Power Quality Enhancement in Distribution System with Solar Powered Three Phase Inverter Based DVR

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Abstract
The use of non-linear loads, heavy load switching, and line failures have all contributed to an explosion in power quality problems. Three phase bridge inverter that acts as a dynamic voltage restorer is fed by a solar-powered DC-DC converter. The distribution system and DVR are in synchronism. The use of DVRhas resolved the power quality issue. By injecting the compensating voltage from the alternate source into the main distribution system, the DVR recovers the sag voltage. This suggested system uses the Perturb and Observe algorithm to maximise the power output from the solar panels. MATLAB /Simulink is used to model and simulate the entire system. The outcomes are acquired and shown. The analysis of results that anytime sag occurs in the suggested system, it dynamically performs better.

Keywords: Dynamic Voltage Restorer, Power quality, Sag, Solar Photovoltaics, Boost Converter, Three phase inverter

1.Introduction

The need for improved power quality in distribution networks is demonstrated by the growth of the power industry economically and by the high level of customer satisfaction. Maintaining a steady supply is necessary to boost the power system's efficiency. To meet consumer needs, the power supply must be available continuously and without interruption.
The use of non-linear loads such as computers, mobile chargers, variable frequency drives, etc., introduces harmonics into electrical systems in today's advanced modern world. Abrupt switching of high loads and line failures have also contributed to an increase in power quality issues, such as harmonics, voltage sag, and swelling. The system may completely collapse as a result of these power quality disruptions, or sensitive components may malfunction or sustain damage.
Different compensators have been used; a popular device to reduce voltage fluctuations in the distribution system is the Dynamic Voltage Restorer (DVR). The

series compensation technique is used by the solar-powered DVR to introduce voltage into the distribution system.

In recent times, producing electricity with Solar Photovoltaic (SPV) technology has emerged as the most practical choice.

The usage of solar PV for power has increased recently due to the depletion of fossil fuel supplies and growing worries about the environmental effects of using fossil fuels. Power produced by photovoltaic cells is a low-maintenance, clean energy source that produces little noise.

By offering better solutions to power quality issues, the dynamic voltage restorer is a specialised power tool that can help avoid malfunctions with sensitive loads. DVR is a voltage source inverter and is often attached at the utilisation side to maintain the quality of the supply by providing the load with the required voltage. The main purpose of a DVR is to counteract power quality issues like harmonics, outages, and voltage sag/swell. By injecting the voltage on the utility side with the necessary phase angle, amplitude, and frequency, the voltage compensation is achieved.

1.1 A High-Light of the Suggested System

Dynamic Voltage Restorer, an advanced system that incorporates solar energy to power the DVR and combines the benefits of renewable energy with voltage correction technology, is based on a three-phase inverter and is designed to mitigate voltage sags, swells, or interruptions in three phase electrical systems.

This DVR solves voltage-related problems in three-phase networks with a sustainable and eco-friendly method by using solar energy. By introducing regulated voltage to offset irregularities, it improves grid stability and guarantees a more dependable and steady supply of electricity. This creative fusion of DVR technology and solar power is a big step towards effective and environmentally responsible power quality control.

The proposed system's block diagram, which includes a three-phase supply system, solar panel, a step up converter,a three-phase inverter and a rectifier load, is shown in figure 1.1.[1] [5]

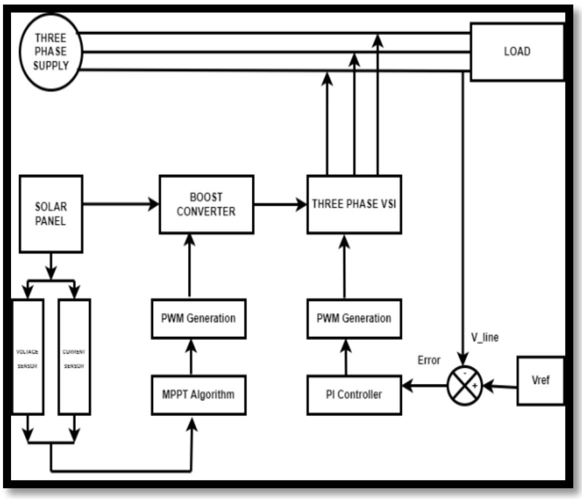

Fig. 1.1 Block diagram of the proposed system

1.1 Working of the Proposed System

The suggested solution operates on the basis of a dynamic voltage restorer powered by solar photovoltaic energy. In a conventional distribution system, the load receives power from the grid. Increased use of non-linear loads, sudden changes in heavy loads, and line failures intensify power quality problems such as voltage swell and sag. Solar photovoltaics is used as a source in the dynamic voltage restorer concept. [6]

Operating point corresponding to maximum power solar panel is traced using the Maximum Power Point Tracking Algorithm (MPPT). As the algorithm runs, the voltage and current from the panel are measured, and the voltage and current conditions are checked. The PI controller receives the conditioned value.The power electronic switch in the boost converter is switched by the controller's output. The boost converter receives the solar power and increases the voltage from the solar panel to the necessary voltage to compensate for voltage sags. [7] [8] [9]

The DC is transformed into AC using a three phase voltage source inverter.The LCL filter creates a sinusoidal output by removing harmonics from the inverter's output.The distribution system and the inverter's AC voltage synchronize at a frequency of 50 Hz. A 1:1 transformer connects the distribution system to the DVR.[2]

To determine the error voltage, the source voltage is compared to the constant three-phase voltage. The control approach processes the incorrect voltage. The inverter's switching sequence is provided by the controller's output. As a result, in the allotted time, the load and line voltage were attained without any power quality issues, or sag[1] [2][5]

2. Power Quality

In the end, power quality is a customer-driven problem, and the end user's perspective is most important. Any power fault exhibited in voltage, current or frequency variations which causes the failure or mis-operation of client equipment.

