

# A PV BASED SINGLE STAGE POWER CONDITIONING SYSTEM FOR DYNAMIC VOLTAGE RESTORER

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**Abstract:** Voltage sags and voltage swells are major power quality issues which adversely affect the sensitive loads connected to a distribution system. A Dynamic Voltage Restorer (DVR) connected to the point of common coupling, injects a voltage in series with the line to present a pure sinusoidal voltage of desired RMS value to the critical loads, when the supply side is affected by voltage disturbances. The compensation capability of a DVR mainly depends on its energy storage. The design and development of a Photo Voltaic (PV) based, single stage power conditioning system for a single phase DVR is proposed in this paper. The PV based power conditioning system of the DVR employs energy stored Quasi impedance (Z) Source Inverter (QZSI) to achieve the voltage boost, inversion, and energy storage in a single stage. The integrated control system controls the inverter output power, track the PV panel's maximum power point, and manage the battery power, simultaneously. A sliding mode controller, which ensures a robust control under any supply side disturbances and parameter variations, effectively achieves the DVR's compensation strategy.

**Key Words:** Power Quality, Dynamic Voltage Restorer (DVR), PV power conditioning system, energy stored quasi Z source inverter (QZSI), Sliding mode controller

## 1. Introduction

Sensitive loads connected to the electric network are constantly under risk due to the power quality issues such as voltage sags and voltage swells. Loads such as medical equipment, factory automations, and manufacturing units of semiconductor-devices incur huge operational and production losses as they are vulnerable to power supply disturbances [1-3]. Major voltage disturbances such as voltage sags and voltage swells occur, due to short circuits in upstream power transmission lines or parallel power

distribution lines connected to the point of common coupling (PCC), inrush currents involved in starting of large machines, sudden changes of load, energization of transformers or switching operations in the grid. As per the IEEE1159-2009 standard, voltage sag is defined as a decrease in magnitude of 0.1 to 0.9 p.u. in the RMS voltage at system frequency and with the duration of half a cycle to 1 min [3-4]. A dynamic Voltage Restorer (DVR) is a custom power device which restores the quality of voltage at the load side terminals when the voltage quality at the supply side is affected [5-8].

The DVR injects a compensating voltage through a series transformer connected to the line. The energy required for the compensation is drawn from the line or any other energy source or a lead acid battery [5-8]. Though fast switching compact IGBTs reduces the size of the inverter, the cost and size of the DVR is large due to the energy storage element and series transformer. The compensation capability of the DVR depends on the availability of stored energy. A new class of power converters called Z source and quasi Z source converters with reduced component usage, simple control strategies and buck boost capabilities [9-11] find wide applications in renewable power generation. A quasi Z source inverter based DVR proposed [12] is found to exhibit superior performance due to reduced energy storage and low total harmonic distortion (THD) in the output waveform. An energy stored QZSI is proposed [13] to use with PV systems to mitigate the stochastic variations in the environmental conditions, so that the inverter output voltage is controlled as per the load demand. Since they combine the voltage boost, inversion and energy storage in a single stage, this

removes the need for multistage conversion and control. A PV energy based dynamic voltage restorer with significant energy conservation is proposed in [14]. It uses a high step up DC-DC converter along with voltage source inverter to convert the PV panel output voltage to appropriate levels of AC voltage input to the primary of the injection transformer. This set-up involves additional control and power circuits. An attempt is made to replace the double stage power conversion with a single stage conversion by the use of an energy stored QZSI. Hence a PV based energy stored Quasi Z source inverter power conditioning system for the efficient operation of the DVR is proposed in this paper.

Conventional controllers used in DVR require accurate, linear mathematical models and their performance suffer from parameter variations [15]. Sliding mode controllers alleviate this need for accurate mathematical models. With the knowledge of parameter variation range to ensure stability and satisfactory reaching conditions, sliding mode controllers perform better in nonlinear systems [16-17]. Apart from simple implementation, sliding mode controllers provide stable and robust operation even for large variation in the supply and load side parameters and exhibit fast dynamic response, as the converters have highly variable structure.

This paper presents the design of a PV based single stage power conditioning system with a quasi Z source inverter for a single phase DVR. The single stage power conditioning control system simultaneously achieves voltage boosting from the low voltage PV output, maximum power point tracking, battery control, and DC/AC conversion. The dynamic response of the DVR is improved with the sliding mode control. The PWM controlled quasi Z source inverter with its buck boost action, reduces the need for large battery storage for compensation of voltage variations of high magnitudes. Thus the proposed PV based DVR is capable of compensating for any variation in the supply voltage even in conditions of the PV output power fluctuations. The design methodologies are verified by extensive simulation studies and results.

## 2. Development of the PV based power conditioning system for the DVR

A schematic diagram of the PV based dynamic voltage restorer installed in series with a sensitive load is shown in Fig.1. This single phase DVR consists of a energy stored Quasi Z source inverter fed from a PV array, a passive filter, an injection transformer, and a sliding mode controller to regulate the inverter output voltage.

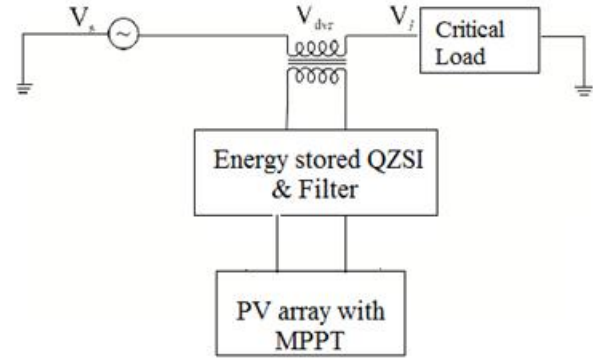


Fig.1 Structure of the proposed DVR with PV power conditioning system

To achieve efficient utilization in trapping the solar power a Maximum Power Point Tracking (MPPT) algorithm based on Perturb & Observe (P&O) method is implemented.

### 2.1 Description & modeling of the PV array with MPPT:

Modeling of the PV cell and PV array has been widely discussed in literature [18-19]. To achieve maximum power point tracking (MPPT) of the solar power at fixed voltage, various algorithms have been proposed in the literature. An overview of the various MPPT algorithms can also be found [20]. A simplified model of a PV cell used in the study is shown in Fig 2. Many such cells are arranged in series parallel fashion to form a PV module. The specification of the module used for simulation studies is shown in Table I. In the present system 4 such modules are connected in series to get a string and two such strings are connected in parallel to obtain a PV array or panel of required voltage and power rating for the DVR operation under consideration.

