COMPENSATION OF VOLTAGE SAG AND SWELL USING SMES WITH FUEL CELL BASED DVR IN TRANSMISSION SYSTEMS

S.Divya Priya[1] | R.Vijayakumar[2] | V.Divya[3]

[1] *Department of Electrical and electronics engg, , Karpagam Academy of Higher Education, Coimbatore, India, divyapriya.eee@gmail.com*

[2] *Department of Electrical and electronics engg, SNS College of Technology, Coimbatore, India, r.vijayakumarpse@gmail.com*

[3] *Department of Electrical and electronics engg, SNS College of Technology, Coimbatore, India, divyavasum@gmail.com*

Abstract— *Superconducting magnetic energy storage with the fuel cell (hybrid system) is possessed by its high efficiency storage of energy which is expected to contributing of high quality power in power systems. SMES has ability for real power storage with high power and energy density. This SMES characteristics is used for protecting consumers from the grid voltage fluctuations. They are voltage sag, voltage swell and interruptions. This paper analyze the operational principle of SMES with fuel cell based DVR. It is designed by using fuzzy logic control for the compensation of grid voltage fluctuations. This model is established using MATLAB/SIMULINK and the system performance is evaluated by simulation tests.*

Keywords— Superconducting magnetic energy storage (SMES); Voltage Sag; Voltage swell; Fuzzy logic; Dynamic Voltage Restorer (DVR); Fuel cell.

1. INTRODUCTION

The research on SMES with fuel cell(hybrid system) for the enhancement of power quality is based on two methods. The first method is to protect the sensitive loads by using hybrid system as UPS. The second method is used for the compensation of system voltage fluctuations by connecting hybrid system parallel with power system. The large interconnection network is more complex and less secure because of growth in electrical loads and high power transmission. In order to make it more flexible and controllable an energy storage device is used in power system for instant balance between supply and demand. This facilitates the renewable sources that improve the flexibility, reliability and efficiency.

TABLE I. Voltage sag and swell

Type of Disturbance	Voltage	Duration
Voltage Sag	0.1-0.9 p.u.	0.5-30 cycles
Voltage Swell	1.1-1.8 p.u	0.5-30 cycles

The cause of sags has been categorized in a area of occurrence, the transmission, the distribution and utilization point. Swells are treated under a single category. A common underlying cause of sag and swell in all categories is a sudden change of current flow through the source impedance. The issues related to power quality are of two categories that is voltage quality and the frequency quality. Voltage sag, voltage swell, under voltage and over voltage are the issues of voltage quality in power system. Whereas harmonic and transient are related with the frequency quality in power system. By using voltage sensitive devices the voltage sag issue in power quality is more important. The voltage sag and swell can be described as shown in Table 1.The classification of energy storage devices are two categories based on their applications they are short term response energy storage device and long term response energy storage device. Flywheel, Super capacitors and SMES are short term response energy storage devices. Compressor, batteries and Redox are long term response energy storage devices.

Due to less power rating and energy rating flywheel and super capacitors cannot be use in the application of short term high power. Therefore SMES has been used to overcome this disadvantage. This improves the power system performance as it has high power rating with high efficiency than the other energy storage devices. In order to overcome the problems of power system faced in superconducting and power electronics are rectified. This benefits lead to the recent development and advancement. The SMES advantages are high flexible, reliable and fast real power compensation.

The various applications of SMES are Power Quality, Custom Power, Dynamic Response, Stabilization, Voltage/VAR Control, Spinning Reserve, Load Leveling, and Frequency Control Application. The dynamic voltage restorers is used for voltage sag compensation which is connected in series topology has the most efficiency in cost. In this paper, a SMES with fuel cell is introduced as energy storage unit of DVR. The SMES and fuel cell applications are put forth for power conditioning with DVR. The dynamic response of SMES with fuel cell (hybrid system) based DVR on voltage sag and swell is simulated using MATLAB simulator.

2. ENERGY STORAGE UNITS

The energy storage devices are of two types they are direct energy storage and indirect energy storage. The energy storage device is shown in fig.1.

