Modelling And Analysis of DVR With SEPIC Converter And Supercapacitor

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Abstract - *Dynamic Voltage Restorer along with battery is used to compensate voltage sag in the sensitive load side. Conventional DVR systems use battery alone as energy source. But the batteries won't be able to cop up the rapid fluctuations in voltage. In this paper a battery super capacitor combination is used as the energy storage system for DVR. In order to reduce the burden of the battery energy storage system we can effectively use photovoltaic (PV) array along with battery, so as to support the DVR during day time. A Single Ended Primary Inductor Converter (SEPIC) is also introduced to maintain constant voltage as the converter output. The results show that voltage compensation can be effectively done using the proposed method. This is modelled and simulated using MATLAB/SIMULINK.*

Key Words: **Dynamic Voltage Restorer (DVR), Voltage sag, supercapacitor, photovoltaic array, Single Ended Primary Inductor Converter (SEPIC).**

1. INTRODUCTION

The quality and continuity of the electric power supplied is very important for the efficient functioning of the end user equipment. Most of the commercial and industrial loads demand high quality uninterrupted power. The quality of the power is affected if there is any deviation in the voltage and frequency values at which the power is being supplied. The major power quality issues are voltage sag, swell, flicker, harmonics and transients. Among these voltage sag is considered as the most severe issue. It is defined as the sudden reduction of RMS voltage in the range of 0.1 to 0.9pu [1]. The typical duration of voltage sag ranges from 10 ms to 1 minute. Many techniques are used to palliate voltage sag, among which the use of custom power devices are considered to be the most efficient method.

Custom power devices refer to a special category of power conditioning devices, used to protect the grid from voltage disturbances. Dynamic Voltage Restorer (DVR) is one of the most efficient and effective custom power device [2]. It works by boosting the voltage at the load bus during voltage sags, utilizing the energy from a storage unit and a voltage source converter. In a DVR the active power and the reactive power can be controlled independently. Additionally, DVR systems are bidirectional, so they can either absorb or generate active and reactive power. DVR systems are known to provide a fast response to system disturbances and consume zero real power during steady state. All these advantages make DVR the best choice for voltage sag mitigation.

The main component of the DVR is its energy storage system. Earlier the energy to generate the compensating voltage was received from the grid or load side by the use of parallel rectifiers. But it leads to more voltage sag. Nowadays DVR uses dedicated energy storage system for its working. Batteries are used the most commonly used energy storage device. But it has low dynamics, less potential power density, and short life cycle [3]. Another option is to use supercapacitors. Supercapacitor's energy density is 20% lower than battery's. But it has high power density and energy storage capability and also adoptable for adverse environment. Thus by using a hybrid combination of battery and supercapacitor, the overall performance of the storage element can be improved.

Energy storage system voltages are highly fluctuating at its terminals. In order to provide a constant voltage to the DVR a DC-DC converter is used in between the DVR and energy storage systems. Usually buck converters are used for this purpose. But it has many disadvantages like high ripple current, higher flux density, high harmonics. In this paper a Single Ended Primary Inductor Converter (SEPIC) is used in place of conventional converters. SEPIC converter is similar to buck boost converter but it has a non-inverted output. The SEPIC converter allows a range of dc voltage to be adjusted to maintain a constant voltage output. The rising market of photovoltaic (PV) power generation can be taken as an opportunity here as the PV panels can be used to supply energy for the DVR during daytime. Thus the burden of the battery can be further reduced.

In this paper a DVR that uses a hybrid combination of battery, supercapacitor and photovoltaic energy is proposed. Battery supercapacitor energy storage system operated parallel with the photovoltaic energy system. The conventional dc-dc converter is replaced by a SEPIC converter. The entire system is modelled in MATLAB/SIMULINK environment. The performance of the proposed system is compared with the conventional DVR system and the Total Harmonic Distortion (THD) due to the introduction of SEPIC converter is studied.

