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Voltage Sag Compensation using SMES Based DVR Technology & Pi Controller

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Abstract- Power quality is one of the most important topic that electrical engineering have been noticed in recent years. This paper describes the super conducting magnetic energy storage SMES based dynamic voltage restorer protect consumers from the grid voltage transients. A fine solution to power quality and optimization related concerned issues can be easily provided through DVR..Voltage sag is the most prominent problem as paer the P-Q issue. The voltage sag is mitigated and real power is restored and thus wastage is overcome, providing protection to consumers from grid voltage fluctuations by the Superconducting magnetic energy storage (SMES) technology based DVR. Power flow stabilization and control in the transmission network level are some of the increasing interest in application of Superconducting magnetic energy storage (SMES) systems. The properties and characterstics of high energy density and quick response incorporates a superconducting magnet as the energy storage unit to improve the compensation capability of DVR. This paper analyses the operation principle of the SMES based DVR, and designs the DVR output voltage control method using MATLAB SIMULINK, the models of the SMES based DVR is established, and the simulation tests are performed to evaluate the system performance.

Keywords-*Matlab/Simulink, SMES, PCS, DVR,PWM, IGBT*

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1. INTRODUCTION

Power quality is one of the most important topic that electrical engineering have been noticed in recent years.The voltage sag ,swell, interruptions & flicker fluctuations etc. causes voltage waveforms to be disturbed from ideal waveform and also due to the use of non-linear loads. Such voltage distortion adversely affects the performance of equipment connected in the system. Voltage sag is one of the problems related to power quality. This phenomenon happen continuously in transmission and distribution systems. Power quality problems, such as voltage sag which arise due to a fault or a pulsed load, can cause interruption on critical load. [1][5]The power disruption on the load can be avoided by installing DVR on sensitive load, restores the line voltage to its nominal value within the response time of a few milliseconds. Modern Pulse-Width Modulated (PWM) inverters capable of generating accurate high quality voltage waveforms form the power electronic heart of the new Custom Power devices. [2].

Active power will be supplied through DVR with help of SMES and required reactive power is generated internally without any means SMES storage. DVR can compensate voltage at both transmission and distribution sides. Usually a DVR is installed on a critical load feeder. During the normal operating condition (without sag condition) DVR operates in a low loss standby mode [2]. During this condition the DVR is said to be in steady state. When a disturbance occurs (abnormal condition) and supply voltage deviates from nominal value, DVR supplies voltage for compensation of sag and is said to be in transient state. The DVR is connected in series between the load and the supply voltage [3].

Dynamic voltage restorer can provide the most cost effective solution to mitigate voltage sags by establishing the proper voltage quality level that is required by customer. [4][5][6].Voltage sags are characterized by a reduction in voltage, but the load is still connected to the supply. [6][21].A large power system is subjected to various disturbances very changes in operating conditions cause’s oscillations and electromagnetic torque in the system. The system variables such as frequency, load angle, active and reactive power of generator should be maintained within permissible limits and oscillations should be damped out as quickly as possible for a secured operation of a power system .SMES is very effective to improving dynamic performance of power system due to its large energy storage capacity, fast response and negligible losses. [7][8][14][15][16]

Out of the various voltage disturbances, voltage sag is a frequent disturbance in power system. 92% of the interruptions in industrial installations are due to voltage sags. So in order to overcome this deficiency SMES based DVR has been used to improve the performance of power system by improving voltage profile as it is having high power rating with maximum efficiency then any other energy storage devices. In this paper proposes a super conducting magnetic energy storage unit, as the energy storage unit of DVR.[9][10]

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2. MODELLING & METHODOLOGY OF PROPOSED SMES BASED DVR –

2.1CONFIGURATION OF DVR-

The DVR can be used for protection and recovery or restore the quality of voltage to the sensitive load. Dynamic Voltage Restorer (DVR) is one of the effective custom power devices that can be used to improve power quality from any disturbances in the distribution line A set of three phase voltages with an appropriate magnitude and duration can be injected through injection transformer and must be in phase with the grid voltage. A DVR is a solid state power electronics switching device consisting of either GTO or IGBT, a capacitor bank as an energy storage device and injection transformers.

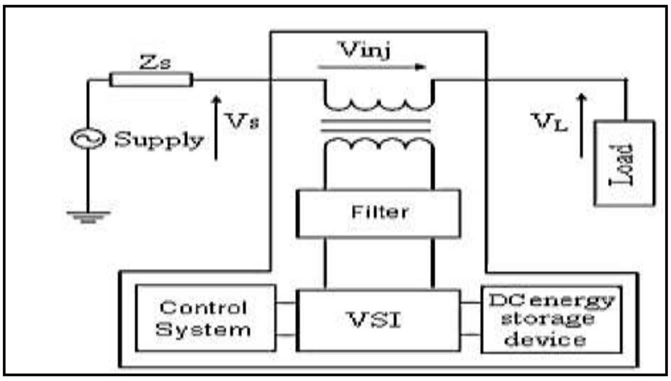

Fig 2.1- Schematic representation of a DVR

2.2 SMES AS ENERGY STORAGE DEVICE OF DVR

SMES is the Super Conducting Magnetic Energy System used in DVR as energy storage device.SMES systems have very fast charge and discharge times which make them an attractive energy storage system for sag mitigation. Another advantage of SMES systems is the very low losses due to the superconducting characteristics. It consists of super conducting magnetic energy storage unit, capacitor bank, VSI, low pass filter.It consists of main system and its sub systems. An SMES unit includes of a large superconducting coil, whose temperature is maintained below the cryogenic temperature by a cryostat or Dewar that contains either helium or nitrogen liquid as the coolant.[16][17] During standby condition, to reduce the energy losses a bypassswitch is used[18][19]. Finally a transformer which provides the power system connection and co-ordination and PCS operating voltage will reduce to acceptable levels.

