Super conducting Magnetic Energy Storage Unit for Power Conditioning

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Abstract— **Superconducting magnetic energy storage (SMES) technology has been progressed actively in recent years. SMES technology has the potential to bring real power storage characteristic to protect consumers from the grid voltage fluctuations. This paper analyses the operation principle of the SMES based DVR for power conditioning in the event of voltage sag, and its design is based on simple PI control method to compensate voltage sags. Using MATLAB SIMULINK, the models of the SMES based DVR is established, and the simulation tests are performed to evaluate the system performance.**
Keywords- *SMES; Dynamic Voltage Restorer (DVR); Voltage Sag; Power conditioning system (PCS); Pulse-width modulated (PWM)*

I.   INTRODUCTION

Power systems have been experiencing dramatic changes in electric power generation, transmission, distribution, and end-user facilities. Continuing electric load growth and higher power transfer in a largely interconnected network lead to complex and less secure power system operation. Power system engineers facing challenges seek solutions to operate the system in more a flexible and controllable manner. So role of energy storage devices play important role as Energy storage appears to be beneficial to utilities since it can decouple the instantaneous balancing between the demand and the supply. Therefore it allows the increased asset utilization, facilitates the penetration of renewable sources and improves the flexibility, reliability and efficiency of the grid [1].

Energy storage devices can be classified into two different categories, depending on their application: short-term response energy storage devices and long-term response energy storage devices [1]. Short term response energy devices which include flywheel, super capacitor, SMES whereas long term response energy storage devices include compress air, hydrogen fuel cell, batteries, Redox flow [1]. Here we are more concern with short term response energy devices.

Flywheel and super capacitor are having less power rating and energy rating so they cannot use for Short time high power application. So in order to overcome this deficiency SMES has been used to improve performance of power system as it is having high power rating with max efficiency than any other energy storage devices.

Recent development and advances on both superconducting and power electronics technology have made the application of SMES (superconducting magnetic energy storage) systems a viable choice to bring solutions to some of the problems experienced in power systems. The power industry demand for more flexible, reliable and fast real power compensation devices provides the ideal opportunity for SMES applications [2].

SMES used for various application such as Power Quality, Custom Power, Stabilization, Voltage/VAR Control, Load Leveling, Dynamic Response, Spinning Reserve, Frequency Control Application[3]. However, here we dealt with SMES Power Quality Application based on DVR for sag compensation.

For voltage sag compensation, the dynamic voltage restorer (DVR) which act as series-connected topology is a more cost-effective solution [4]. In this paper, a superconducting magnetic energy storage unit is introduced as the energy storage unit of the DVR. In section II, the configuration of SMES is analyzed. In section III, Application of SMES for power conditioning with DVR is put forth. In section IV, the dynamic response of the SMES based DVR on voltage sag is evaluated using MATLAB simulation.

II.   CONFIGURATION OF SMES

It was not until 1970s superconducting magnetic energy storage (SMES) was first proposed as a technology in power systems. Energy is stored in the magnetic field generated by circulating the DC current through a superconducting coil.

As can be seen from Fig. 1, a SMES system consists of several sub-systems. A large superconducting coil is the heart of a SMES system, which is contained in a cryostat or dewar consisting of a vacuum vessel and a liquid vessel that cools the coil [5]. A cryogenic system is also used to keep the temperature well below the critical temperature of the superconductor. An ac/dc PCS is used for two purposes: One is to convert electrical energy from dc to ac,

and the other is to charge and discharge the coil. Finally, a transformer provides the connection to the power system and reduces the operating voltage to acceptable levels for the PCS.
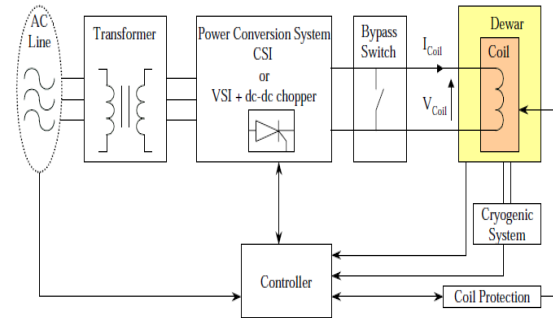

Fig.1 Component of SMES

For a SMES system, the inductively stored energy (E in Joule) and the rated power (P in Watt) are commonly the given specifications for SMES devices, and can be expressed as follows:

$$E = \frac{1}{2}LI^2 \tag{1}$$

$$P = \frac{dE}{dt} = LI\frac{dI}{dt} = VI \tag{2}$$

Where L is the inductance of the coil, I is the dc current flowing through the coil, and V is the voltage across the coil.