2. PROPOSED SYSTEM

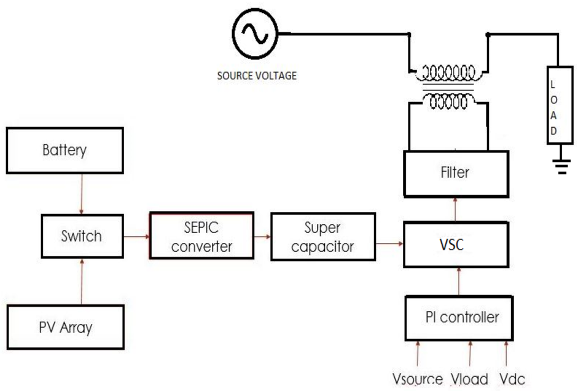

Fig-1: Block diagram of proposed DVR

Fig-1 shows the proposed system block diagram for voltage sag compensation. It consist of an energy storage device, Voltage Source Converter (VSC), filter Circuit, converter circuit, controller and series transformer. Energy storage device includes battery supercapacitor hybrid combination and a parallel connected photo voltaic (PV) array system to provide the required amount of voltage. The supercapacitor connected in parallel to the battery which acts as a low pass filter that prunes out rapid voltage changes. Fast compensation of voltage occurs because of high charging and discharging capability of supercapacitor. The other storage system used here is a photovoltaic array storage system, which support the DVR during day time. So we can reduce the use of battery. This energy storage system is connected to the converter through a manually operating switch. Storage system has variable terminal voltage which is paired with switching DC-DC converter to supply a regulated voltage to the load. SEPIC converter used for this purpose. This converter has more advantage than the other converter in terms of harmonic reduction and efficiency. The converter output is connected to the VSC for converting the DC voltage to AC. This is connected to distribution load through series insertion transformer. Series transformer is a step-up transformer that can reduce the DC-side voltage level of the inverter and it also functions as a buffer between the inverter and grid. Proportional and Integral (PI) controller is used to detect the presence of voltage sags in the system. It is considered as a monitor of the load-bus voltage. If a sag voltage is sensed, the controller will be initiated in order to inject the missing voltage after determination of its magnitude and phase. Filters are used for rectifying high-order harmonic contents generated by the voltage source converter.

The working of DVR can be explained as follows. The DVR controller monitors the load-bus voltage consequentially. This voltage is compared with the reference voltage. If a voltage sag occur an error signal is generated which is fed to a Proportional and Integral (PI) Controller. Its output is provided to the PWM signal generator that controls the DVR inverter to generate the required injected voltage. During day time or favourable condition of weather PV array provide the required compensation voltage. During unfavourable condition or night time battery supercapacitor hybrid combination inject the sag compensation voltage.

1.1 Supercapacitor

Supercapacitor are electrical energy storage devices which offer high power density and High cycling capability. It can be used as a rapid discharge energy storage for power applications. Supercapacitor are used for short duration storage applications such as power stabilization, power quality ride through applications, which require high power density and rapid recharge [4].

Normally capacitors store electric energy by accumulating positive and negative charges separated by an insulating dielectric. The capacitance, C, represents the relationship between the stored charge, q, and the voltage between the plates, V, as shown in (1). The capacitance depends on the permittivity of the dielectric and the area of the plates, A and the distance between the plates, d, as shown in (2).

$$q = CV \tag{1}$$

$$c = \frac{\varepsilon A}{d} \tag{2}$$

Equivalent capacitance of supercapacitor depends on the number of series and parallel connected capacitance. The number of series connected cells Ns in one branch is found out by the rating of supercapacitor cells Ucell, and the maximum available voltage Umax.

$$N_S = \frac{U_{max}}{U_{cell}} \tag{3}$$

The number of parallel cells Np is found by

$$N_p = \frac{N_s C_{eq}}{C_{cell}} \tag{4}$$

For sufficient energy storage capacity number of parallel cells are greater than one.

$$C_{eq} = \frac{N_p C_{cell}}{N_s} \tag{5}$$

For higher capacitance number of parallel arms are should be greater than series arms value. Based on these parameters supercapacitor is designed.

1.2 Single Ended Primary Inductor Converter

It is a bi-directional dc-dc converter which has the capability to step down or step up the voltage based on the load requirement. SEPIC converter basically works on the buck-boost topology but the only difference is that it has an extra inductance and capacitance [5]. Fig-2 shows the equivalent model of SEPIC converter. One end of the primary inductor is connected to the positive terminal of the battery. The capacitor is used to eliminate the dc component between input and output. The main advantage over other converters is that SEPIC converter have a non -inverted output so no need of extra converting circuit.