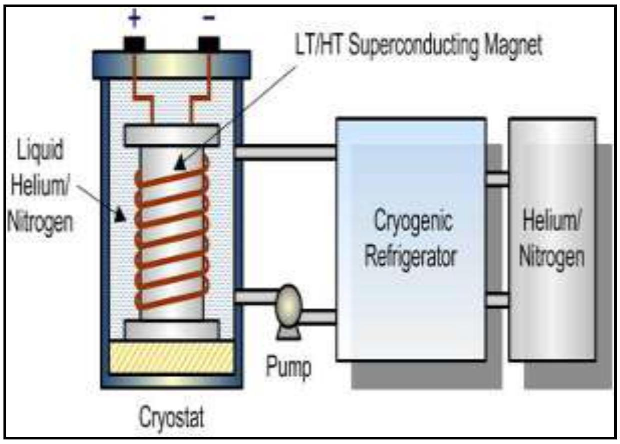

Fig 2.2.1- SMES schematic model

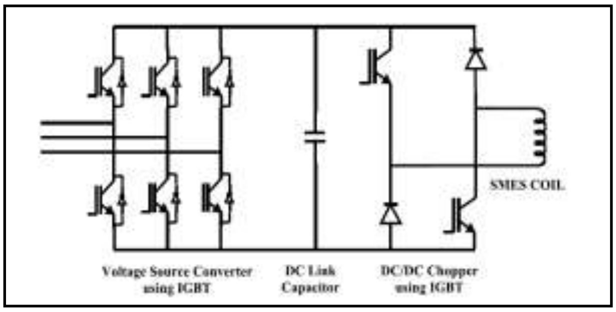

Fig 2.2.2VSC Based SMES model

The structural figure 2.2.2 of the SMES unit with VSC-based PCS includes of a star-delta transformer, a basic six-pulse PWM converter with insulated gate bipolar transistor (IGBT) as the switching device, a two quadrant bidirectional dc-dc chopper using IGBT, and an inductor as the superconducting coil. The decoupling of ac/dc converter and the dc-dc bidirectional converter is obtained by a large dc link capacitor.A power electronic link between the ac supply network and the dc current controlled superconducting coil is established by the PWM VSC.The PWM signal is obtained for the switching of IGBT by comparing the reference signal obtained from abc conversion with the high frequency triangular carrier signal. Throughout the operation the dc voltage across the capacitor is kept at its reference value by the six-pulse PWM converter .In our model VSC based SMES is used.[12].

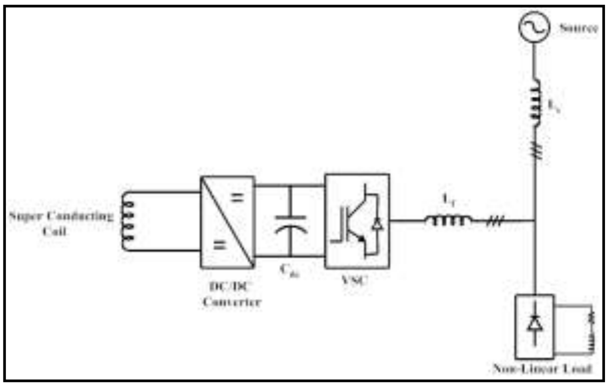

Fig:2.2.3 Proposed System Topology

Here, the PCS consists of a VSC and A DC/DC converter to control the source current as well as the charge-discharge cycle of SMES. DC/DC converter is a simple voltage bidirectional converter consists of IGBTs and diodes . When the switches are 'ON' SMES coil gets charged and positive voltage is applied on it; when they are 'OFF' negative voltage is applied on it and it discharges through diode. In both modes current remains unidirectional. During standby condition one of the switches is 'ON' and current circulates between that switch and one diode. The switching of this is regulated to get a constant dc-link voltage. Here, VSC is a six-pulse conventional full bridge converter. IGBT anti-parallel with a diode is used as the switch to get bidirectional current. It is controlled to operate in both rectifying and inverting modes.[20][21]

A voltage bidirectional dc-dc chopper is used to regulate the charge-discharge of the superconducting coil. The dc-dc chopper is controlled to make the voltage across SMES coil such as positive (IGBTs are switched ON) or negative (IGBTs are switched OFF) and then the energy reserved in SMES can be supplied or consumed accordingly. Hence, the charging and discharging of superconducting coil depends on the average voltage per cycle across the coil that is calculated by the duty cycle of the two-quadrant chopper. In order to obtain thePWM gate pulses for the IGBTs of the dc/dc converter, the estimated signal is compared withthe triangular/saw-toothed carrier signal .[21].

The applied voltage across SMES coil is controlled by regulating the conduction time of the IGBT over the switching cycle. While the duty cycle is 0.5, average voltage across the SMES coil and average DC current in the VSC are both zero, and net power transferred throughout one complete switching cycle is zero. For a duty cycle larger than 0.5, the coil gets charged; while at less than 0.5, the coil gets discharged. Therefore, the control of charge/discharge is established by regulating the duty cycle of the switching devices.