There are three categories of energy storage devices

(i) Small categories (<10MW)

(ii) Medium categories (10MW < energy < 100 MW)

(iii) Large categories (≥ 100 MW)

The small category includes flywheel, ultra capacitor and capacitor. Medium category includes large scale batteries, lead acid, NAS and Redox. Large category includes compressed air energy storage and pumped storage.

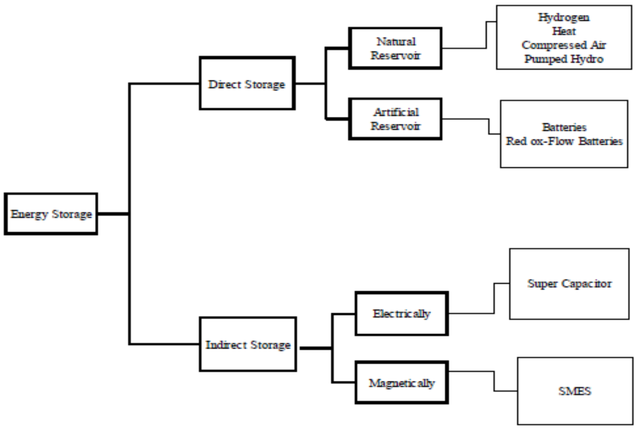

Fig. 1. Energy storage devices

The application of energy storage with respect to their discharging time period and storage capacity is shown in TABLE II. Efficiency of storage devices are given by the equation (1).

TABLE II. Classification of stored capacity

Application	Stored Capacity	Discharge Period
Power Grid Leveling	11 MJ-201 GJ	Few Sec. - Few Days
Power Quality	0.11-11 MJ	Few Sec.
Custom Devices	0.11-11 MJ	Few Cycle

The SMES with fuel cell may not be cost effective, at present they have an environmental impact by reducing emission and fuel consumption. SMES with fuel cell is exploited in different applications, which includes the efficiency of SMES and their fast response capability. The application level of electric power system is shown in TABLE III.

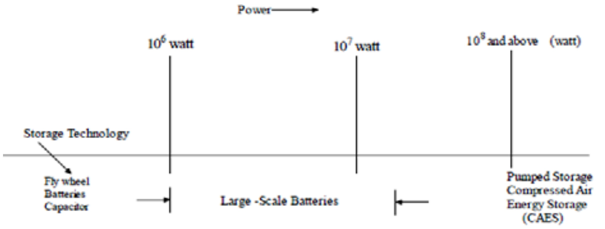

Fig. 2. Technical capability of energy storage devices

TABLE III. Characterized Application of SMES

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

3. SCHEME OF SMES

SMES is stores energy in the magnetic field which is developed due to the flow of direct current in a superconducting coil. The superconducting coil is in helium vessel. Below the critical temperature the superconducting coil is cooled. The stored energy can be released as whenever required. The coil is maintained in a superconducting state by immersing it in liquid helium in a vacuum insulated crystal. The SMES block diagram is shown in fig.3.

The SMES consists of more subsystems, for the high performance compensation, the system must be designed carefully. The base of the SMES unit is large superconducting (SC) which is composed of cold component. The cryogenic refrigeration system is at bottom side of system as shown in fig.3. By using lumped parameter the SMES equivalent circuit can be obtained. The network of lumped parameters is represented by a model called six segment which consists of (Li) selfinductance, (i, j and Mij) Mutual coupling, (Rsi) resistance loss, (Rpi) skin effect resistance, (shunt-Cshi) turn-ground and (series-Csi) turn-turn capacitances. This model is accurate for transient system in electric systems. The range of frequency is from dc to several thousand Hertz. The (Csg1 and C3q2) surge capacitor and a (Cf) filter capacitor is in parallel with grounding balance resistor(Rg1 and Rq2) which reduces the resonance effect. Between the SMES model and dc/dc converter a (MOV) metal oxide semiconductor is used. (MOV) is used for transient voltage surge suppression.