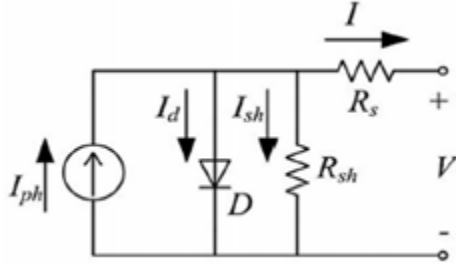


Fig 2. Circuit model of the PV cell

Table 1. PV module specification

Rated Power	37.08 W
Voltage at Maximum power (Vmp)	16.56 V
Current at Maximum power (Imp)	2.25A
Open circuit voltage ( VOC)	21.24V
Short circuit current ( ISCr)	2.55A
Total number of cells in series (Ns)	36
Total number of cells in parallel (Np)	1

Due to the changes in solar irradiation and temperature of the solar cell, the output voltage and power output of a PV array is not constant always. Fig 3 shows the PV array characteristics between the output voltage and the power output at different temperatures but at a constant irradiation. It is important to track the maximum power operating point at the same output voltages

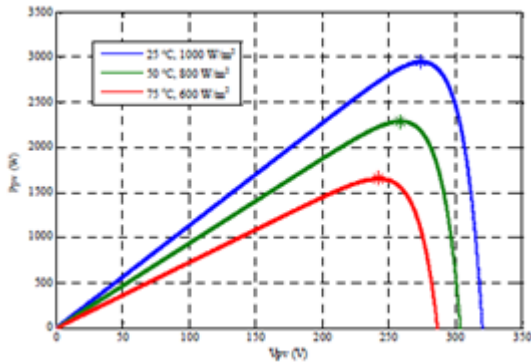


Fig 3. Power Vs Voltage characteristics of the PV array

to utilize the full potential of the PV panel, irrespective of the climatic conditions. There are a number of maximum power point tracking (MPPT) algorithms exists. The power conditioning system proposed here employs P&O MPPT algorithm as given in Fig 4.

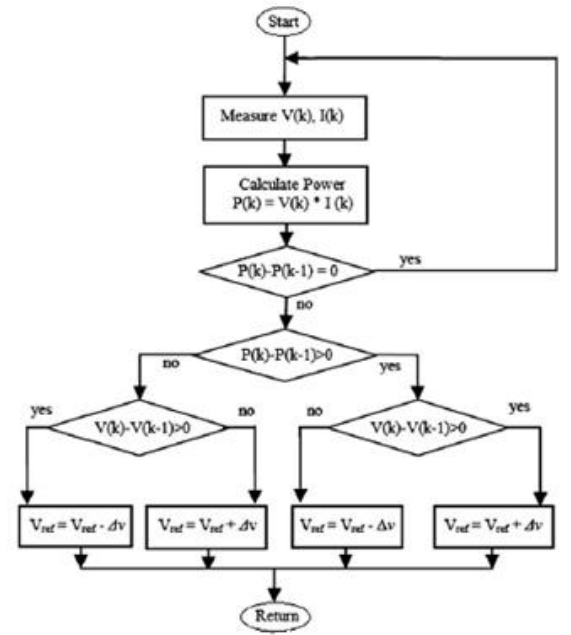


Fig 4. Flow chart used for MPPT

## 2.2 Design of the single stage PV based power conditioning System:

An energy stored quasi Z source inverter is employed to achieve single stage power conversion from the PV panels to the injection transformer. This section analyses the design and integration of the quasi Z source inverter with the PV panel output as the energy source.

The circuit topology of the Quasi Z source inverter is shown in Fig 5. The most important feature of this inverter compared to conventional voltage source inverter is the introduction of shoot through states along with the normal active states. During the shoot through states, either both switches of the same leg or all four switches of the inverter are turned on simultaneously, leading the output voltage of the inverter to be zero. This feature enhances the capability of the inverter to act as a voltage boosting circuit.

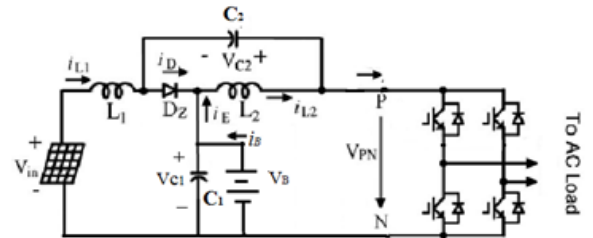


Fig 5. Single phase energy stored Quasi Z source inverter with PV input

The energy stored Quasi Z source inverter (QZSI) used in this DVR power conditioning system consists of a QZSI with a battery connected across the capacitor  $C_1$ . It receives input power directly from the PV array. The power balance in the circuit is achieved as per the equation

$$P_{in} + P_B - P_{out} = 0 \quad (1)$$

Where,  $P_{in}$ ,  $P_B$ ,  $P_{out}$  are the PV Power, battery power and output power of the inverter respectively. Among them, PV power is always positive,  $P_B$  is positive when battery delivers energy and  $P_{out}$  is positive when inverter delivers power to the DVR connected load.

The circuit operates in two modes in continuous conduction state. In mode I, the shoot through state, the inverter legs are short circuited through any one leg or both the legs.

In a switching cycle with period  $T$ , if  $T_0$  is considered as the shoot through period, the remaining duration  $T_1$  is the active state of the inverter.

$$\text{Thus } T = T_0 + T_1 \quad (2)$$

$$\text{The shoot through duty ratio } D = \frac{T_0}{T} \quad (3)$$

The circuit equations during shoot through state, mode I are

$$C \frac{dV_{C1}}{dt} = i_B - i_{L2} \quad (4)$$

$$C \frac{dV_{C2}}{dt} = -i_L \quad (5)$$

$$L \frac{di_{L1}}{dt} = V_{in} + V_{C2} \quad (6)$$

$$L \frac{di_{L2}}{dt} = V_{C1} \quad (7)$$

Where  $i_{L1}$ ,  $i_{L2}$  and  $i_B$  are the currents through the inductor  $L_1$ ,  $L_2$ , and battery respectively. The voltages across the capacitor  $C_1$  is denoted as  $V_{C1}$  and across  $C_2$  as  $V_{C2}$ . The PV array output voltage

is  $V_{in}$ . The capacitance of the capacitors  $C_1$  and  $C_2$  is denoted as  $C$  and  $L$  is the inductance of the inductors  $L_1$  and  $L_2$ .