2.3 PRINCIPLE OF OPERATION OF SMES

Principle of Operation-The systems works on the principle of energy balance between sources, load and SMES coil. The source current can be described as

$$I_s = I_l \pm I_i \qquad \text{(i)}$$

Where Is= Source Current

Il= Load Current

Ii= Inverter Current

The output current of inverter is

$$I_i = f(I_o, D, M) \qquad \text{(ii)}$$

Where Io= SMES coil current

D = Duty cycle of dc/dc converter

M = Modulation index of inverter

Under load leveling condition the source current charges the coil when load power is less then source power. When, there is an increase in load occurs source power increases with load to its maximum and coil discharges to make energy balance between source, load andSMES.[21] In the whole operation dc link voltage is kept constant.

2.4 CONCEPT OF COMPENSATION TECHNIQUES IN DVR -Voltage injection or compensation methods by means of a DVR depend upon the limiting factors such as DVR power ratings, various conditions of load, and different types of voltage sags. Some loads are sensitive towards phase angle jump and some are sensitive towards change in magnitude and others are tolerant to these. Therefore the control strategies depend upon the type of load characteristics. [8][11][27][28][34].

There are four different methods of DVR voltage injection which are as follows:

1. Pre-sag compensation method
2. In-phase compensation method
3. In-phase advanced compensation (IPAC) method
4. Voltage tolerance method with minimum energy injection

1. Pre-sag/dip compensation method The pre-sag method tracks the supply voltage continuously and if it detects any disturbances in supply voltage then it will inject the difference voltage between the sag or voltage at PCC and pre-fault condition, so that the load voltage can be restored back to the pre-fault condition. [8][9][10]

Compensation of voltage sags in the both phase angle and amplitude sensitive loads would be achieved by pre-sag compensation method. In this method, the injected active power cannot be controlled and it is determined by external conditions such as the type of faults and load conditions.[8][10][11]

VDVR = Vprefault – Vsag… (i)

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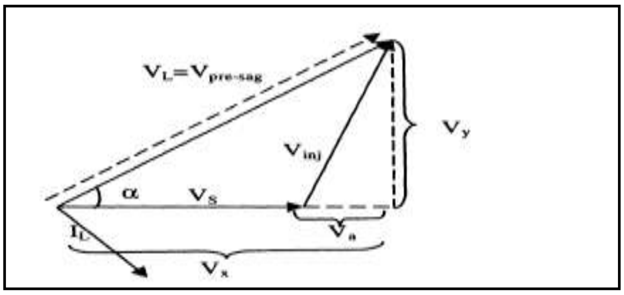

Figure 2.4.1: Pre sag compensation.

2. In-phase compensation method - In this method, the injected voltage is in phase with the supply side voltage irrespective of the load current and pre-fault voltage[8][10][22] .The phase angles of the pre-sag and load voltage are different but the most important criteria for power quality that is the constant magnitude of load voltage are satisfied. [8][10]

When the source voltage drops to voltage sag then the voltage source inverter (VSI) injects the missing voltage based on magnitude of the voltage drop. One of the advantages of this method is that the amplitude of DVR injection voltage is minimum for certain voltage sag in comparison with other strategies. Practical application of this method is in non-sensitive loads to phase angle jump.In our model in phase compensation method used.

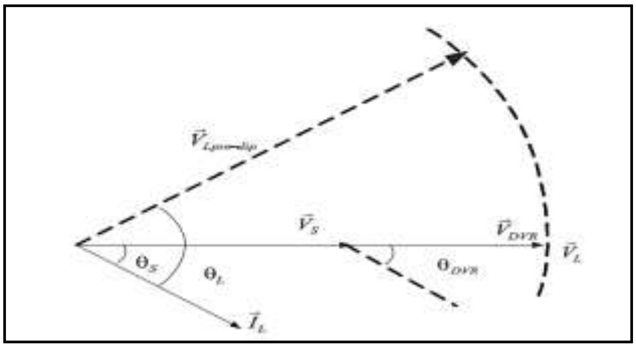

Figure 2.4.2 : In-phase compensation method

3. In-phase advanced compensation (IPAC) method -In this method, the real power spent by the DVR is decreased by minimizing the power angle between the sag voltage and load current. In case of pre-sag and in-phase compensation method the active power is injected into the system during disturbances.[31][32].

The minimization of injected energy is achieved by making the active power component zero by having the injection voltage phasor perpendicular to the load current phasor.[34][36][40][8] In this method, the values of load current and voltage are fixed in the system. So we can change only the phase of the sag voltage. IPAC method uses only reactive power and, not al1 the sags can be mitigated without real power, as a consequence, this method is only suitable for a limited range of sags. [8]

4. Voltage tolerance method with minimum energy injection -A small drop in voltage and small jump in phase angle can be tolerated by the load itself. If the voltage magnitude lies between 90%-110% of nominal voltage and 5%-10% of nominal state that will not disturb the operation characteristics of loads. Both magnitude and phase are the control parameter for this method which can be achieved by small energy injection.[8][9][10][32]

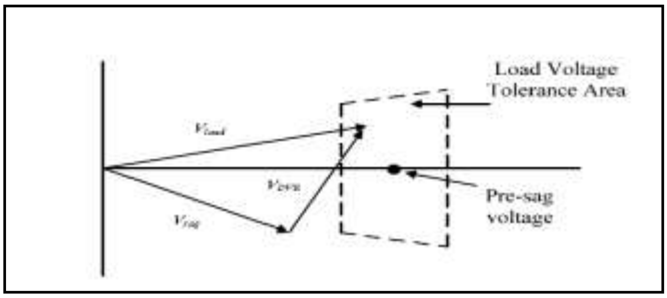

Figure 2.4.3: Voltage tolerance method with minimum energy injection

2.5 SCHEMATICS & WORKING OF DVR-The basic functions of a controller in a DVR are the detection of voltage sag/swell events in the system; computation of the correcting voltage, generation of trigger pulses to the PWM based DC-AC inverter, correction of any anomalies in the series voltage injection and termination of the trigger pulses when the event has passed[4][5][6][7].