Coil inductance (*L*) or PCS maximum voltage (*Vmax*) and current (*Imax*) ratings determine the maximum energy/power that can be drawn or injected by a SMES coil. Increasing any of these parameters improves the energy/power capability of SMES. But, there are other factors that need to be taken into consideration which is as shown in below table.1:

Increasing Imax	Larger conductor cross section
	Larger current leads and associated lead losses
	Larger and more expensive PCS
Increasing Vmax	Larger more expensive PCS
	Insulation problem
Increasing L	More turns in the magnet

Table.1 Energy capability of SMES

Although SMES systems may not be cost effective, at the present time, they have a positive cost and environmental impact by reducing fuel consumption and emissions. SMES' efficiency and fast response capability has been and can be further exploited in different applications in all level of electric power systems which have been characterized in Table 2 below.

Field	Application	Discharge time required
Generation	Load Leveling	Hours
	Dynamic Response	Hours
	Spinning Reserve	Minutes
	Frequency Control	Seconds
Transmission	Load Leveling	Minutes/Hours
	Stabilization	Seconds
	Voltage/VAR Control	Cycles
Distribution	Load Leveling	Minutes/Hours
	Power Quality	Seconds
	Custom Power	Cycles

Table.2 Characterized Application of SMES

III. INTEGRATION OF SMES WITH DVR

The basic structure of a DVR based on SMES is shown in Fig.2. It consists of super conducting magnetic energy storage unit, capacitor bank, voltage source inverter (VSI), low pass filter and a voltage injection transformer.
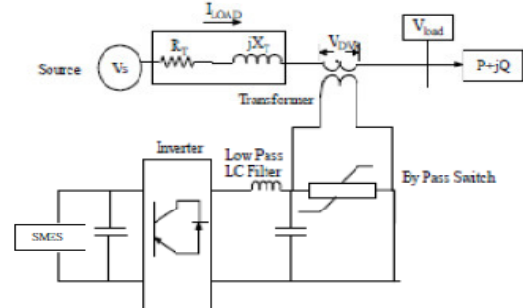

Fig.2 Basic structure of DVR based on SMES.

Where SMES is designed based on its simple principle. Its energy released circuit model is as shown in Fig.3
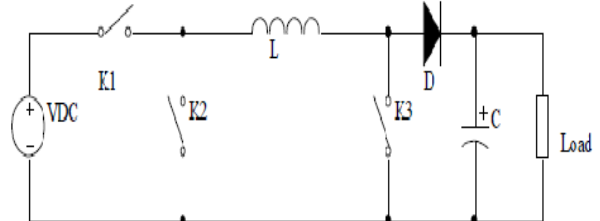

Fig. 3 SMES energy released circuit

The circuit model has three operating states:
1) Energy-charging state (close *K1* and *K3,* open *K2*);

2) Energy-storing state (close *K2* and *K3*, open *K1*);
3) Energy discharging state (close *K2*, open *K1* and *K3*).

Practically switches *K1* and *K3* should be closed to store magnetic energy. In the energy-discharging stage, close switch *K2* first and then open switch *K1* and *K3* after time delay.

In order to mitigate the simulated voltage sag in practical application, a discrete PWM-Based control scheme is implemented, with reference to DVR as shown in Fig 3. The aim of the control scheme is to maintain a constant voltage magnitude at the sensitive load point, under the system disturbance. The control system only measures the rms voltage at load point; The DVR control system exerts a voltage angle control as follows:
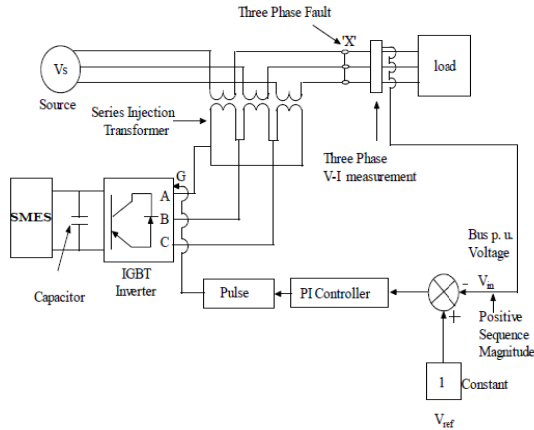