The viewpoints of the utility and the client frequently diverge significantly. Although both parties often attribute roughly two thirds of the incidents to natural phenomena like lightning, customers believe the utility is to blame far more frequently than utility employees. [10]

2.1 Voltage Sag

A sag is a drop in voltage or current at the power frequency over periods ranging from 0.5 cycle to 1 minute, with a magnitude between 0.1 and 0.9 pu. Although large motors or heavy loads can also create voltage sags, system breakdowns are typically the source of them.

The three categories of sag durations—instantaneous, momentary, and temporary—correspond to the three types of swells and interruptions. These durations are meant to match both the period divisions suggested by international technical organizations and the usual utility protective device operation times. [12]

2.2 Dynamic Voltage Restorer

A device called a dynamic voltage restorer can be used in distribution networks to rectify small voltage reductions by injecting three-phase voltage in series and synchronism with the distribution feeder voltages.
[11] [14] [15]

When end consumers are experiencing unintentional brief disruptions in their power quality, DVRs may be a suitable solution. Conversely, they should not be used in systems that are susceptible to voltage breakdown or that experience continuous reactive power shortages. In fact, because DVRs maintain the proper supply voltage in these systems, they can potentially cause cascading interruptions and make collapses harder to prevent.

Dynamic voltage restorers are complex static devices that add the "missing" voltage to offset voltage dips. This basically means that the voltage is raised to the required level by the device by injecting electricity into the system. A transformer linked in series with the load and a switching system work together to inject voltage. DVRs come in two varieties: those with and without energy storage.

2.3 Compensation Mode

The DVR detects the voltage sag, and compensation is applied for the three phase load based on the type of voltage disturbances. To lessen the disturbances, the injection transformers are used to inject the three-phase compensation voltages in series.The voltage is expressed in equation 2.1

$$V_L = V_S + V_{DVR} \qquad (2.1)$$

Where V_L,V_S andV_{DVR} are the voltages at load, supply and DVR respectively.
The figure 2.1 represents the vector diagram of the DVR. Thus after the occurance of voltage sag, the load voltage is the vector sum of the supply voltage and the DVR voltage.1]

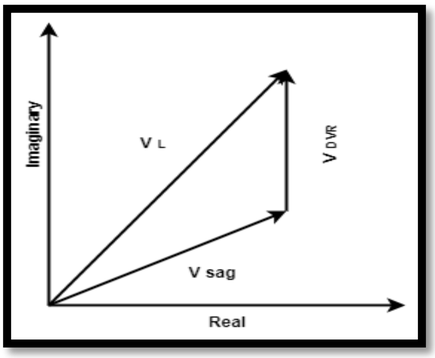

Fig. 2.1 Vector diagram of DVR

3. Design Aspects

The Figure 3.1 portrays the circuit diagram of the proposed system. It consists of solar array, step up chopper, three phase inverter and non linear load. This is modelled in MATLAB / Simulink and simulated.

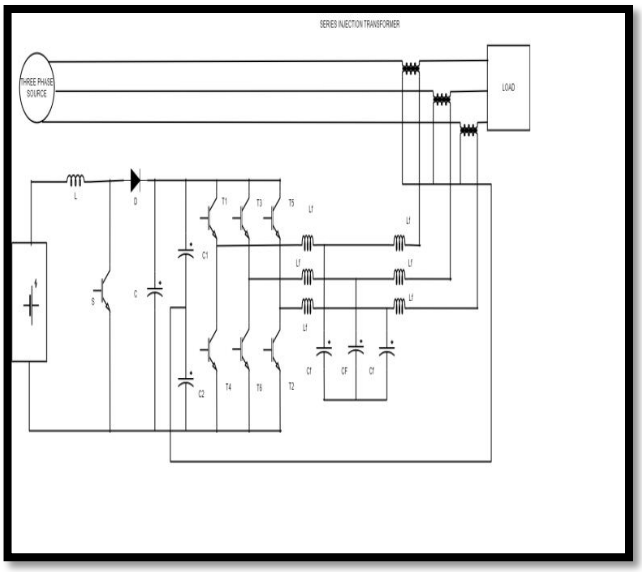

Fig 3.1 Circuit diagram of the proposed system

3.1 Design of Panel

The DVR is powered by solar photovoltaicssystem . The panel ratings used for the proposed system is with open circuit voltage V_{OC} of 36.3 V and short circuit current I_{SC} of 7.84 A and maximum power of 213 W. By connecting the solar cells in series and parallel, one can achieve higher power using low power solar cells. A total of ten modules are connected in cascade to achieve a panel voltage of 300 volts.[7] [8]

The Figure 3.2 shows the I-V characteristics of the solar array used in the proposed system. The plot is obtained for various irradiations i.e 100, 500,1000 W/m² with constant temperature of 25°C