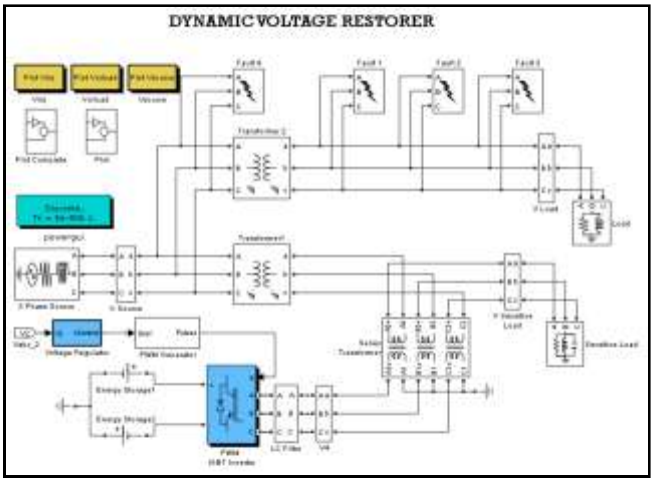

Figure 2.5.1- DVR various Blocks & its working

Figure 2.5- represents Dynamic voltage restorer with various blocks & working [10].It represents a Voltage

sag is created at load terminals by three phase faults. Load voltage is converted into per unit quantity. Then the magnitude is compared with the reference voltage through which error signal is fed to PI controller.[22][23][7] The voltage is then fed to triggering circuit PWM (pulse width modulated) control technique along with subsystem voltage regulator is applied for inverter switching so as to produce three phase sinusoidal voltage at the load terminals. The PI controller processes the error signal and generates the required angle δ to drive the error to zero PI controller input is an actuating signal which is a difference between Vref and Vin. The controller output compared at PWM signal generator results in desired firing sequence.[10][21]

The basic functions of a controller in a DVR are the detection of voltage sag/swell events in the system; computation of the correcting voltage, generation of trigger pulses to the PWM based DC-AC inverter, correction of any anomalies in the series voltage injection and termination of the trigger pulses when the event has passed. The controller may also be used to shift the DC-AC inverter into rectifier mode to charge the capacitors in the DC energy link in the absence of voltage sags/swells. [8][10][11].

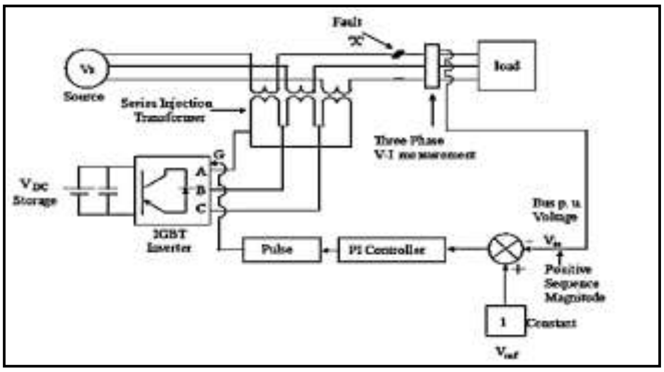

Fig 2.5.2- Simplified model of DVR

Fig 2.5.2- represents the simplified mode of DVR describing the working and circuit model of DVR.[11].The dqo transformation or Park's transformation is used to control of DVR. The dqo method gives the sag depth and phase shift information with start and end times. The quantities are expressed as the instantaneous space vectors. Firstly convert the voltage from a-b-c reference frame to d-q-o reference. For simplicity zero phase sequence components is ignored. The detection is carried out in each of the three phases. the measured terminal voltage (Va,Vb,Vc)[10][20][22][8].The voltage sags is detected when the supply drops below 90% of the reference value whereas voltage swells is detected when supply voltage increases up to 25% of the reference value.[1][2][11].The error signal is used as a modulation signal that allows to generate a commutation pattern for the power switches (IGBT's) constituting the voltage source converter. The commutation pattern is generated by means of the pulse width modulation technique (PWM); voltages are controlled through the Modulation The controller output when compared at PWM signal generator results in the desired firing sequence.[4][5] The sinusoidal voltage V control is phase-modulated by means of the angle δ or delta as shown in figure 4.2 and the modulated three-phase voltages are given by

$$VA=\sin(\omega t+\delta) \qquad \text{(iii)}$$

$$VB=\sin(\omega t+\delta-2\pi/3) \qquad \text{(iv)}$$

$$VC=\sin(\omega t+\delta+2\pi/3) \qquad \text{(v)}$$

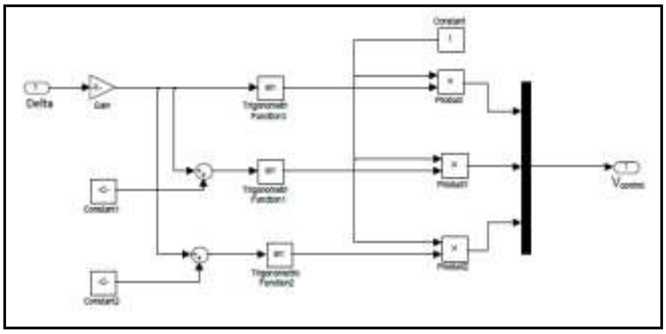

Fig 2.5.3 Phase-Modulation of the control angle δ (Subsystem 1)

Fig 2.5.3 represents the alpha beta phase modulation of subsystem[5]. The modulated angle is applied to the PWM generators in phase A. The angles for phases B and C are shifted by 120o and 240o. In this PI controller, only voltage magnitude is taken as a feedback parameter in the control scheme.[5][8][11].