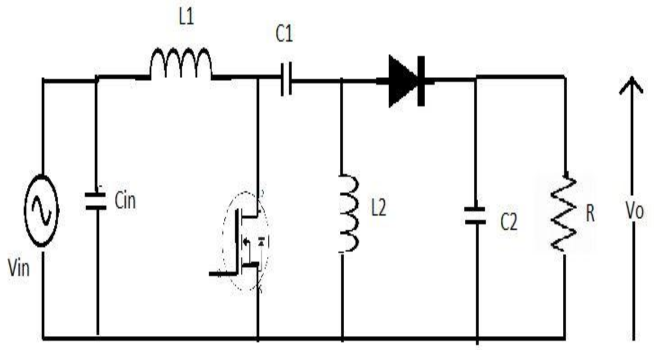

Fig-2: Sepic converter

The capacitor coupling energy from input to output allows the converter to prevent short circuit in a very controlled manner than buck converter. It also saves the overall cost and board space as it is designed with minimal active components and is supervised by a simple controller. It reduces noise and harmonics from its high frequency switching operation.

Working principle of converter as follows. When the MOSFET is on, inductor L1 is charged by the voltage source and L2 is charged by the capacitor C1. Diode is reverse biased and the output is maintained by C2. When the MOSFET is off, the inductor output through the diode to the load and the capacitor C2 is charged. By changing the switching cycle, SEPIC can be used as buck and boost converter. If duty cycle is greater than 50%, it will step up and if the duty cycle is below 50% it will step down the voltage.

Duty cycle:

By considering the diode voltage drop VD and input voltage Vi and output voltage Vo

$$D = \frac{Vo + VD}{Vi + Vo + VD} \qquad (6)$$

Inductor:

Inductance is determined based on the peak to peak current, which is 40% of maximum input current. The ripple current flowing through both inductors are given by

$$\Delta I_L = I_{IN} \times 40\% = I_{OUT} \times \frac{V_{OUT}}{V_{IN(min)}} \times 40\% \qquad (7)$$

Inductance is calculated by the equation,

$$L1 = L2 = \frac{V_{IN(min)} \times D_{max}}{\Delta I_L \times f_{sw}} \qquad (8)$$

Output capacitor:

When the MOSFET is turned on, the inductor is charging and the output current is supplied by the output capacitor. Due to this the output capacitor sees large ripple currents. Thus the selected output capacitor must be capable of handling the maximum RMS current.

$$C_{OUT} \geq \frac{I_{OUT} \times D}{V_{ripple} \times 0.5 \times f_{sw}} \qquad (9)$$

MOSFET selection:

MOSFET selection is done on the basis of minimum threshold Voltage, Vth (min), the on resistance Rds(on), gate drain charge Qgd and the maximum drain to source voltage Vds (max). The peak switch voltage is equal to Vin + Vout.

Diode selection:

The peak current and the reverse voltage should be managed and controlled by the diode. In SEPIC, the diode peak current is equal to the switch peak current IQ1 (peak) and for the minimum peak reverse voltage the diode must be withstand.

$$V_{RD} = V_{in(max)} + V_{out(max)} \qquad (10)$$

1.3 PV Array Modelling

The basic device of pv is the pv cell which are grouped to form panels or modules. Panels can be grouped to form large photovoltaic arrays. Array can be used to describe a panel or a group of panels.

Ideal photovoltaic cell:

Fig.3 shows the equivalent circuit of the ideal photovoltaic cell. For developing the model following assumptions are made.

- Light generated current is equal to short circuit current.
- VI characteristics depends on internal characteristics of device and external parameters like irradiation level and temperature.

The basic equation from the theory of semiconductors [6] that mathematically describes the I-V characteristic of the ideal photovoltaic cell is:

$$I = I_{pv,cell} - Id \qquad (11)$$

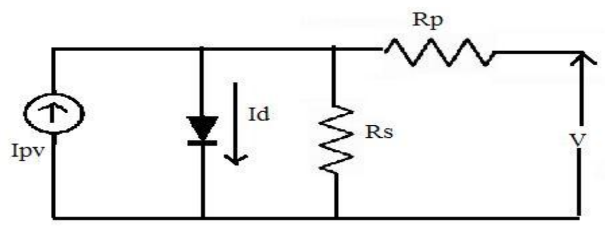

Fig- 3: Ideal PV cell

Where Ipv, cell is the current generated by the incident light, Id is the Shockley diode equation, Io, cell is the reverse saturation or leakage current of the diode, q is the electron charge [1.60217646 ·10−19C], k is the Boltzmann constant whose value is [1.3806503·10−23J/K], T is the temperature of the p-n junction, in K and a is the diode ideality constant.