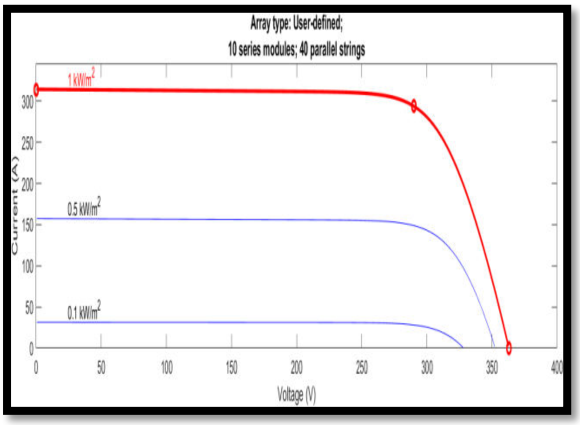

Fig.3.2 I-V characteristics

The PV curves of the solar array are obtained for different irradiation level of 100, 500 and 1000 W/m² with constant temperature of 25° C

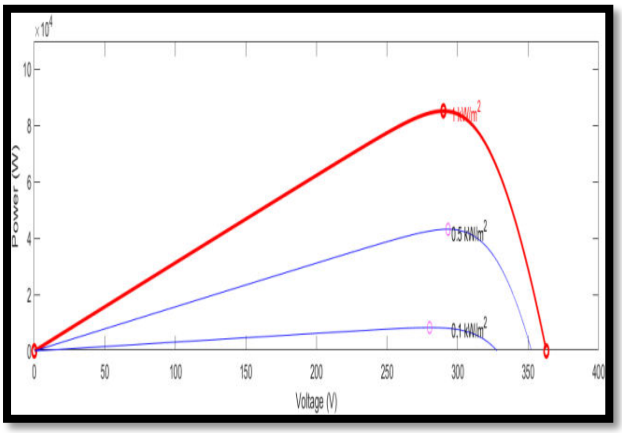

Fig. 3.3 P-V characteristics

The Figure 3.4 shows the voltage obtained from the panel.

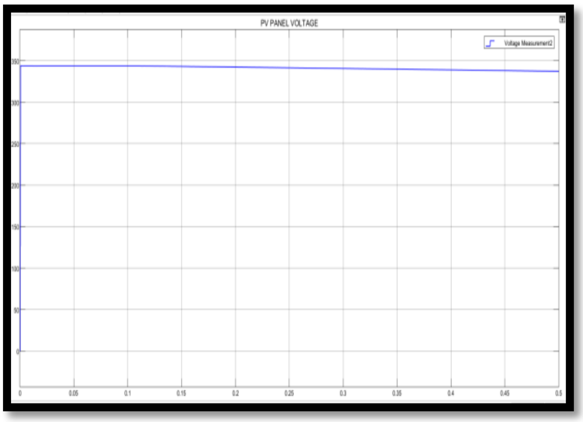

Fig. 3.4 PV panel voltage

3.2 Design of MPPT Algorithm

The idea behind MPPT is to force PV modules to run at the voltage that corresponds to their maximum power in order to extract as much power as possible from them. Under all circumstances, the maximum power point technique is employed to optimize the power extracted from solar panels. It examines the output of the PV module, compares it to the reference voltage, and then determines the optimal voltage for the module. Two main issues with PV power generation are the expensive cost of PV cells and the low efficiency of electric power conversion. PV system generation is weather-dependent, therefore conversion efficiency ranges from 9 to 16%. Although the maximum power point is unknown and fluctuates constantly, search techniques and calculation models can be used to find it. Therefore, the primary purpose of MPPT approaches is to keep the solar array operating at its maximum power point.
For the suggested system in the Simulink platform, the Perturb and Observe Algorithm is utilized to maximize the power obtained from the solar panel. The flow chart of the perturb and observe algorithm, which is used to switch the DC-DC converter so that the solar panel's maximum power is extracted under all working conditions, is shown in figure 3.5.[7] [8]

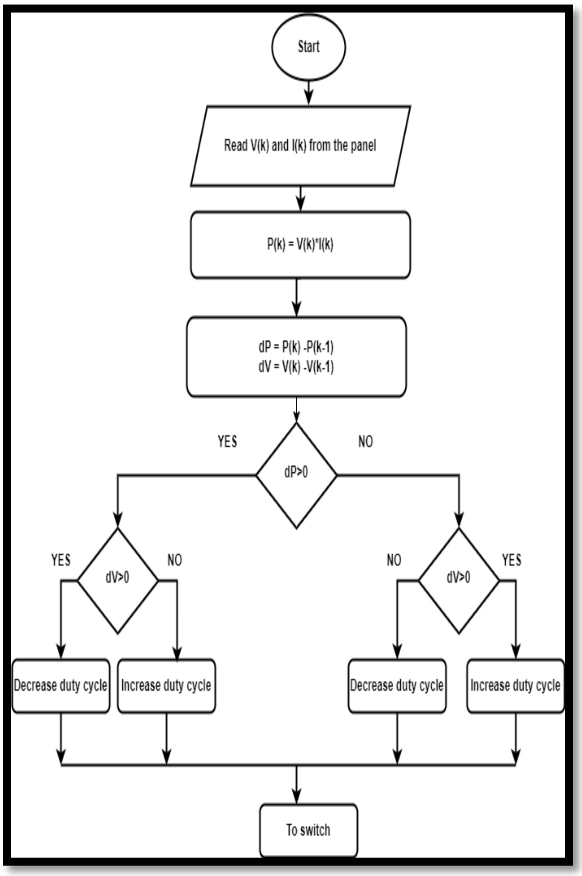

Fig. 3.5 Flow chart of P&O algorithm

The figure 3.6 shows the simulink model of the P&O algorithm.