2.6 CONTROL SECTION

Fig 2.5.2 represents a model is simulated by injecting a three phase voltage on a three phase source voltage. Load voltage is converted into per unit quantity . Then the magnitude is compared with the reference voltage through which error signal is fed to PI controller. The voltage is then fed to triggering circuit PWM (pulse width modulated) control technique along with subsystem voltage regulator is applied for inverter switching so as to produce three phase sinusoidal voltage at the load terminals. The PI controller has fault processes the error signal and generates the required angle δ to drive the error to zero PI controller input is an actuating signal which is a difference between Vref and Vin. The controller output compared at PWM signal generator results in desired firing sequence.

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The firing of the SMES coil in a VSI inverter of SMES coil during voltage sag through PWM generator having phase angle 0 degree, 120 degree and 240 degree for a set of 6 pulse thyristor.At a time any two thyristor conducts with firing angle 60 degree.At a time Pair of thyristor, T1,T6 or T2,T4 Or T3,T5 conducts in a universal bridge.The controller may also be used to shift the DC-AC inverter into rectifier mode to charge the capacitors in the DC energy link in the absence of voltage sags/swells.DC to dc link voltage is held constant through DC-DC chopper in SMES coil.

The dqo transformation or Park's transformation is used to control of DVR. The dqo method gives the sag depth and phase shift information with start and end times. The quantities are expressed as the instantaneous space vectors. Firstly convert the voltage from a-b-c reference frame to d-q-o reference. And then to alpha beta in the voltage regulator. For simplicity zero phase sequence components is ignored. The detection is carried out in each of the three phases. the measured terminal voltage.

The voltage sags is detected when the supply drops below 90% of the reference value whereas voltage swells is detected when supply voltage increases up to 25% of the reference value. The error signal is used as a modulation signal that allows to generate a commutation pattern for the power switches (IGBT's) constituting the voltage source converter. The commutation pattern is generated by means of the pulse width modulation technique (PWM); voltages are controlled through the Modulation The controller output when compared at PWM signal generator results in the desired firing sequence.

2.7SIMULINK MODEL OF THE SMES BASED DVR TEST SYSTEM

2.7.1 SIMULATION PARAMETER

Here simulations are performed on the DVR test system using MATLAB/SIMULINK as shown in detailed figure 2.7.2. The system performance is analysed for compensate the load voltage in distribution networks under SLG fault condition.

Table 1- Simulation Parameters

Sr.No	System Quantity	Specification
1	PI Controller	K p = 0.5,K i = 50
2	Inverter Specification	IGBT based, 3 arms, 6 pulse, Carrier frequency = 1080 Hz. continuous simulation
3	Capacitance	10 micro faraday
4	SMES inductor	1 Henry
5	SMES coil charging time & Discharging time	0.3 sec & 0.8 seconds
6	System voltage	22 KV(line to line)
7	System fault-three phase fault	0.01ohms (for 0.2-0.7seconds transisition time)
8	Load	10 kw RLC Load
9	Injection Transformer	22 KV /10 KV,10 MVA

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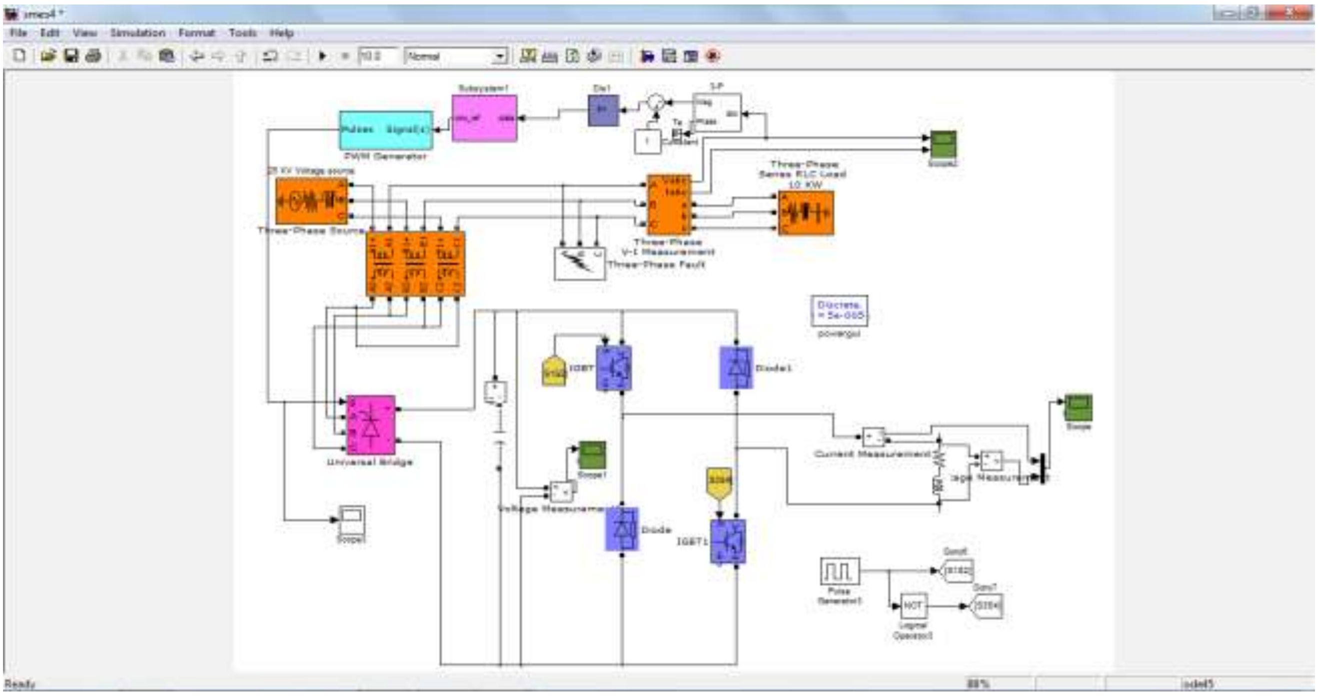