In mode II, the inverter is in active state or zero state. This is also known as non-shoot through state. The circuit equations during this mode are

$$C \frac{dV_{C1}}{dt} = i_B + i_{L1} - i_o \quad (8)$$

$$C \frac{dV_{C2}}{dt} = i_{L2} - i_o \quad (9)$$

$$L \frac{di_{L1}}{dt} = V_{in} - V_{C1} \quad (10)$$

$$L \frac{di_{L2}}{dt} = -V_{C2} \quad (11)$$

Where  $i_o$  is the current flowing into the inverter.

From the above equations, it can be deducted that The DC link peak voltage of the QZSI is

$$V_{PN} = \frac{1}{1-2D} V_{in} \quad (12)$$

$$V_{PN} = V_{C1} + V_{C2} \quad (13)$$

By neglecting the internal resistance of the battery, it can be shown that

$$V_{PN} = 2V_B - V_{in} \quad (14)$$

The peak of the output voltage can be given as

$$V_{op} = V_{PN} \frac{M}{2} \quad (15)$$

The non-linear relation between the PV panel voltage  $V_{in}$  and the output current  $i_{L1}$  is given by

$$V_{in} = f(i_{L1}) \quad (16)$$

### 2.3 Control Methodology of the energy stored QZSI:

Either the PV panel power or the battery power can be controlled through the duty cycle  $D$ . Together with the modulation index and the duty

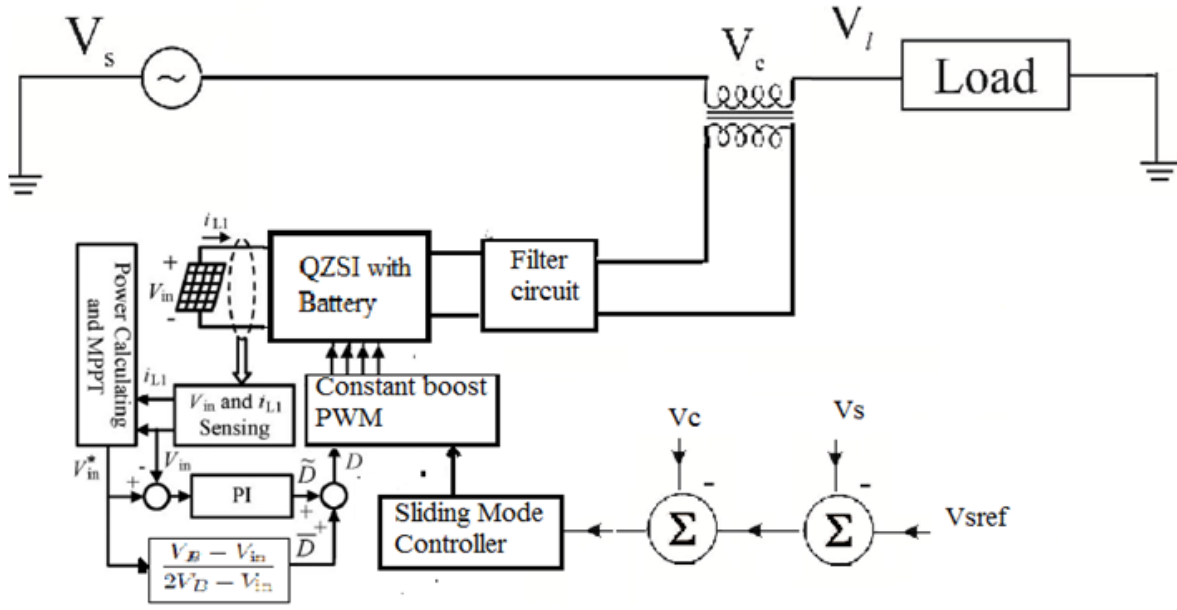


Fig 6. Complete block diagram of the proposed DVR with PV based power conditioning system

ratio  $D$ , the inverter output power can be controlled. A schematic block diagram of the proposed control scheme of the power conditioning system is shown in Fig 6. The PV panel power based control which is adopted here, automatically controls the battery charging as well. From the above equations, it can be deduced that

$$V_{in} = \frac{1-2D}{1-D} V_{C1} \quad (17)$$

$$V_{in} = \frac{1-2D}{1-D} V_B \quad (18)$$

Though the battery voltage changes with the state of charge (SOC) of the battery, it will be relatively constant at certain SOC. Also, the voltage of the PV panel is highly current dependent. Thus, for a given battery voltage greater than both the open-circuit voltage of the PV panel and the inverter's line-to-line output voltage, the voltage  $V_{in}$  of the PV panel can be controlled to track its maximum power point by continuously adjusting the duty cycle  $D$ . Therefore,  $D$  is used to control  $V_{in}$  for working towards the PV panel's maximum power, and

consequently,  $P_{in}$  is controlled. The modulation index  $M$  is used to control the inverter output power  $P_{out}$  and the battery power  $P_B$  as per Equation (1). However, the dc-link peak voltage  $V_{PN}$  is uncontrolled and oscillates with  $V_{in}$ .

If the transpose of the state variable matrix is described as

$$X^T = [x_1, x_2, x_3, x_4] = [V_{C1}, V_{C2}, i_{L1}, i_{L2}] \quad (19)$$

From the above equations involving state variables we can write,

$$C\dot{x}_2 = (1-2d)x_3 + (1-D)i_B + (D-1)i_o \quad (20)$$

$$L\dot{x}_3 = (2D-1)x_2 + DV_{in} \quad (21)$$

Assuming that there are small variations of all variables around their equilibrium states, such as

$$\dot{x}_2 = \bar{x}_2 + \tilde{x}_2, \dot{x}_3 = \bar{x}_3 + \tilde{x}_3, D = \bar{D} + \tilde{D} \text{ etc.}$$

where the symbols “-” and “~” above the variables denote their equilibrium states and small variations, respectively. As a result, the small-signal model will be

$$\begin{aligned} C\dot{\tilde{x}}_2 &= (1-2\bar{D})\tilde{x}_2 + (\tilde{i}_d - \tilde{i}_B - 2\tilde{x}_3)\bar{D} + (1-\bar{D})\tilde{i}_B + (\bar{D}-1)\tilde{i}_d \\ L\dot{\tilde{x}}_3 &= (2\bar{D}-1)\tilde{x}_2 + (2\bar{x}_2 + \bar{V}_{in})\bar{D} + \bar{D}\tilde{V}_{in} \end{aligned} \quad (22)$$