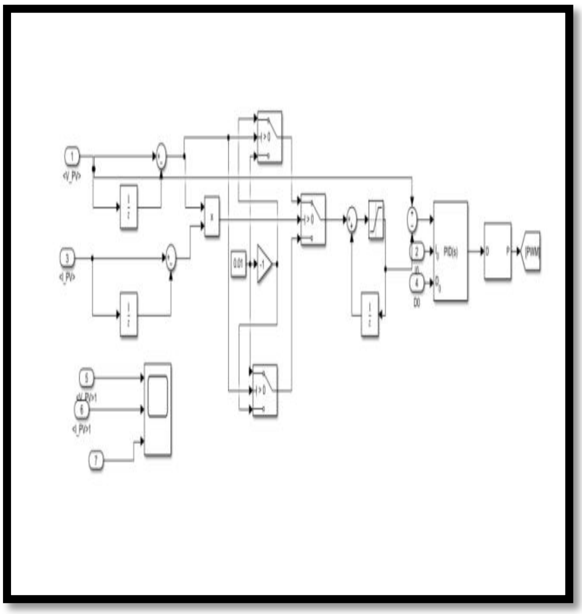

Fig. 3.6 Simulink model of P & O algorithm

3.3 Design of Boost Converter

A boost converter using a IGBT switch is shown in figure 3.7.

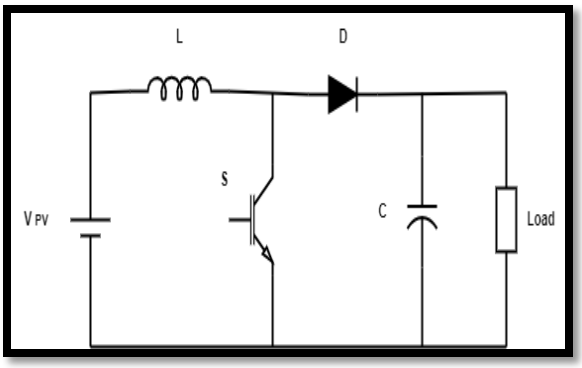

Fig. 3.7 Power circuit of boost converter

A DC-DC converter receives optimized power from the panel. The boost converter receives panel voltage around 300 V and boosts it to 600 V at a fifty percent duty cycle.

By applying the volt-second balance rule to the inductor, the input-output relationship is given by equation 3.1

$$V_0 = \frac{V_i}{1-D} \qquad (3.1)$$

The duty ratio D, can take on values between the closed interval 0 and 1. Thus the output voltage V_0 is always greater than input voltage V_i .To obtain the input-output relationship it is assumed 100% efficiency constraint. Hence the expression given in equation 3.2 is obtained.

$$V_i I_{in} = V_0 I_0 \qquad (3.2)$$

The value of the inductor L on the basis of 10% of current ripple is obtained from equation 3.4

$$\Delta i_L = 10\% \text{ of } I_{in} \qquad (3.3)$$

$$L = \frac{V_i D}{\Delta i_L f_s} \qquad (3.4)$$

Where, f_s : switching frequency ;
Δi_L : ripple current

The value of the capacitor by applying amp-second rule is obtained from equation 3.5

$$C = \frac{I_0 D}{\Delta V_0 f_s} \qquad (3.5)$$

Where, I_0 : Output current;

ΔV_0: Ripple voltage

The Figure 3.8 shows the output voltage obtained from the boost converter for the designed duty cycle. The 300 volts obtained from the solar panel is boosted to 600 volts using a boost converter.

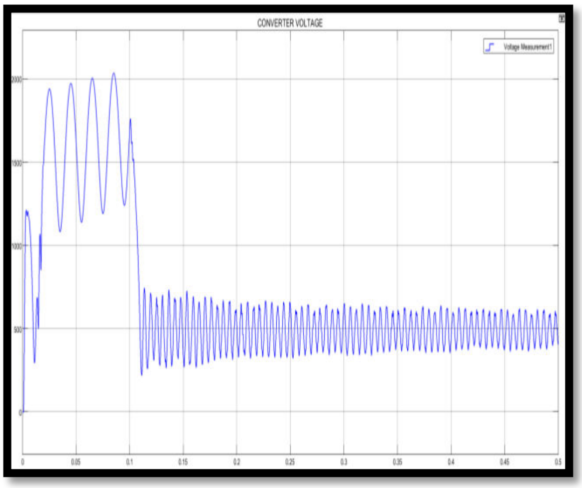

Fig. 3.8 Output voltage of boost converter

Table 3.1 shows the simulation parameters used for the DC-DC converter.