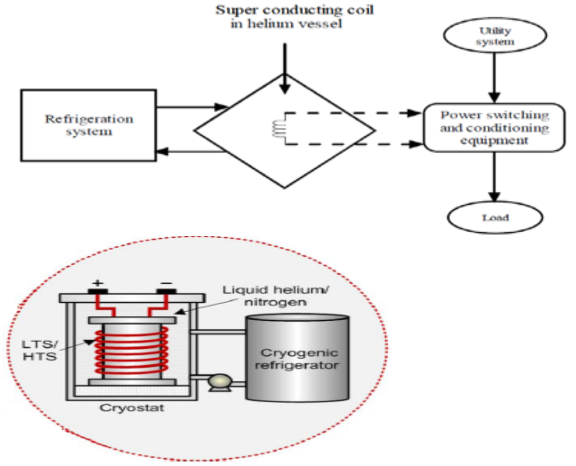

Fig. 3. SMES Scheme

The specification of SMES devices are inductively stored energy (energy in Joules) and the power rate (P in watt). This can be expressed as,

$$E=\frac{1}{2}LI^2 \qquad (1)$$

$$P=\frac{dE}{dt}=LI\frac{dI}{dt}=VI \qquad (2)$$

Where,

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

4. SMES AND FUEL CELL WITH DVR

A DVR based on Superconducting Magnetic Energy Storage with fuel cell is shown in Fig.4. This structure consists of superconducting magnetic energy storage, fuel cell, capacitor bank, voltage source inverter, low pass filter and a voltage injection.

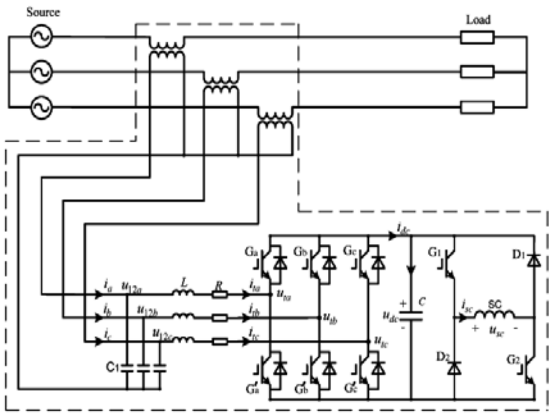

Fig. 4. Basic structure of DVR based on SMES.

Based on its simple principle SMES is designed. The energy released circuit of SMES is shown in fig.5.

The operating states of the circuit models are of three states:

1) Energy charging state (K_1 and K_3 closed, K_2 opened);
2) Energy storing state (K_2 and K_3 closed, K_1 opened);
3) Energy discharging state (K_2 closed, K_1 and K_3 opened).

During charging the cycle, solenoid coil is place across DC source. When certain amount of energy is stored in the coil then DC source removed then the solenoid coil is shorted through superconductor material. Without decay the current flows through coil continuously, in the solenoid coil the energy is stored. For The negative voltage applied across the coil for the discharging of solenoid coil energy.

In practical application, the voltage sag is mitigated by using discrete pulse width modulation based control scheme is implemented. The rms voltage at load point is measured by control system. The control system has to maintain constant voltage magnitude at the sensitive load point.

At load terminal voltage sag, swell and interruption is created by various phase faults as shown in Fig.6. Through the sequence analyzer the load voltage is converted into per unit quantity.

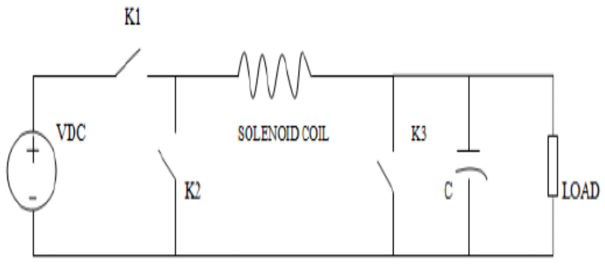

Fig. 5. SMES energy released circuit.

The most promising clean energy source is obtained from the fuel cell. This offers the flexibility of stacking multiple fuel cells by meeting the required power. This has been growing in many applications for the production of electricity and also as a backup power. The advantage of fuel cell includes the system performance, reliability and durability. The controller in the fuel cell is assigned to dampout oscillation. This utilizes the characteristics of fast response of fuel cell. Thereby the effectiveness of fuel cell incorporated in the improvement of stability in the power system.