The small signal variation from the V-I characteristics of the PV panel gives the relation

$$V_{in} = -R \cdot \tilde{x}_3 \quad (23)$$

where R is a fictitious nonlinear resistance.

the small-signal-based transfer function between the the PV panel voltage and the shoot-through duty cycle is by

$$G_0(s) = \frac{\tilde{V}_{in}}{\tilde{D}} = -R \frac{C(2\bar{x}_2 + \bar{V}_{in})s + (1-2\bar{D})(2\bar{x}_2 + \bar{i}_B - i_0)}{LCs^2 + CR\bar{D}s + (1-2\bar{D})^2} \quad (24)$$

$$\tilde{D} = k_p \tilde{e} + k_i \int \tilde{e} dt, \text{ where } e = \tilde{V}_{in}^* - \tilde{V}_{in}$$

The proportional–integral (PI) regulator is employed in the PV voltage closed-loop control to find the desired variation of shoot-through duty cycle for a PV voltage reference variation by

$$G_{PI}(s) = \frac{\tilde{D}}{\tilde{E}} = \frac{k_p s + k_i}{s} \quad (25)$$

The steady state duty ratio  $\bar{D}$  is given by

$$\bar{D} = \frac{V_B - V_{in}}{2V_B - V_{in}} \quad (26)$$

The duty ratio D is derived from the above two relationships. The complete control block diagram of the entire set up with the PV panel power and MPPT controller is given in Fig 6. In the PV panel based control system, the panel voltage  $V_{in}$  and panel output current  $i_L$  is sensed to calculate the actual PV power and this is used to track the desired PV panel voltage  $V_{in}^*$  using the MPPT algorithm as given in Fig 4. In the system under study,  $L=400\mu\text{H}$ ,  $C=500\mu\text{F}$ , the PV panel voltage  $V_{in} = 66\text{V}$ , the DC link voltage of the inverter  $280\text{V}$ , and  $R=0.37$ . As per the equation (25), the PI controller was tuned with  $k_p = -0.0015$  and  $K_i = -1.05$ . The bode plots of  $G_0(s)$ ,  $G_{PI}(s)$ , and  $G_0(s) \cdot G_{PI}(s)$  are shown in curves 1, 2, and 3 of Fig 7. The gain margin and phase margin show that the open loop system is stable. The bode plots of the closed loop transfer function of the PV controller based on small signal analysis shown in Fig 8 also indicate the stability of the model.

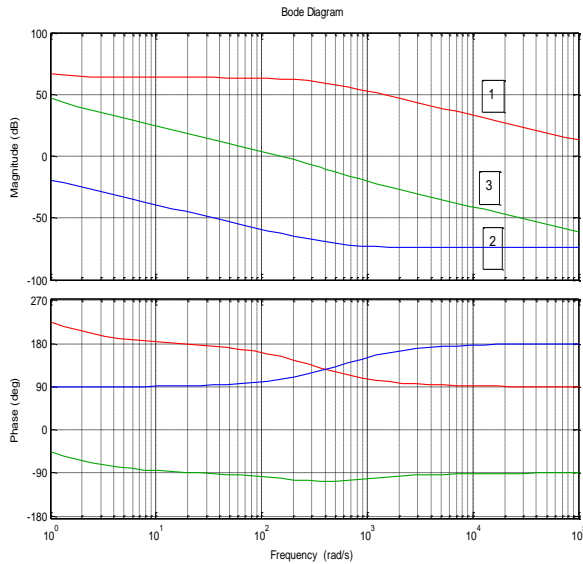


Fig 7. Bode plots of open loop system

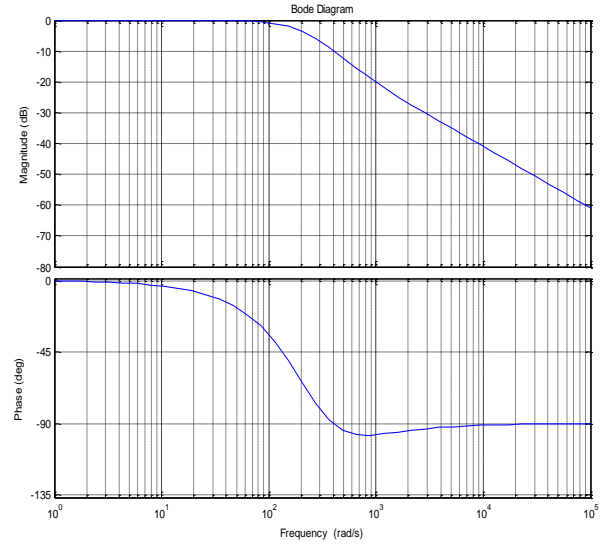


Fig 8. Bode plots of closed loop system



#### 2.4 Sliding mode control scheme of the DVR

The control scheme of the proposed DVR consists of a PV panel voltage control along with sliding mode controller to inject appropriate voltage to the line in the event of a voltage disturbance. Feed forward control uses the steady state shoot through ratio given by (25) to speed up the response in practical systems. A P&O based MPPT scheme tracks the demand power of the PV panel on calculating the actual PV panel power, and maintains a steady output voltage. The sliding mode controller receives a reference voltage signal and the actual injected voltage of the DVR to generate the modulating signal of the PWM controller of the Quasi Z source inverter.

The reference voltage to be injected by the DVR is obtained by subtracting the reference source voltage and actual source voltage. Using a phase locked loop (PLL) a sine template is generated, which is then multiplied with the peak of the supply reference voltage to obtain the reference supply voltage. The actual DVR injected voltage is then subtracted from the reference DVR voltage to obtain the error signal, and then processed by the sliding mode controller. The output of the sliding mode controller is the reference signal for the PWM generator of the inverter. Simple boost modulation technique is combined with the triangular carrier PWM technique to obtain the pulse trains for the QZSI to enable the shoot through stages. This enables the inverter to operate in boost mode also, thus providing compensation for voltage sags with a reduced dc source.