Table 3.1 Specification of the boost converter

Parameters	**Specification**
Input voltage	300V
Switching frequency	20kHz
Inductor	250mH
Capacitor	500μF
Output voltage	600V

3.4 Design of 3-ϕ Inverter

The voltage source inverter depicted in figure 3.9 transforms the DC voltage into three phase AC voltages to match the grid voltage and frequency,

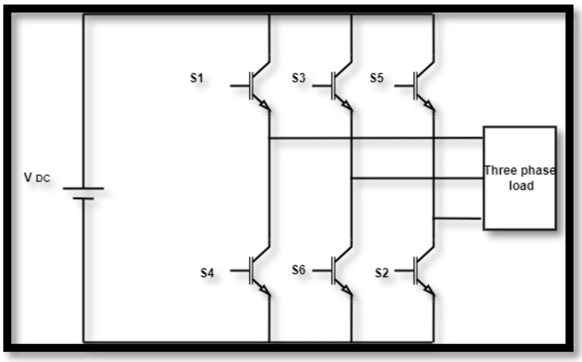

Fig. 3.9 Power circuit of three phase VSI

The IGBT switches are used for designing the three phase inverter. Table 3.2 shows design consideration used in simulation of the three phase inverter.

Table 3.2 Inverter specification

Parameters	**Specification**
DC bus voltage	600 V
Switching frequency	10kHz
KVA rating	100KVA
Output line voltage	415 V rms

Figure 3.10 shows the inverter voltage waveform without LCL filter. Thus the plot is measured before the use of filter in the proposed circuit. It is inferred that ripples are present in the output voltage.

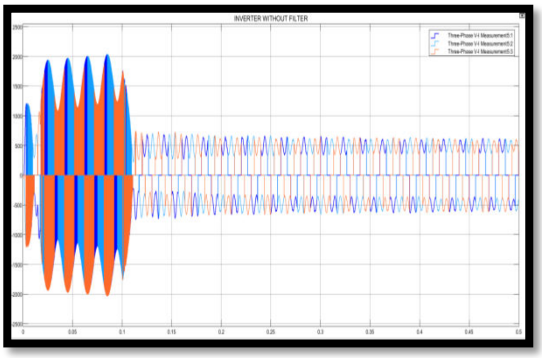

Fig. 3.10 Inverter output voltage without filter

Figure 3.11 shows the harmonic profile of the inverter without filter. It is observed that THD is 36.27% .

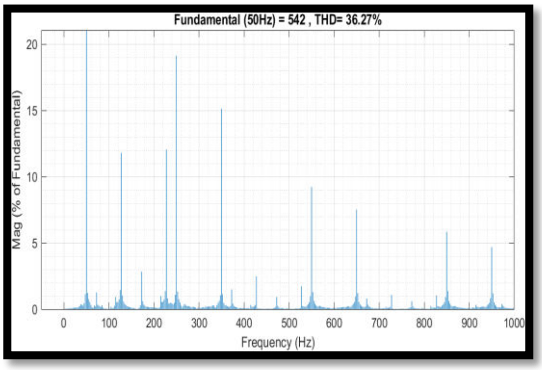

Fig. 3.11 Harmonic profile of the inverter

3.5 Design of LCL Filter

The LCL filter has been chosen for the proposed system.The capacitance value in the filter is designed based on the assumption that reactive power injected to the line is 5% of the real power as given in equation 3.6.

$$Q = \frac{V^2}{1/_{2\pi fC}} = 5\% \text{ of } S \quad (3.6)$$

Where, Q : reactive power ;
S : real power
V : peak to peak voltage of inverter ;
f : switching frequency

The filter inductor value is designed using the equations 3.7 and 3.8.

$$\Delta i_L = \frac{0.1 * S * \sqrt{2}}{3V_{ph}} \quad (3.7)$$

$$L = \frac{V}{8 * f_{sw} * \Delta i_L} \quad (3.8)$$

Table 3.3 shows the filter specification used in the simulation to reduce the ripple obtained in the output of the three phase inverter.

Table 3.3 Filter specification

Parameters	**Specification**
Filter inductance	500μH
Filter capacitance	100.25μF

Figure 3.12 shows the inverter voltage waveform with LCL filter. The plot is measured after the use of filter in the proposed circuit and which has minimum ripples.

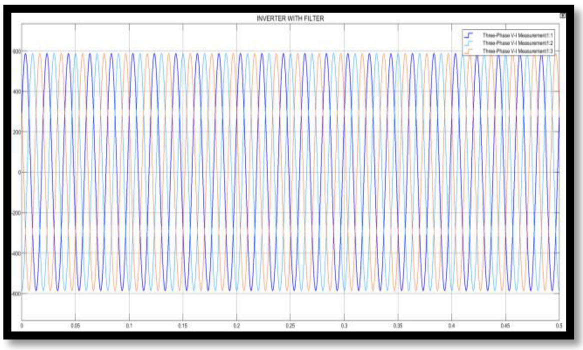

Fig 3.12 Inverter output voltage with filter

3.6 Control Technique

The control technique is capable of reducing total harmonic distortion. In dq control algorithm the three phase voltages V_A ,V_B, $V_C$are transformed into two phase alpha beta voltages V_α,$V_\beta$using park's transformation.The phase locked loop is implemented by using the alpha beta voltages V_α,V_β. The alpha beta voltages are transformed into dq voltages V_d, V_q using the clark's transformation. The inverter side current is measured for the implement of current controller.