Fig 2.7.2 Simulink model of SMES based DVR system with PI controller

2.7.2 DESCRIPTION OF SIMULINK MODEL

Fig 2.7.2 represents a simulink model simulated by injecting a three phase voltage on a three phase source voltage. Load voltage is converted into per unit quantity and is fed to abc to dq converter as shown in simulink model. Then the magnitude is compared with the reference voltage through which error signal is fed to PI controller. The voltage is then fed to triggering circuit PWM (pulse width modulated) control technique along with subsystem voltage regulator is applied for inverter switching so as to produce three phase sinusoidal voltage at the load terminals. The PI controller has fault processes the error signal and generates the required angle δ to drive the error to zero PI controller input is an actuating signal which is a difference between Vref and Vin. The controller output compared at PWM signal generator results in desired firing sequence.

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When the supply drops below 90% of the reference value voltage sag is observed & voltage swells is detected when supply voltage increases up to 25% of the reference value. The error signal is used as a modulation signal that allows to generate a commutation pattern for the power switches (IGBT's) constituting the voltage source converter. The commutation pattern is generated by means of the pulse width modulation technique (PWM); voltages are controlled through the Modulation The controller output when compared at PWM signal generator results in the desired firing sequence.

3.0 SIMULATION RESULTS

To validate the proposed technique for implementation of SMES based DVR a MATLAB simulation is carried out. A MATLAB simulation is carried out in following steps for analysis purpose from fig 4.3.2. The first simulation was done without DVR and a three phase fault is applied to the system at point with fault resistance of 0.001ohm and for a time duration for 0.2-0.7 secs The second simulation is carried out at the same scenario as above but based DVR is now introduced at the load side to compensate the voltage sag occurred due to the three phase fault applied.. The

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working of SMES based DVR for voltage compensation at 0.001Ω fault resistance. The DVR performance in presence of SMES is analysed for symmetrical 3phase fault .

Step1. Generation of voltage sag due a three phase fault in the transmission line without SMES based DVR. Triple line to ground fault.

Step2. Generation of compensating voltage using d − q theory.

Step3. Implementation of SMES based DVR.

Step4. Compensation of voltage sag for type of fault using SMES based technology. Triple line to ground fault.

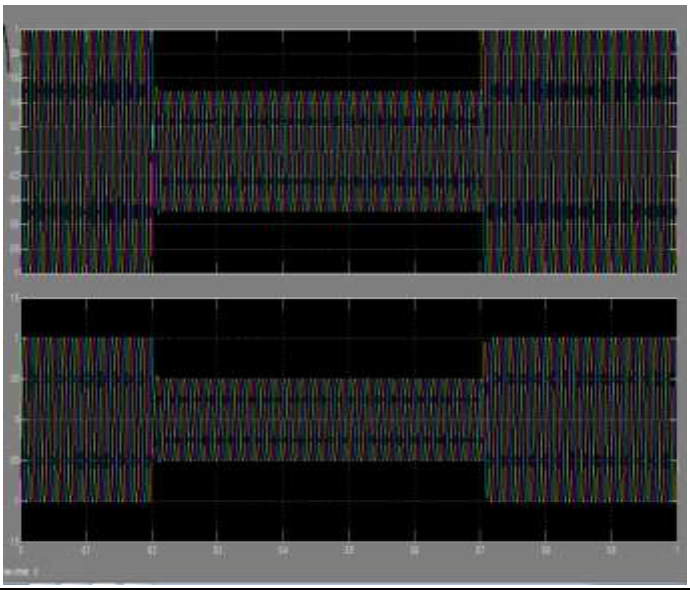

Fig 3.0.1 Simulation of three phase load voltage & current without DVR with three phase fault from fig 2.7.2

Fig3.0.1 represents the compensation without DVR with simulated three phase fault using SMES coil as storage coil. Here transition time of 0.2-0.7 seconds of fault occurrence is taken with fault resistance of 0.001 ohm is taken. On occurrence of 3 phase fault the voltage profile of the system reduced from +1 pu to-1 pu then to 0.5 pu to -0.5 pu . Thus reducing the entire voltage profile to 50% of the fault .On removal of three phase fault voltage profile has recovered as system is able to withstand these transients and able to retain its stability.