### 3. Simulation results and discussion

Entire system with PV panel, MPPT controller, QZSI with the sliding mode controller of the DVR is simulated in MATLAB SIMULINK environment. The system parameters used for the simulation of the proposed DVR is given in Table 2. A 230V distribution system supplying power to a predominantly resistive load was chosen as the part of the network in need of compensation. A 1.5 kVA transformer acts as the injection transformer, whose secondary windings are connected in series with the line, closer to the load end.

Table 2. System parameters for the simulation study of the proposed DVR

Source Voltage	230V	
Frequency	50 Hz	
Injection transformer	1:1, 1.5kVA	
Load	500W, 0.2 pf	
Inverter switching frequency	10kHz	
Quasi Z source impedance	L	500 $\mu$ H
	C	500 $\mu$ F
	Battery	320V, 4Ah
Filter	R	0.3 $\Omega$
	L	12mH
	C	80 $\mu$ F

Simulation tests are conducted to determine the ability of the proposed DVR to mitigate voltage sags and swells under different operating conditions of the PV panel. Three different climatic conditions of the PV panel are considered for analysis. In case I, The PV panel temperature is held constant at 30°C throughout the simulation time. The solar irradiation is changed from 850W/m<sup>2</sup> to 650W/m<sup>2</sup> at 0.15 sec as shown in Fig 9. The resultant changes in the PV panel output power, output current and voltage  $V_{in}$  are shown in Fig 10. It shows that the MPPT system effectively regulates the PV voltage in the event of climatic variations and load demands. Fig 11 shows the DC link voltage of the QZSI along with the panel voltage, voltage across the capacitor  $C_2$  and the battery voltage. Fig 12 shows the voltage disturbances in the line and the subsequent mitigation of that with the DVR. The desired load voltage is shown on top, followed with the actual terminal voltage, compensated load voltage, and the DVR injected Voltage. The system is subjected to 30% sag from 0.05 sec to 0.2 sec and again a 70% sag from 0.25sec to 0.35sec. It can be seen that even under fluctuating climatic conditions, the PV panel along with the stored energy of the inverter, the DC link voltage of the inverter is maintained almost constant. This enables the DVR to mitigate voltage sags of varying depths efficiently. The harmonic content of the load voltage shown in Fig 13 indicates the quality of the injected voltage. This shows the ability of the PV power conditioning system and the sliding

mode controller to support the DVR in mitigating voltage disturbances.

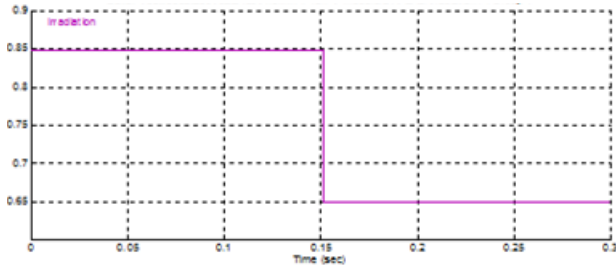


Fig 9. Changes in irradiation at constant temperature

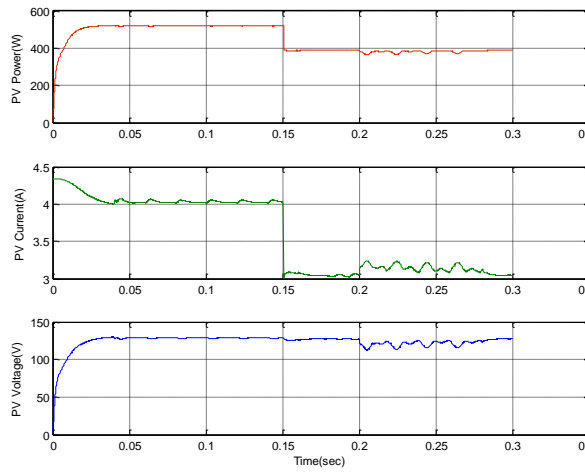


Fig 10. Changes in PV output power, current and voltage

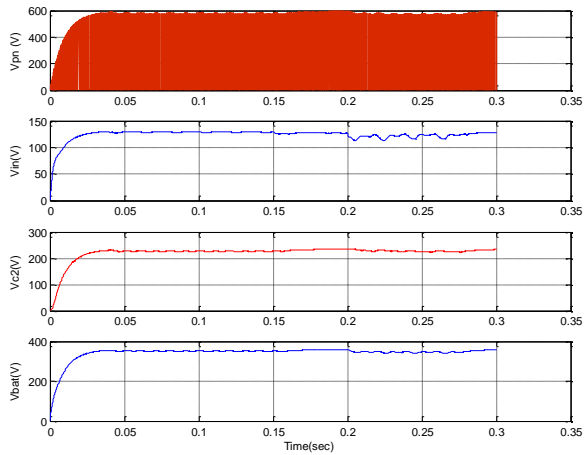


Fig 11. Inverter voltage  $V_{PN}$ , PV panel voltage  $V_{in}$ , Capacitor voltage  $V_{c2}$  and Battery voltage  $V_{bat}$