The three phase currents I_A ,I_B, I_C are transformed into alpha beta currents I_α, I_β using park's transformation and then to dq frame I_d , I_q using clark's transformation. The error value is evaluated by comparing with the reference current. The output value is processed by the PI controller.

PI controller gives the output in the form of dq frame. Equations 3.9 and 3.10 provide the relationship between the modulation index and the inverter voltage for sine pulse width modulation.

$$V_d = m_d \frac{V_{dc}}{2} \quad (3.9)$$

$$V_q = m_q \frac{V_{dc}}{2} \quad (3.10)$$

Then by using the inverse Clark transformation and inverse park transformation dq reference frame V_d, V_q transformed into abc frame V_A ,V_B, V_C. Thus the PWM signals are given to the switches used in the three phase inverter. The K_p, K_i values are shown in Table 3.4

Table 3.4 Controller specification

Parameters	Specification
Proportional constant K_p	5
Integral constant K_i	5000

Tuning of Proportional-Integral (PI) controller in MATLAB Simulink has been carried out manually based on understanding the system behaviour. Proportionality Gain directly influences the response to the current error. Integral gain helps reduce steady-state errors and contributes when the error persists.

These gains are adjusted by running simulations to observe and refine the controller's behaviour until it meets desired performance criteria.

4. Simulink Models

The Simulink model of the proposed system is shown in figure 4.1. The simulation is done in MATLAB 2021A version with ode45 solver. The discrete powergui with time constant of $1e^{-7}$ is used to run the simulation and visualize the results.

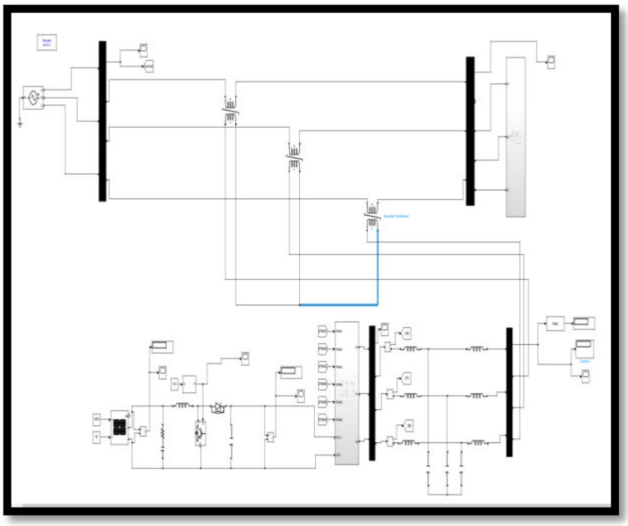

Fig. 4.1 Model of the suggested system in Simulink

4.1 Simulation Results With DVR

The Figure 4.2 portrays the compensation of voltage with DVR. The plot contains the source voltage with 20% sag, the error voltage to be injected is 126 V and the line voltage after connecting the DVR is 415 V rms. It is inferred the DVR voltage compensates the voltage sag and same voltage is maintained in the required level.

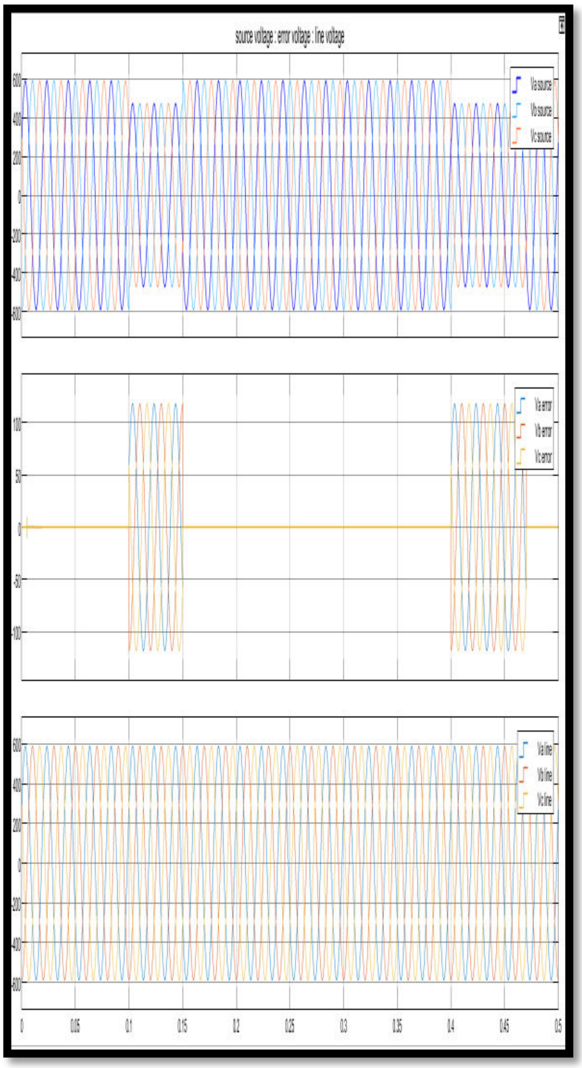

Fig. 4.2 DVR performance with 20% sag

The Figure 4.3 portrays the source voltage with 30% sag from the time instance 0.1 to 0.15 and 10% sag from the time instance 0.4 to 0.47, the error voltage to be injected varies according to the sag voltage and the line voltage after connecting the DVR is maintained as 415 volts.