For practical purpose the PV array is modelled using the following equation.

$$I = I_{pv} - I_0\left[\exp\left(\frac{V+R_sI}{V_t a}\right)-1\right] - \frac{V+R_sI}{R_p} \qquad (12)$$

Here, Io is the saturation current Vt is the thermal voltage of array. Rs and Rp are the series and parallel resistance. Using perturb and observe method find out the maximum power [7]. Based on this power Rs and Rp is designed.

Fig-4 and Fig-5 shows the VI and PV characteristics for a constant irradiance of 1000W/m2. From the V-I curve, it can be inferred that the current is approximately independent in the temperature variation but the voltage changes with temperature. From the P-V curve it can be seen that the maximum power decreases with increase in temperature.

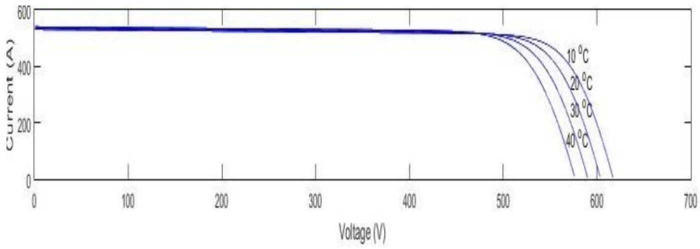

Fig-4: Temperature effect on V-I characteristics at constant irradiation

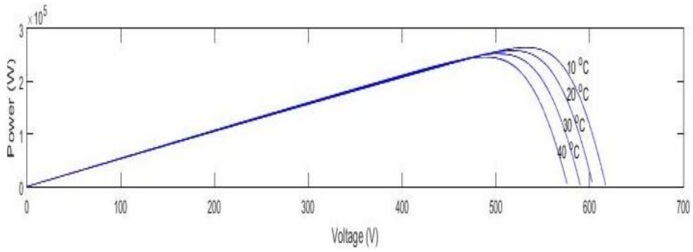

Fig- 5: Temperature effect on P-V characteristics on constant irradiation

3. CONTROL SCHEME

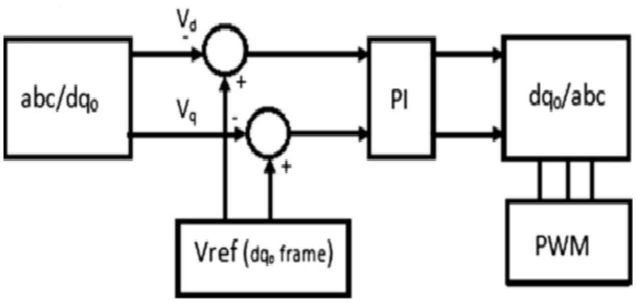

Fig- 4: PI Controller

The control algorithm produces a three-phase reference voltage to the series converter that seeks to maintain the load voltage at its reference value. In this paper Park's transformation is used to control the DVR. By converting three phase abc voltage into the two voltage components Vd and Vq.

The DVR controller continuously monitor the load voltage and this is transformed into dq form. Then compared with the reference value. If a voltage sag occur in the system, an error signal is produced and controller will be initiated in order to compensate the reduced voltage. This error signal drives a PI controller which controls the system depending on the actuating error signal. The output of controller fed back to abc form before it is forwarded to pwm generator.

Pulse width modulation (PWM) for inverter is used to generate switching signal for the voltage source inverter. It uses a triangular carrier wave with higher frequency, which is compare with the voltage reference [8]. When the triangular wave is above the demand voltage, output is high and below the demand voltage output is low. In this paper the switching signal that modulates the 50 Hz signal is taken to be 5 kHz.

4. SIMULATION RESULTS

The simulation of the proposed DVR system is carried out in MATLAB/ Simulink. It is designed for a 415 V, 50-Hz three phase distribution system. Table I shows the parameters used in simulation. Voltage sag is created using three phase to ground fault applied in an interval 0.04 s to .14 s. The system response for a three-phase voltage sag is analyzed. The simulation results for compensation of voltage sag and current harmonics are presented.