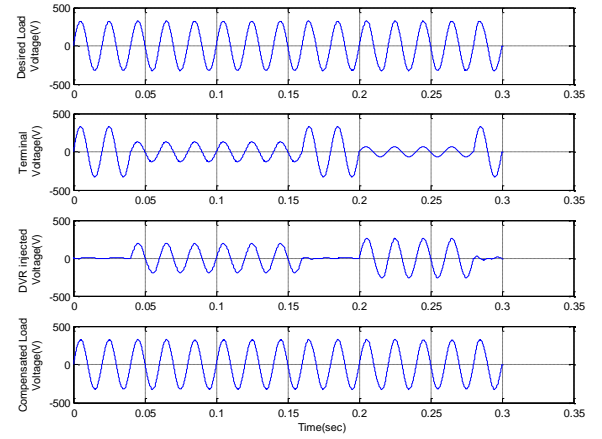


Fig 12. Simulation results for voltage sag conditions 60% and 80%

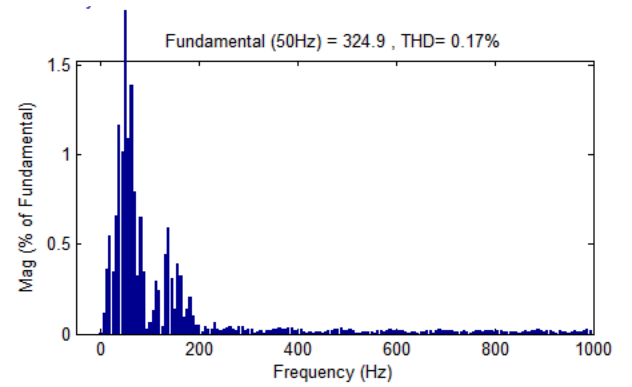


Fig 13. THD profile of the load voltage

In case II, The PV panel irradiation was held constant at  $800\text{W/m}^2$  throughout the simulation time. The cell temperature was changed at .15 sec from  $30^\circ\text{C}$  to  $35^\circ\text{C}$  as shown in Fig 14. This causes a reduction in panel output power. The resultant changes in the PV panel output power, output current and voltage  $V_{in}$  are shown in Fig 15. This again proves the efficiency of the MPPT system in effectively regulating the PV voltage in the event of climatic variations and load demands. Fig 16 shows the DC link voltage of the quasi Z source inverter along with the panel voltage, voltage across the capacitor  $C_2$  and the battery voltage. Fig 17 shows the voltage disturbances in the line and the subsequent mitigation of that with the DVR. The desired load voltage is shown on top, followed with the actual terminal voltage, compensated load voltage, and the DVR injected Voltage. The system was subjected to 60% sag from 0.05 Sec to 0.15 Sec and a 40% voltage swell from 0.2Sec to 0.28Sec. During voltage swells, the DVR injects a voltage in phase opposition. Here again it can be seen that even under fluctuating climatic conditions, the PV panel along with the stored energy of



the inverter, the DC link voltage of the inverter is maintained almost constant. This enables the DVR to mitigate voltage sags and swells of varying depths efficiently. The harmonic content of the load voltage shown in Fig 18 indicates the quality of the injected voltage.

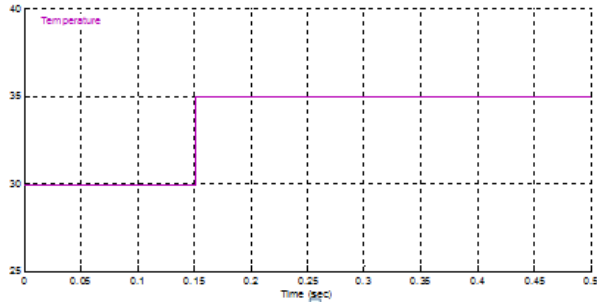


Fig 14. Variation in temperature of the PV panel

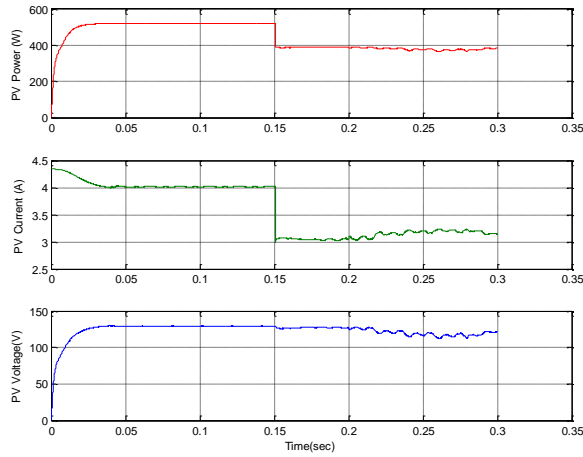


Fig. 15. Changes in PV output power, current and voltage

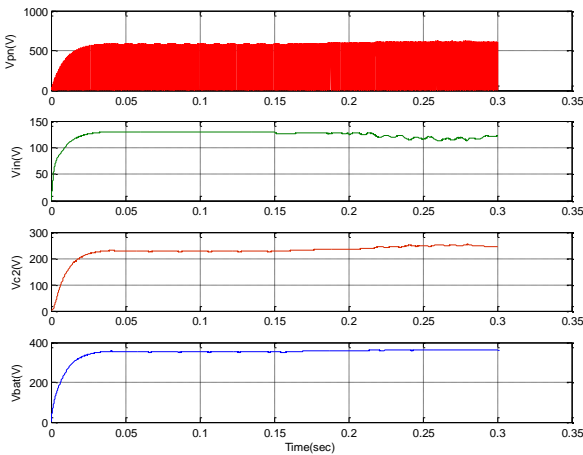


Fig 16. Inverter voltage  $V_{PN}$ , PV panel voltage  $V_{in}$ , Capacitor voltage  $V_{c2}$  and Battery voltage  $V_{bat}$