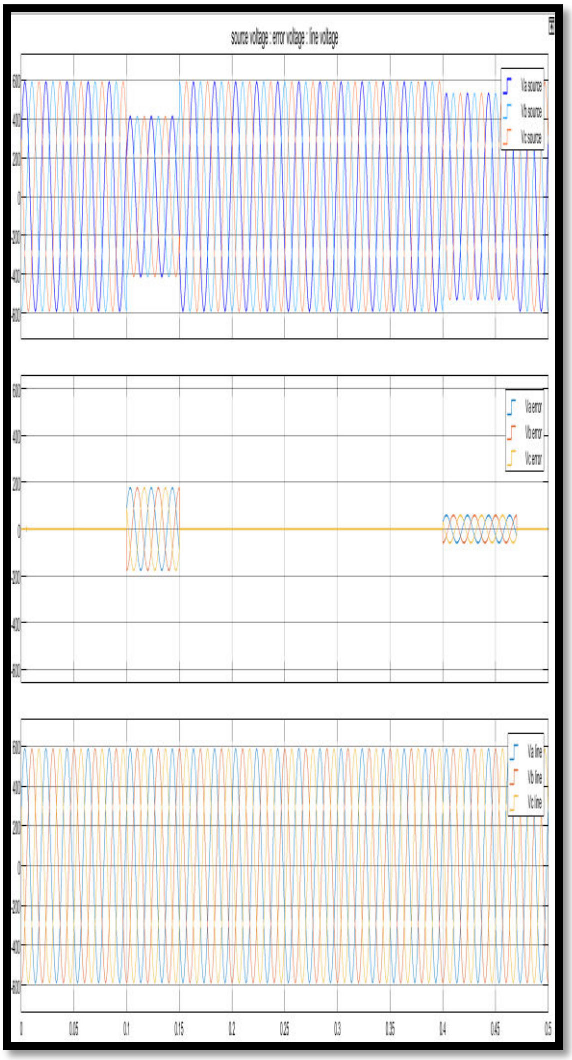

Fig. 4.3 DVR performance with 30% and 10% sag

Table 4.1 shows the dynamic voltage performance with different sag magnitude at different time instance.

Table 4.1 DVR performance

Sag magnitude (pu)	**Sag instance (time)**	**Compensating voltage (volts)**	**THD**
0.1	0.4 0.47	58.6	3.01%
0.2	0.1	117.2	6.18%

	0.15		
	0.4	117.2	6.18%
	0.47		
0.3	0.1	175.8	9.52 %
	0.15		

4.2 Analysis of Load Waveform

The source voltage waveform with sag is depicted in Figure 4.4. The load voltage without DVR is displayed in figure 4.5. The load voltage with the DVR is displayed in figure 4.6.

The performance of the connected load will be impacted by the distribution system's voltage sag. Additionally, it results in dissatisfied customers. Therefore, the DVR enters the picture to enhance the load profile and provide the user with distortion-free power.

The sag voltage in the suggested system happened between time instants 0.1 and 0.15 and 0.4 and 0.47. The sag voltage has a magnitude of 126 volts. The Dynamic Voltage Restorer, which runs on solar power, is made to maintain the load profile while injecting lower voltage.

The Figure 4.7 shows the source voltage waveform with sag. The load voltage without DVR is given in figure 4.8. The figure 4.9 shows the load voltage with DVR. In the proposed system the 30% sag in time instance from 0.1 to 0.15 and 10% sag in time instance from 0.4 to 0.47. The solar powered Dynamic Voltage Restorer has designed to inject the reduced voltage and maintain the load profile.