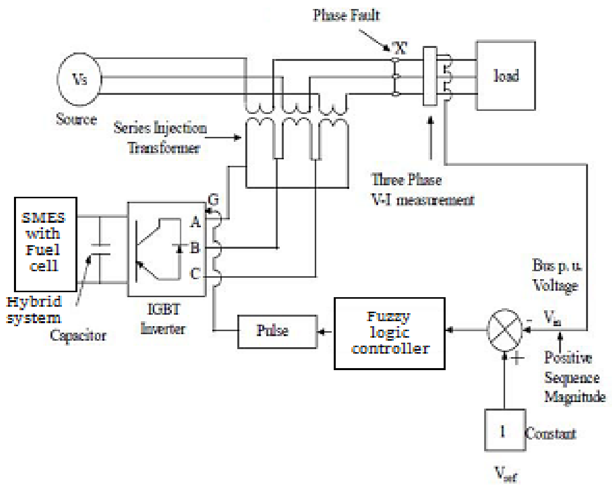

Fig. 6. DVR with SMES.

To the fuzzy logic controller, the compared magnitude with reference voltage (V_{ref}) through which error signal is fed. This voltage is fed for the circuit triggering. To produce three phase 50Hz sinusoidal voltage at load terminal, pulse width modulated control technique is applied for inverter switching. The chopper frequency is range of a few kilo Hertz. The IGBT is controlled by the fuzzy logic controller which maintains 1per unit voltage at load terminal as the base voltage as 1. The voltage angle exerted by DVR control system is as follows:

The error is processed by fuzzy logic controller and the required angle δ is generated. The angle δ drives the error signal to zero. For eg; the reference voltage is brought back by load rms voltage. Here the assumption is made on balanced network and operating condition. In phase A the modeling angle δ is applied to pulse width modulating generator. The phase angle is shifted by 240° or -120° and 120° for the phase B and C.

$V_A = \sin(\omega t + \delta)$ (3)

$V_B = \sin(\omega t + \delta - 2\pi/3)$ (4)

$V_C = \sin(\omega t + \delta + 2\pi/3)$ (5)

The advantage of fuzzy logic controller is that it causes the steady errors to be zero for a step input. Actuating signal is the input for fuzzy logic controller. Which is the difference between V_{ref} and V_{in}. The controller block output is in the form of an angle δ which includes phase lag/lead in three phase voltage V_{ref}-V_{in} is the error detector output.

V_{ref} is equal to 1 p.u. voltage

V_{in} is voltage in p.u. at the load terminals.

The desired firing sequence is achieved by controlling the output when compared at pulse width modulating signal.

5. FUZZY LOGIC CONTROLLER

The fuzzy logic based control system is of human reasoning approach that which makes use of tolerance, uncertainty and the decision making process that offers a satisfactory performance. By using the function membership input the rules of the inputs are fuzzied and with the interface system which then produces the output are then defuzzied and then fed into the main control system. The input is chosen by the error from their reference and their deviation of error with time interval chosen. The output is added to the prior output to produce the new output which is a reference output.

The fuzzy consist of Rotor Side Converter (RSC). The objective of RSC is active power control and the voltage regulation. The rotor manages to follow active power and the voltage separately which are done using fuzzy controller. The trapezoidal membership function are chosen to have constant and smooth region which also avoids the miscalculations that occur due to the effect of noise on data and in the change of wind speed.

5. SMES SIMULATION MODEL

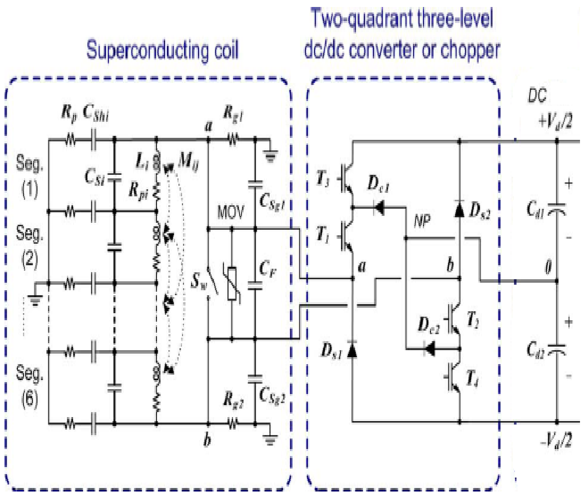

Fig. 7. Detailed model of the proposed SMES system.