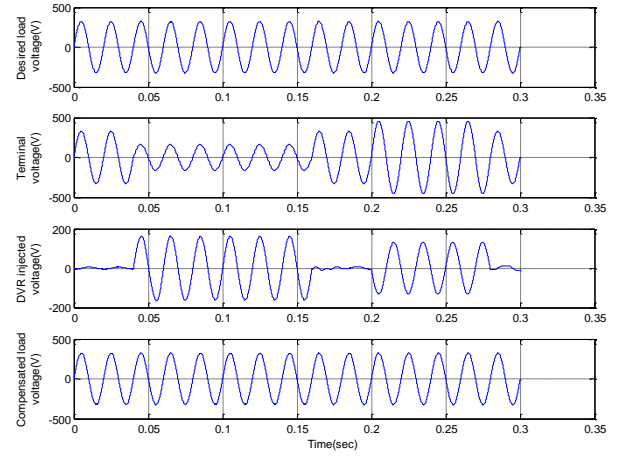


Fig 17. THD profile of the load voltage

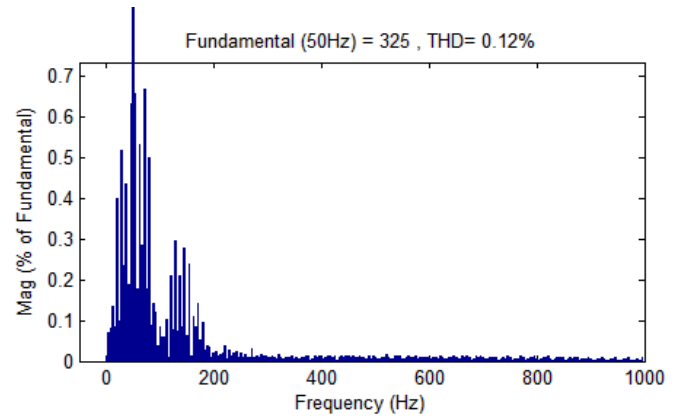


Fig. 18. THD profile of the load voltage

In case III, The PV panel irradiation was held constant at  $850\text{W/m}^2$  till 0.15sec, then reduced to  $650\text{W/m}^2$  till 0.3sec and subsequently raised to  $750\text{W/m}^2$  till the end of simulation as shown in Fig 19. The cell temperature was changed at 0.1 Sec from  $27^\circ\text{C}$  to  $33^\circ\text{C}$  as shown in Fig 14. These changes in atmospheric conditions cause a reduction in panel output power. The resultant changes in the PV panel output power, output current and voltage  $V_{in}$  are shown in Fig 21. This again proves the efficiency of the MPPT system in effectively regulating the PV voltage in the event of climatic variations and load demands. Fig 22 shows the DC link voltage of the quasi Z source inverter along with the panel voltage, voltage across the capacitor  $C_2$  and the battery voltage. Fig 23 shows the voltage disturbances in the line and the subsequent mitigation of that with the DVR. The desired load voltage is shown on top, followed with the actual terminal voltage, compensated load voltage, and the DVR injected Voltage. The

system was subjected to 30% sag from 0.05 sec to 0.15 sec and a 70% voltage sag from 0.2sec to 0.28sec. Here again it can be seen that even under fluctuating climatic conditions, the PV panel along with the stored energy of the inverter, the DC link voltage of the inverter is maintained almost constant. This enables the DVR to mitigate voltage sags and swells of varying depths efficiently. The harmonic content of the load voltage shown in Fig 24 indicates the quality of the injected voltage.

For the same climatic conditions as discussed for case III, the supply voltage disturbances were changed. The panel output quantities shown in Fig 25 and the dc link voltage, panel voltage, capacitor and battery voltages are shown in Fig 26. The system was subjected to 60% sag from 0.04 sec to 0.16 sec and a 40% voltage swell from 0.2sec to 0.28sec as given in Fig 27. It shows that the designed DVR power conditioning system is capable to efficiently support the distribution system, despite the atmospheric conditions affecting the PV panel power output. The THD profile shown in Fig 28 indicates the high quality of the injected voltage of the DVR.

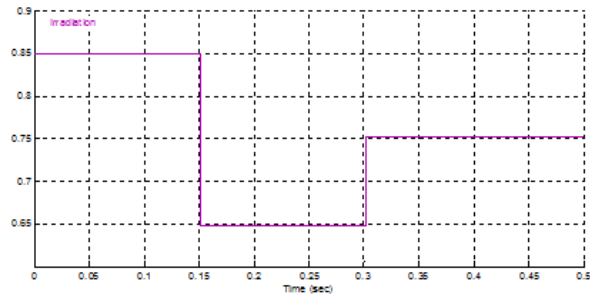


Fig 19. Changes in irradiation of the PV panel

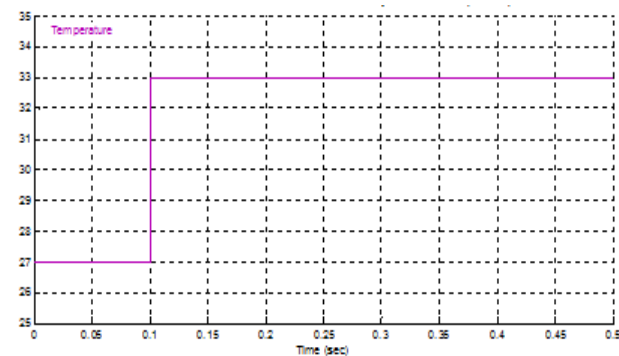


Fig 20. Variation in temperature of the PV panel

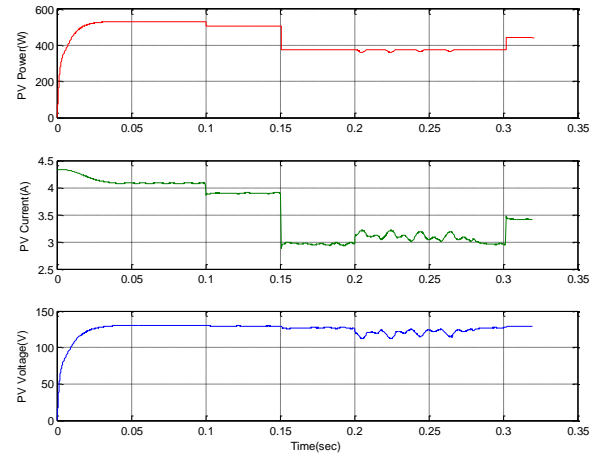


Fig 21. Changes in PV output power, current and voltage

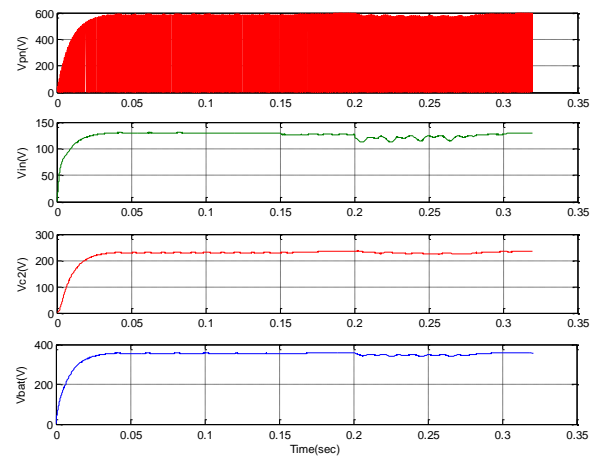


Fig 22. Inverter voltage  $V_{PN}$ , PV panel voltage  $V_{in}$ , Capacitor voltage  $V_{c2}$  and Battery voltage  $V_{bat}$