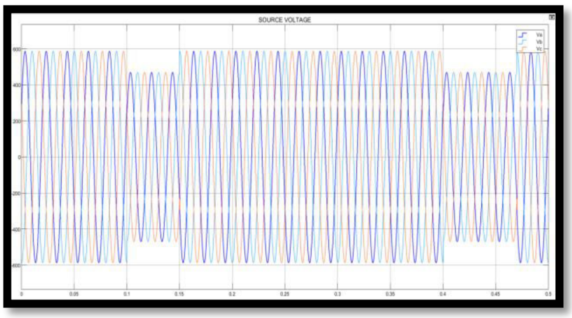

Fig.4.4 Voltage waveform with 20% sag

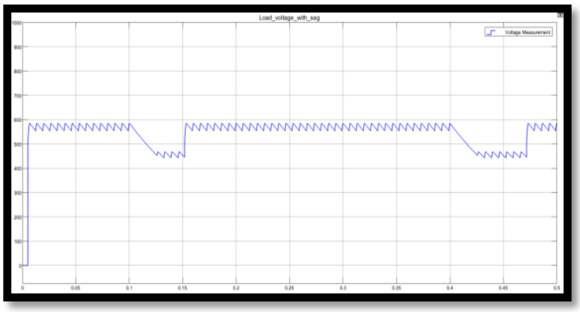

Fig 4.5 Load voltage profile without DVR

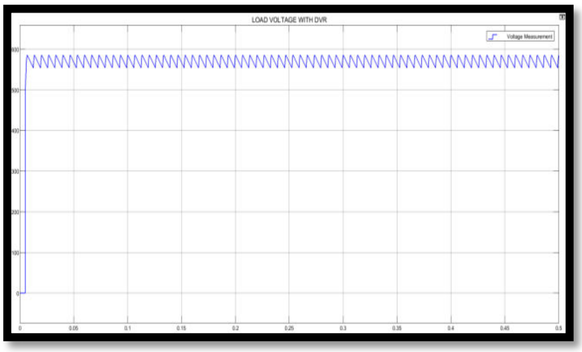

Fig.4.6 Load voltage profile with DVR

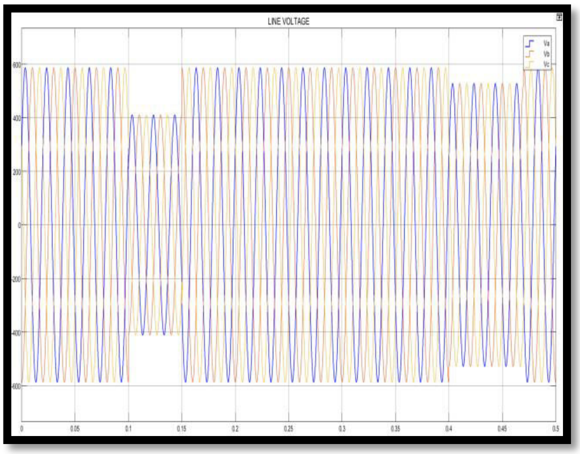

Fig.4.7 Voltage waveform with 30% and 10% sag

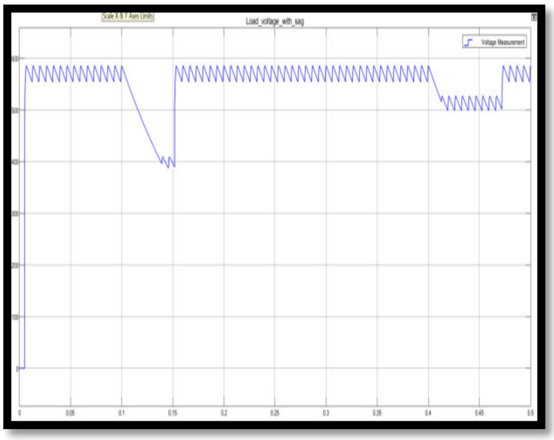

Fig 4.8 Load voltage profile without DVR

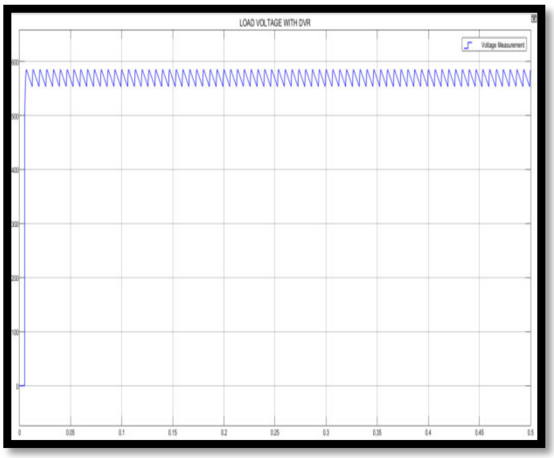

Fig.4.9 Load voltage profile with DVR

The Figure 4.10 shows the harmonic profile of the proposed system.

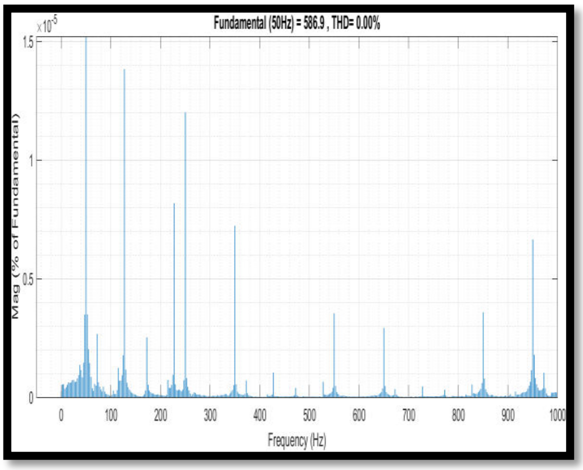

Fig. 4.10 Harmonic profile of the line voltage

5. Conclusion

The dynamic voltage restorer of the suggested system was created utilising photovoltaic energy, a renewable energy source. The three phase voltage source inverter receives the increased DC supply voltage from the panel via a boost converter. After synchronisation, the distribution end three phase voltage is interfaced with the inverter supply.
The purpose of the inverter is to boost the load's performance by supplying voltage when the conventional distribution end voltage drops. By employing the DVR, the load voltage is prevented from dropping. It is recommended that the harmonic profile of the system be set to zero percent in order to retain the required load performance.

The Distribution system line with the voltage level of 415 volts rms has been chosen for the proposed system. The sag has been simulated at the particular instant. The dynamic voltage restorer designed with solar panel voltage of 300 volts which has been boosted by the boost converter operated at 20kHz to reach voltage level of 600 volts. To feed the voltage again into the distribution system the three phase inverter converts the dc into ac. The series injection transformers connects the DVR to the distribution system.

Thus in the proposed system , the voltage profile in the distribution system has been improved by identifying the sag problem and restoring it instantly by dynamic voltage restorer. Therefore the uninterrupted power supply will be distributed to the utility services.

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