The three level chopper output voltage vector and their IGBT switching status are shown in TABLE IV. MATLAB model is shown in Fig.8. SMES charging and discharging output are shown in Fig.9, 10.

TABLE IV. three-level chopper output voltage vectors and their IGBT switching states

States	T_1	T_2	T_3	T_4	V_{ab}
1	1	1	1	1	$+V_d$
2	0	0	0	0	$-V_d$
3	0	1	0	1	0
4	1	0	1	0	0
5	1	1	0	0	0
6	1	1	0	1	$+V_d/2$
7	1	1	1	0	$+V_d/2$
8	1	0	0	0	$-V_d/2$
9	0	1	0	0	$-V_d/2$

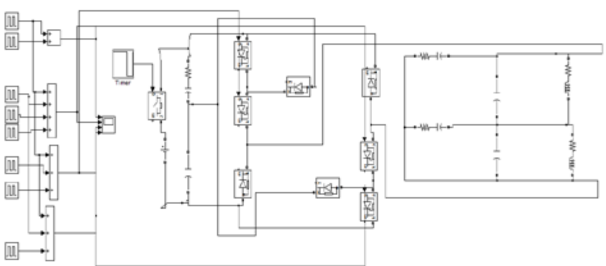

Fig. 8. MATLAB/SIMULINK diagram of SMES model

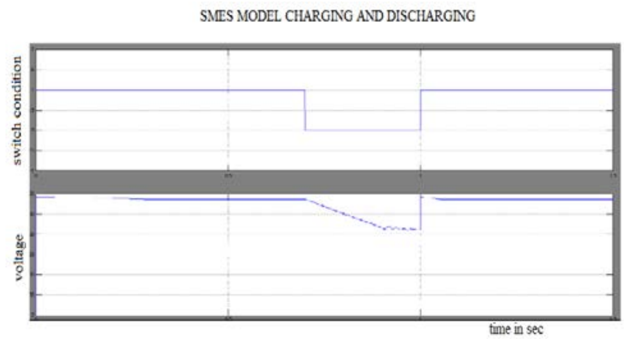

Fig. 9. Output waveform for SMES model and discharging

6. SMES BASED ON DVR TEST SYSTEM

Single line diagram of the test system composes of 13kV DVR. Based on SMES, the generating system has the frequency of 50Hz feeding two transmission lines of 3-winding transformer which is connected in star/delta/delta, 13/115/115k. Such a transmission lines feed two distribution network through the two transformer which is connected in delta/star of 115/11kV. The working of DVR for voltage compensation is verified at the fault resistance of 0.44ohms for fixed time duration of 200ms. The DVR performance for hybrid system is analyzed for symmetrical three phase to ground fault. For the analysis of system performance i.e. voltage sag compensation we take SMES with 588KA current flow through it.

The MATLAB/SIMULINK diagram of Hybrid system based DVR for voltage sag compensation is shown in fig.17. The first simulation was done with the Hybrid system based DVR and a three phase to ground fault is applied to a system point with the 0.44ohms fault resistance for the time duration of 200ms, this results in voltage sag as shown in fig.5. The second simulation was done by hybrid system based DVR to compensate the voltage sag which occurred due to three phase to ground fault as shown in fig.7. The per unit of load voltage profile for hybrid system based DVR and without hybrid system based DVR is shown in fig.10.