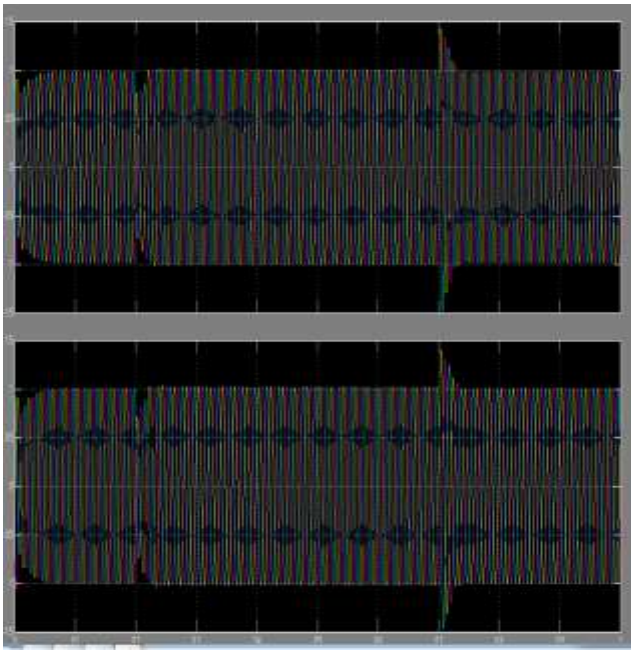

Fig3.0.2 a) Load Voltage With Compensation using DVR with three phase fault from fig 2.7.2in per unit

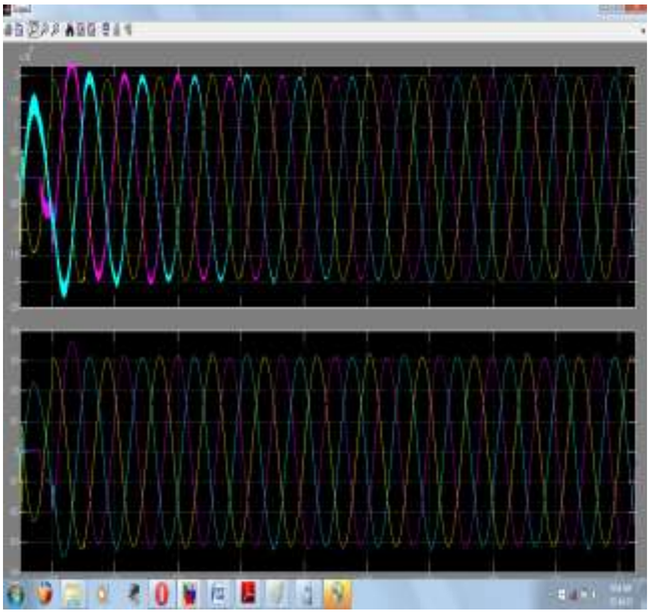

Fig3.0.2 b)Load Voltage With Compensation using DVR with three phase fault from fig 2.7.2

Fig 3.0.2 a)&b) represents the compensation using DVR with simulated three phase fault using SMES coil as storage coil where 3.0.2 a) represents compensation in pu voltage & current & 3.0.2 b) in actual voltage & current with 22kv load voltage. Here transition time of 0.2-0.7 seconds of fault occurrence is taken with fault resistance of 0.001 ohm is taken. On occurrence of 3 phase fault the voltage profile of the system remained to +1 pu to-1 pu .Thus the entire voltage profile remain same to 100% despite of the fault .On removal of three phase fault again voltage profile

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recovered as system able to withstand this transients and retain its stability for that time duration again voltage recovered. DVR inject the voltage in place of missing voltage to maintain the entire voltage profile.

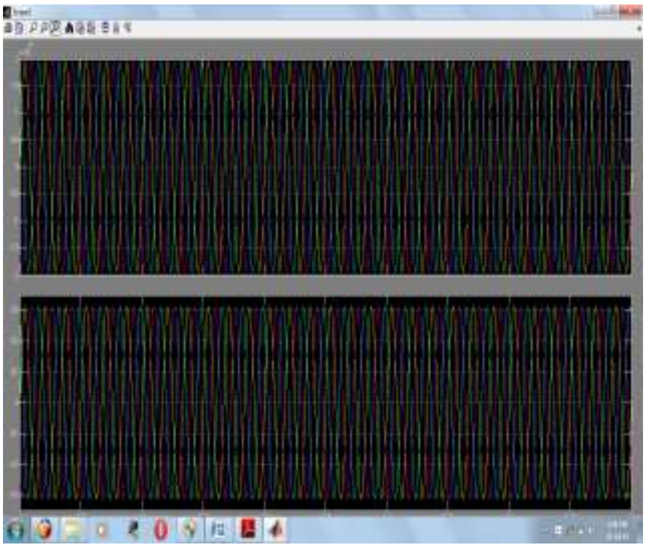

Fig 3.0.3 Compensation with DVR without three phase fault from fig 2.7.2

Fig 3.0.3 represents the compensation using DVR without simulated three phase fault using SMES coil as storage coil..Thus the entire voltage profile remain same to 100% (+22 kv to -22 KV) despite DVR remain in standby mode & the injection voltage in place of missing voltage is zero as the entire voltage profile is maintained.

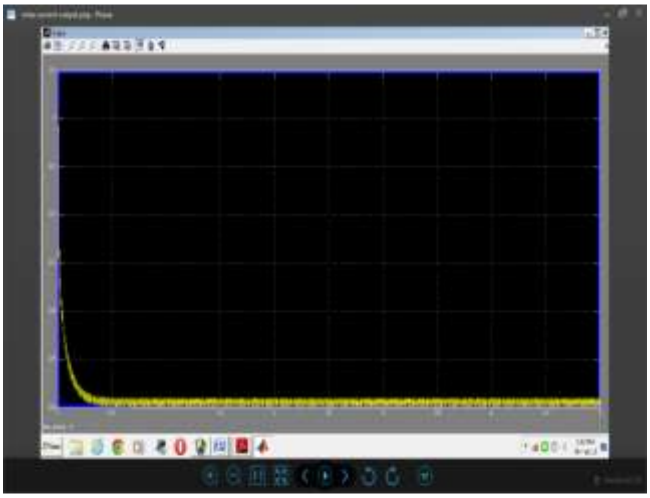

Fig3.0.4 DC Current through SMES coil during standby mode from fig 2.7.2

Fig 3.0.4 Represents the DC current flowing through SMES coil during standby mode .The coil having charging and discharging time as 0.3 sec/0.7 sec is simulation result of fig 2.7.2