Table-1: Parameters used in simulation

Grid voltage	415V
Series transformer turns ratio	1:1
Battery	400V
Load	10KvA
Line frequency	50Hz
Filter inductance	1.35mH
Filter capacitance	900µF
Supercapacitor	60F

4.1 Voltage Compensation Analysis

The simulation result for DVR using conventional battery storage system as shown in Fig-7. A sag is introduced to the load voltage by applying a three phase to ground fault at 0.04sec and last till 0.14 sec. From the graph it is observed that at the time of fault, the voltage compensation using battery storage system takes a little time to respond to this condition. So it takes a delay for providing the required voltage. This is because of the slow discharging time of battery. Due to this delay the end connected equipment's produce voltage flicker and it may getting damaged.

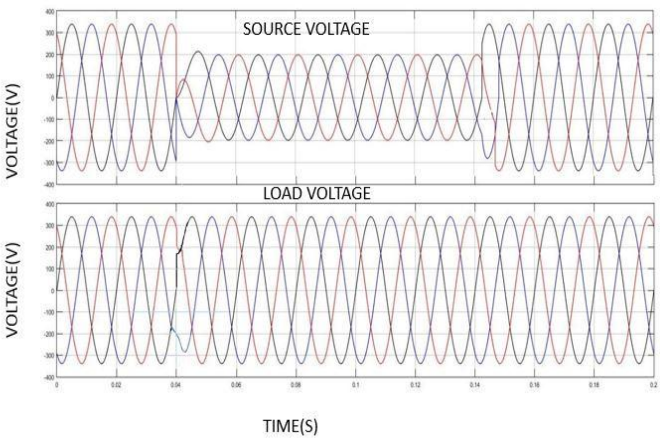

Fig-7: Conventional DVR voltage waveform

Fig-8 shows the proposed system voltage waveform of input and output. Here battery supercapacitor combination used as energy storage system. From the graph it is found out load side voltage is effectively maintained during fault condition. At the time of fault the DVR inject the required voltage. This fast response is because of the high discharging capability of supercapacitor.

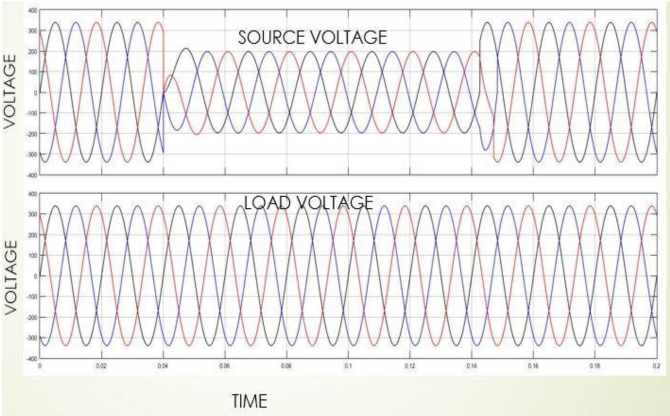

Fig- 8: Source and load voltage during sag

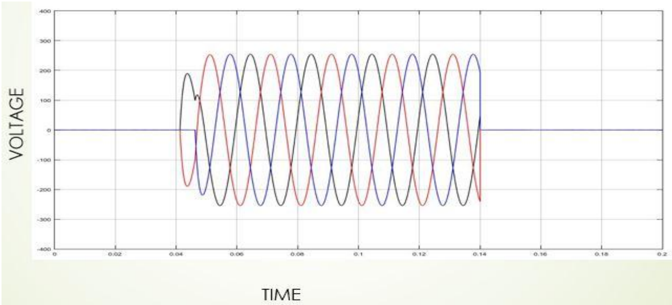

Fig-9: DVR voltage during sag

Fig-9 shows the DVR output voltage which is given to the grid for compensation. Normal condition DVR voltage is zero. When a voltage sag occur, at that instant DVR supply the required voltage to grid.
From the above voltage waveforms it is found out that the compensation is faster in proposed method than the conventional method. So that the load side voltage is effectively maintained using the proposed method.

4.2 Harmonic Analysis

Harmonic spectrum of load voltage using conventional and proposed method is analysed. The following graph shows the reduction in THD using buck and sepic converter. Fig-10 shows the harmonics in load voltage for conventional DVR. Here battery and buck converter is used as the storage system. The THD is 5.37%. Harmonic spectrum of load voltage using battery supercapacitor with sepic converter as shown in Fig-11. THD of proposed method is 1.75%.

From the comparison it is found out that a significant reduction in THD occur from 7.14 to 5.37%. So the proposed storage system and converter is better than the conventional one.