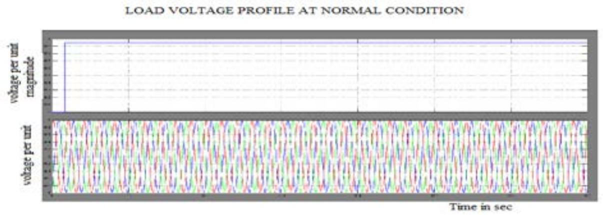

Fig. 10. Phase-phase voltage without any fault

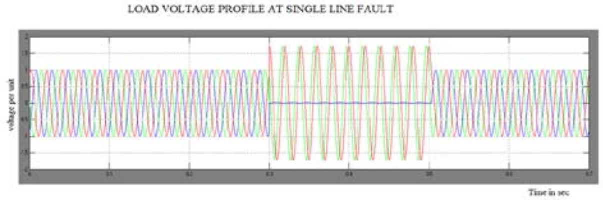

Fig. 11. Single line fault, phase-phase voltage without SMES based DVR

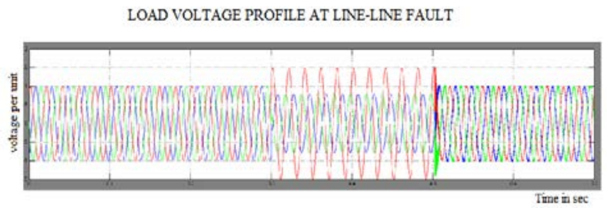

Fig. 12. Line- line fault, phase-phase voltage without SMES based DVR

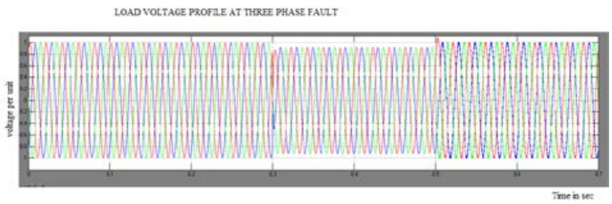

Fig. 13. Three phase fault, phase-phase voltage without SMES based DVR

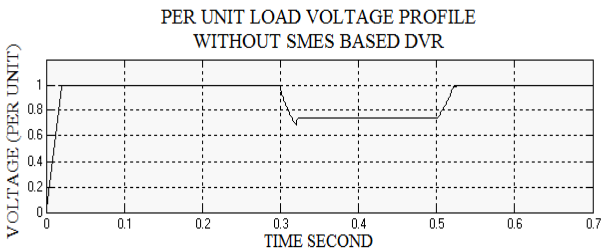

Fig. 14. Voltage P.U at load point without SMES based DVR

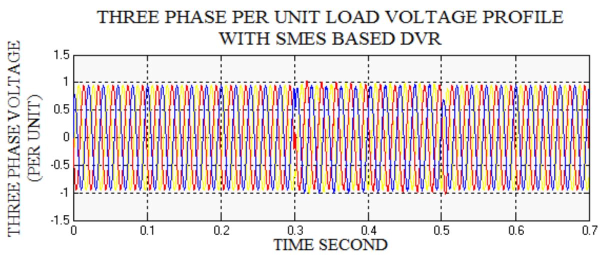

Fig. 15. Three phase P.U. voltage at the load point with SMES based DVR

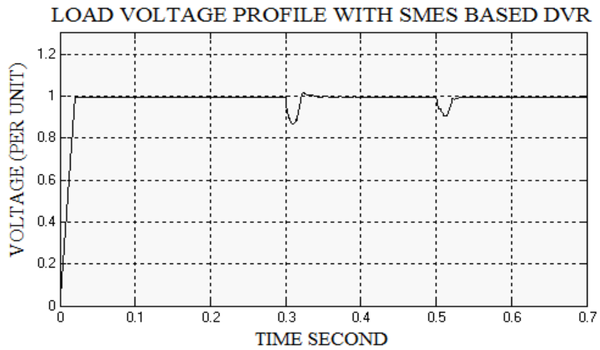

Fig. 16. Voltage P.U. at the load point with SMES based DVR

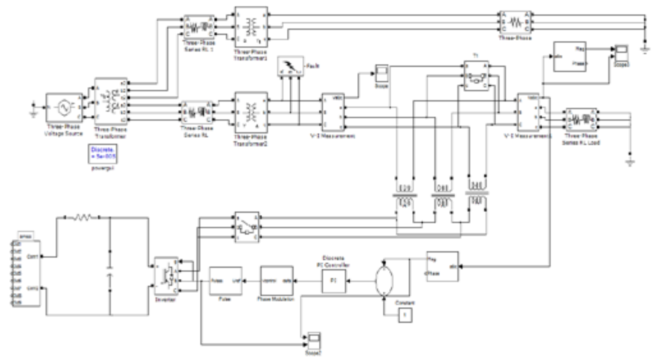

Fig. 17. MATLAB/SIMULINK diagram of DVR based on SMES for sag and swell compensation.

CONCLUSION

A new design which incorporates a superconducting magnetic energy storage module as a DC voltage source to mitigation voltage sag, swells 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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