Fig.4 DVR SMESB (SMES based)

Voltage sag is created at load terminals by a three phase fault as shown in Fig.4. Load voltage is converted into per unit quantity and is passed through a sequence analyzer. The magnitude is then compared with reference voltage (*Vref*) through which error signal is fed to PI controller. This voltage is then fed to triggering circuit. Pulse width modulated (PWM) control technique is applied for inverter switching so as to produce a three phase 50 Hz sinusoidal voltage at the load terminals. Chopping frequency is in the range of a few KHz. The IGBT inverter is controlled with PI controller in order to maintain 1 p.u. voltage at the load terminals i.e. considered as base voltage =1p.u.

The PI controller processes the error signal and generates the required angle δ to drive the error to zero, for example; the load rms voltage is brought back to the reference voltage. It should be noted that, an assumption of balanced network and operating conditions are made. The modulating angle δ or delta is applied to the PWM generators in phase A, whereas the angles for phase B and C are shifted by 240° or -120° and 120° respectively.

$$V_A = \text{Sin } (\omega t + \delta) \qquad (3)$$
$$V_B = \text{Sin } (\omega t + \delta - 2\pi/3) \qquad (4)$$
$$V_C = \text{Sin } (\omega t + \delta + 2\pi/3) \qquad (5)$$

An advantage of a proportional plus integral controller is that integral term causes the steady-state error to be zero for a step input. PI controller input is an actuating signal which is the difference between the *Vref* and *Vin*. Output of the controller block is of the form of an angle δ, which introduces additional phase-lag/lead in the three phase voltages. The output of error detector is

$$Vref - Vin. \qquad (6)$$

Vref equal to 1 p.u. voltage
Vin voltage in p.u. at the load terminals.

The controller output when compared at PWM signal generator results in the desired firing sequence.

IV. SMES BASED ON DVR TEST SYSTEM

Single line diagram of the test system for DVR Based on SMES is composed by a 13 kV, 50 Hz generation system, feeding two transmission lines through a 3-winding transformer connected in Y/Δ/Δ, 13/115/115 kV. Such transmission lines feed two distribution networks through two transformers connected in Δ/Y, 115/11 kV. We verify the working of DVR for voltage compensation at 0.88 ohms fault resistances for fixed time duration of 200 ms. The DVR performance in presence of Superconducting magnetic energy storage unit (SMES) is analyzed for symmetrical three phase to ground fault.

Sr.No	System Quantity	Specification
1	Transmission Line Parameter	R=0.001 Ohms L=0.005 Henry
2	Inverter Specifications	IGBT Based, 3 Arms, 6 Pulse, Carrier Frequency=1080 Hz, Sample time=5 microseconds
3	PI Controller	Kp=0.5 Ki=50 Sample time=50 microseconds

Table.3 System parameter

Fig.10 is MATLAB/SIMULINK diagram of DVR based on SMES for sag compensation. The first simulation was carried out with no DVR and a three phase fault is applied to the system at point with fault resistance of 0.88Ω for time duration of 200 ms as shown in Fig.5. The second simulation is carried out at the same scenario as above but a DVR is now introduced at the load side to compensate the voltage sag occurred due to the three phase to ground

fault applied as shown in Fig. 9. For that SMES carrying 540KA current circulating through solenoid coil used.
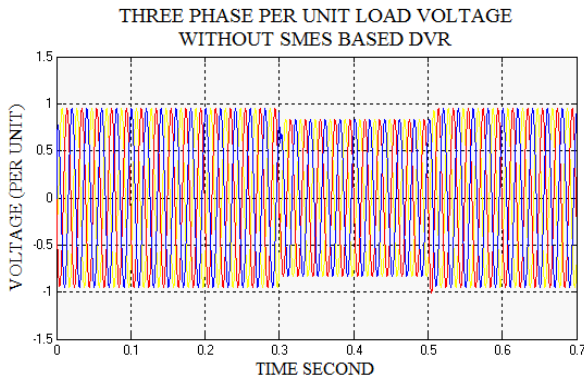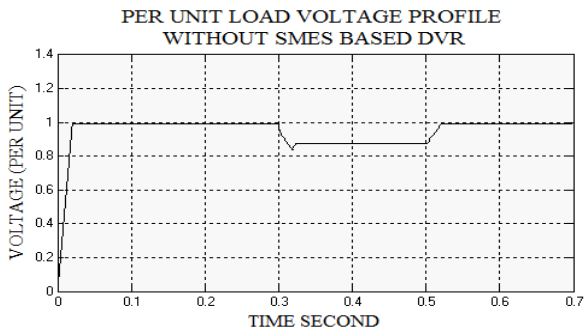
THREE PHASE PER UNIT LOAD VOLTAGE
WITHOUT SMES BASED DVR