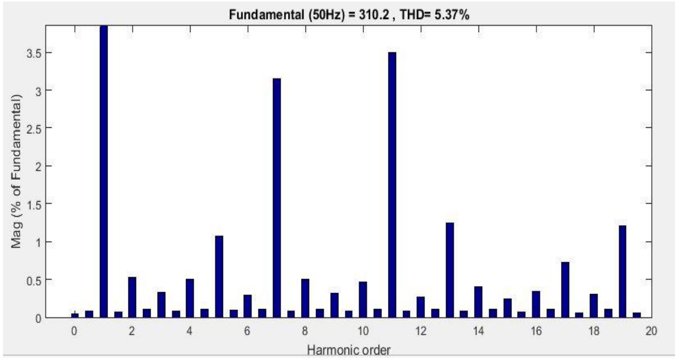

Fig-10: Battery and buck converter

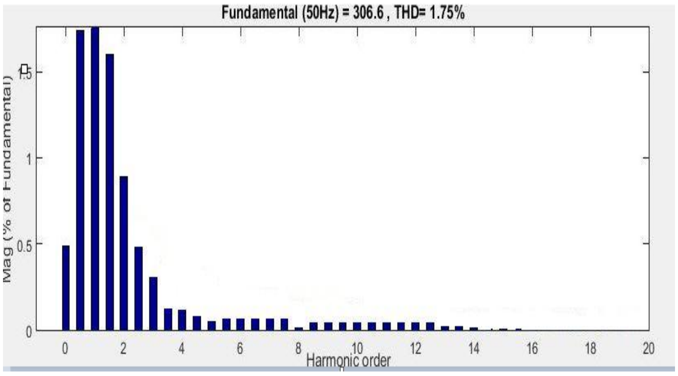

Fig-11: Battery- Supercapacitor and SEPIC converter

Fig-12 demonstrates the THD analysis of PV with SEPIC converter and THD is 2.69%. THD of PV array instead of battery is same as the conventional battery.
From the comparison we can infer that the use of SEPIC converter has pulled down the THD to a low value.

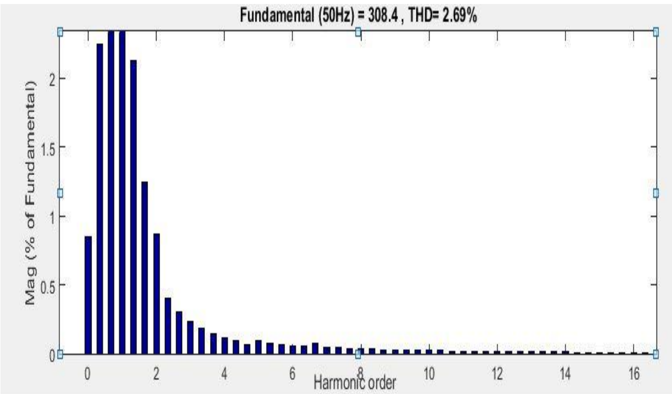

Fig-12: PV and SEPIC converter

From the table below, it is clear that reduction in harmonics occur using proposed storage system and converter. The harmonics reduced from 5.37% to 1.75%. So it improves the system performance during fault condition.

Table-2: Reduction in THD using different storage system

Storage system	THD in Load Voltage (%)
Battery with Buck converter	5.37
Battery Supercapacitor with SEPIC Converter	1.75
PV with SEPIC	2.69

5. CONCLUSION

A dynamic voltage restorer based on hybrid energy storage has been proposed and is used for mitigating voltage sag problems. Two different energy storage system and converters are used for voltage compensation. Battery supercapacitor hybrid combination provide the instant compensation voltage at the time of fault. Supercapacitor can compensate long term voltage sag because of its large capacity and it can improve the battery life by avoiding the fast discharge of battery during fault condition. A PV array is included parallel to the battery- supercapacitor energy storage system. This relieves the burden on the battery and improves battery life and hence the overall system performance. The analysis has been done and it is observed that the voltage compensation occurs faster than in the conventional system. It is also observed that the voltage compensation results obtained when we add PV array is same as the conventional system. .A SEPIC converter has replaced the buck converter in the system for the reduction of harmonics in the voltage. The analysis shows that a reduction in THD occur using proposed method. THD reduced from 5.37% to 1.75% when use the proposed method. The operation of proposed system has been verified through simulations with MATLAB/SIMULINK software. It is obvious that the proposed DVR is capable of effective correction of the voltage sag while minimizing the grid voltage unbalance and harmonics distortion, regardless of the fault type.

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