The use of two- quadrant dc chopper in between SMES coil and the dc side of the inverter allows charging and discharging in very controlled manner. The system parameters and their limitation are very important for later implementation of the HTS-SMES. The ratio of SMES inductance to source inductance, value of coil inductance and capacitor value at the dc link are important parameters in the PCS design. The control scheme has been tested for its performance by laboratory implementation. The control scheme is very easy to implement and the results shows that such a system will be able to control the source current to be constant, sinusoidal in waveform and has unity power factor irrespective of the varying load demand and its harmonic content.

8. ACKNOWLEDGMENTS

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9. REFERENCES

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