Fig.5: Three phase, phase-phase voltage without SMES based DVR

PER UNIT LOAD VOLTAGE PROFILE
WITHOUT SMES BASED DVR

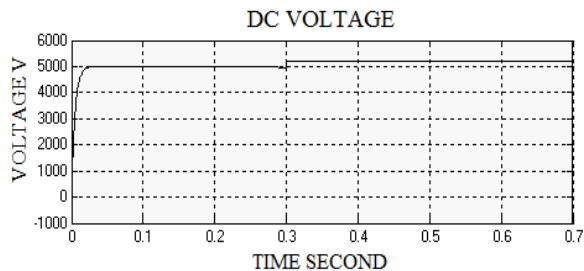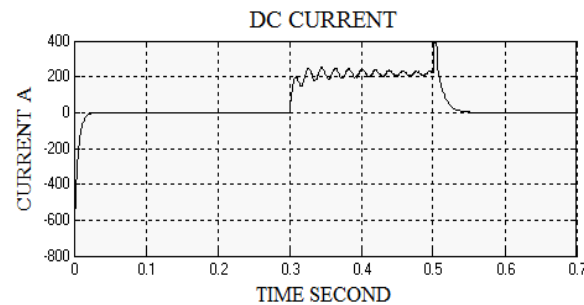Fig.6: Voltage P.U at load point without SMES based DVR

DC CURRENT

DC VOLTAGE

Fig. 7 SMES supplying Voltage & Current during its operation on system with DVR
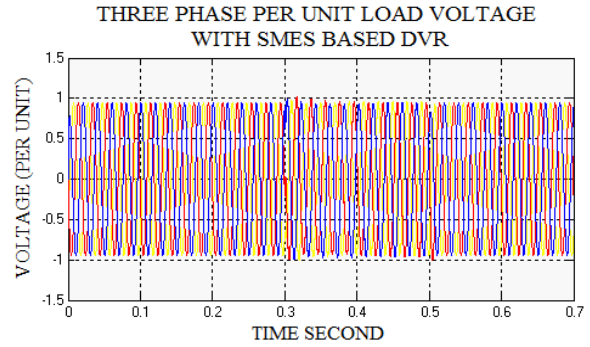
THREE PHASE PER UNIT LOAD VOLTAGE
WITH SMES BASED DVR

Fig.8: Three phase, phase-phase voltage with SMES based DVR
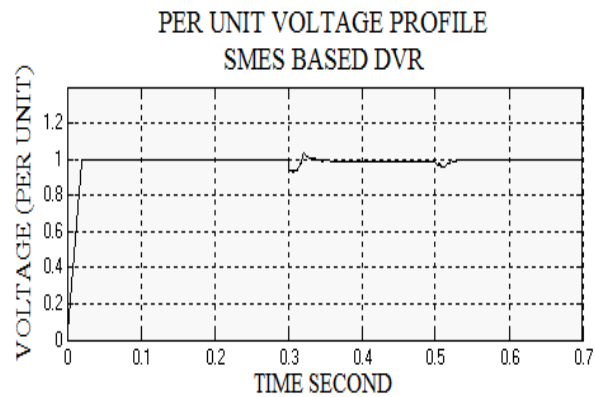
PER UNIT VOLTAGE PROFILE
SMES BASED DVR

Fig.9: Voltage P.U. at the load point with SMES based DVR

CONCLUSION

A new design which incorporates a superconducting magnetic energy storage module as a DC voltage source to mitigation voltage sags and enhances power quality of a distribution system based on DVR has been presented. The Simulation results prove that the SMES can be a useful alternative DC source for the DVR.

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Fig.10 MATLAB/SIMULINK diagram of DVR based on SMES for sag compensation.