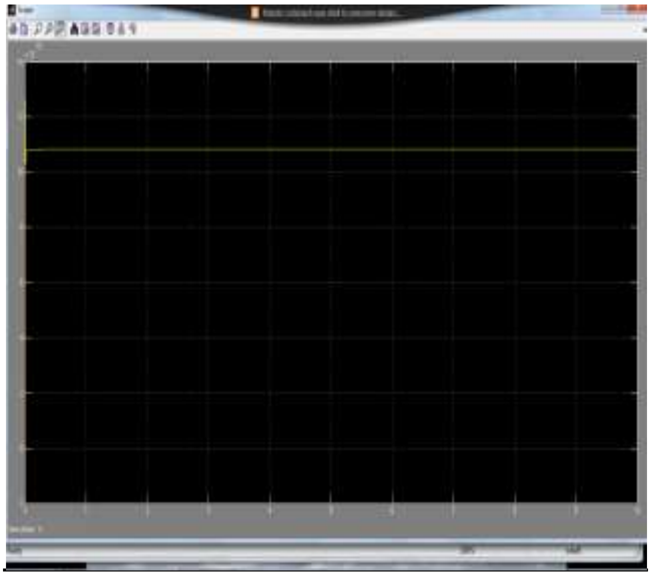

Fig 3.0.5 DC Current through SMES coil during standby mode from fig 2.7.2

Fig 3.0.5 Represents the DC current flowing through SMES coil during normal mode .The coil having charging and discharging time as 0.3 sec/0.7 sec

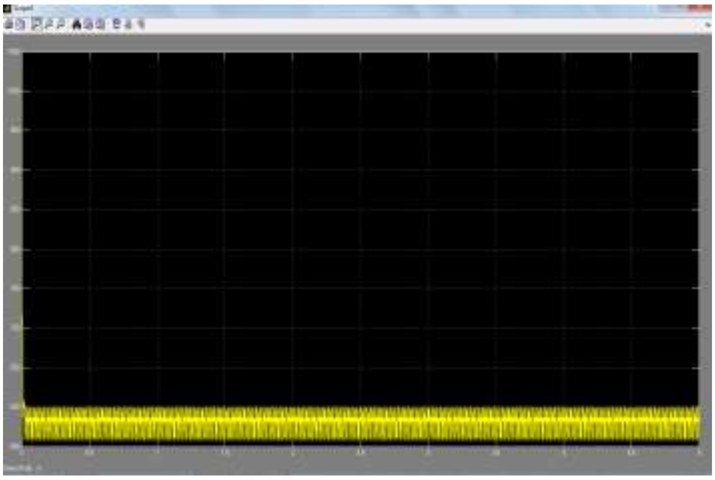

Fig 3.0.6 DC link voltage of SMES coil from fig 2.7.2

Fig 3.0.6 Represents the DC voltage across capacitor .This is the dc link to link voltage feed to dc-dc chopper is basically a pulsating DC converted into pure DC at chopper output terminal.

TABLE 2. VOLTAGE MAGNITUDE WITH & WITHOUT DVR

S.NO	TYPE OF SAG	VOLTAGE MAGNITUDE WITH DVR(in	VOLTAGE MAGNITUDE WITHOUT DVR(in percent)

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		percent)	
1	3-phase fault	100	50

Table 2 Comparison of voltage magnitude with and without DVR

Three phase fault is considered for the test system delivering linear & non linear load. Here the fault resistance is 0.001 ohm and the ground resistance is 0.001 ohm. The fault is created for the duration of 0.2s to 0.7s. The output waves for the load voltage without and with compensation are shown in Figure 3.0.1(a) & Figure.3.0.1(b). Here it is clear from the output wave shapes that the voltage in the phase where fault is created is increasing during the fault duration in the uncompensated feeder. When DVR is connected in the system the unbalancing is reduced.

4.0 CONCLUSION

A design of superconducting magnetic energy storage module as a dc voltage source to mitigate voltage sags and enhance power quality of a distribution system based on DVR has been presented. The simulation results prove that the SMES based DVR compensate the sags quickly and provide excellent voltage regulation the DVR handles both balanced and unbalanced situation without any difficulties and injects the appropriate voltage. The simulation shows that DVR performance is satisfactory in mitigating voltage sags. DVR has been found to regulate voltage under varying load condition and load unbalancing. The DVR handles fault conditions without any difficulties and injected the appropriate voltage to keep the load voltage balanced and constant at the nominal value. In this study, the DVR has shown the ability to compensate for voltage sags at the distribution side; this can be proved through simulation and experimental results. The efficiency and the effectiveness in voltage sags compensation showed by the DVR makes it an interesting power quality device compared to other custom power devices.

5.0 FUTURE SCOPE

In this dissertation, it is shown that DVR can compensate harmonics in voltage. The work can be expanded in the following area:

1. Other advanced controllers adaptive fuzzy controller, ANFIS, SVPWM Technique can be employed with DVR to increase the effectiveness of DVR in distribution networks.
2. Dynamic loads can be considered in future work and then the effect of DVR can be studied.
3. Wide spread use in power quality improvement.

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