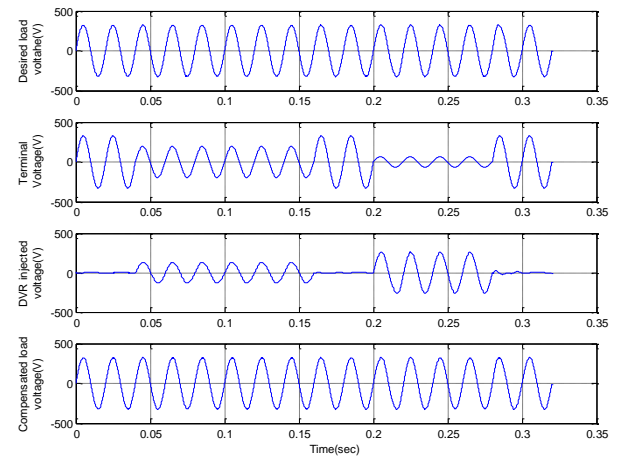


Fig 23. Simulation results for voltage sag and swell conditions

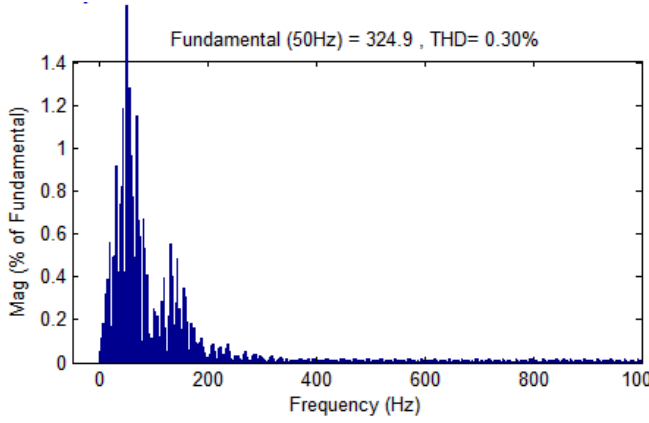


Fig 24. THD profile of the load voltage

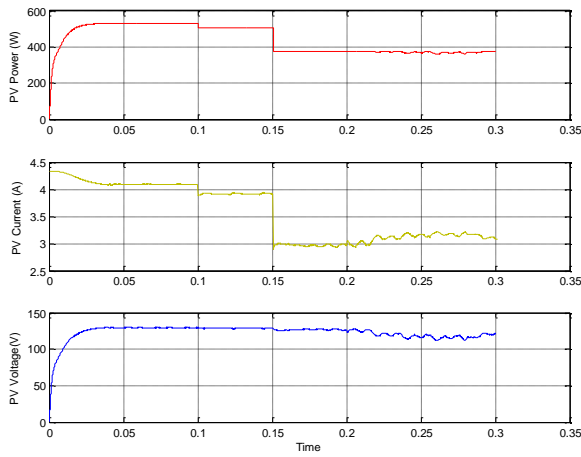


Fig 25. Changes in PV output power, current and voltage

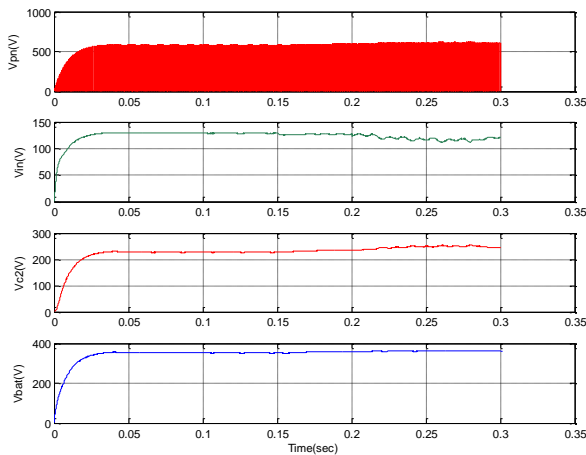


Fig 26. Inverter voltage  $V_{PN}$ , PV panel voltage  $V_{in}$ , Capacitor voltage  $V_{c2}$  and Battery voltage  $V_{bat}$

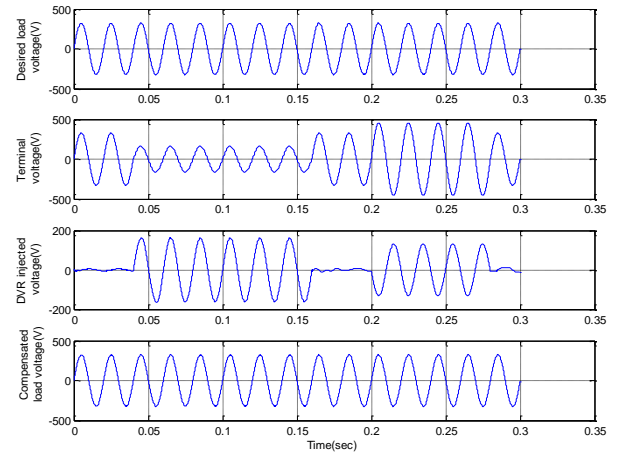


Fig 27. Simulation results for voltage sag and swell conditions

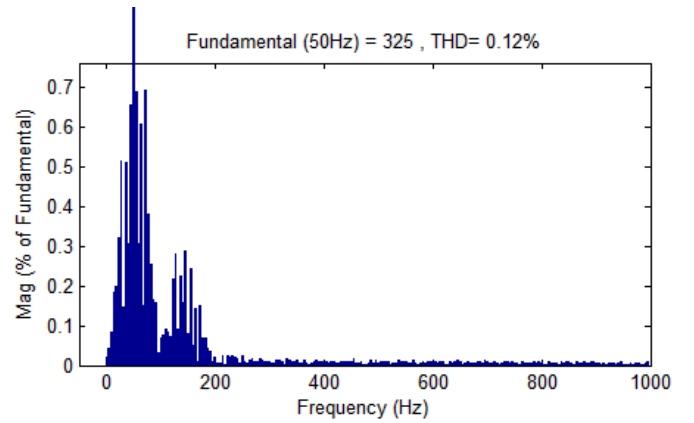


Fig 28. THD profile of the load voltage

#### 4. Conclusions

This paper describes the design, analysis and simulation of a PV based, single stage power conditioning system for a single phase DVR. The PV based power conditioning system of the DVR employs energy stored Quasi Z Source Inverter (QZSI) to achieve the voltage boost, inversion, and energy storage in single-stage. The designed control system controls the inverter output power, track the PV panel's maximum power point, and manage the battery power, simultaneously. The performance of the proposed system is excellent and it involves less switching circuits compared to the systems described in the literature. Test conditions were developed to mimic various climatic conditions and supply side disturbances. Detailed simulation studies show that the designed power conditioning system offers excellent support to the performance of the DVR under different operating conditions. The compensating capability of the DVR is found to be highly

effective. The stability of the power conditioning system was studied and found satisfactory. The DVR's compensation strategy is achieved by a sliding mode controller which ensures a robust control under any supply side disturbances and parameter variations. Thus the paper presents an effective PV based solution to meet the stored energy requirements of a DVR to compensate for various voltage disturbances.

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