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Analysis of Power Quality Improvement Scheme for a PVECS using Dynamic Voltage Restorer

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Abstract*— This work investigates the critical aspects of power quality and the role of the Dynamic Voltage Restorer (DVR) in mitigating common power disturbances. It begins by defining key power quality issues such as voltage sag, swell, flicker, and harmonics, including Total Harmonic Distortion (THD), and highlights their detrimental effects on electrical equipment and system efficiency. Dynamic Voltage Restorer its importance, principle of operation, and essential components including the Voltage Source Inverter (VSI), injection transformer, energy storage unit, harmonic filter, bypass switch, and control system is discussed. Various modes of operation, compensation methods (pre-sag, in-phase, energy optimization, reactive power), and diverse DVR topologies (based on DC-link/energy storage, power converter structure, and connection method) are discussed. The advantages and disadvantages of DVRs, along with their practical applications in sensitive industries like semiconductor manufacturing and data centers, are also presented. Simulation is carried out in MATLAB Simulink environment. Standalone DVR system and PV inverter system integrated with a DVR is simulated for both R and RL load to check the effectiveness in voltage disturbance compensation and THD reduction.

Index Terms*— PV Inverter System, DVR, Power Quality, THD, Voltage Sag, Voltage Swell

I. INTRODUCTION

Power quality is a fundamental concern in modern electrical power systems, directly impacting the reliability, efficiency, and longevity of electrical equipment and sensitive electronic devices. In an increasingly interconnected and automated world, the consistency and purity of the electrical supply are paramount [1-2]. Deviations from ideal sinusoidal voltage and current waveforms, often caused by non-linear loads, faults, or switching operations, can lead to a myriad of problems, including equipment malfunction, reduced operational lifespan, data loss, and significant economic repercussions for industrial and commercial consumers [3].Critical aspects of power quality, beginning with an in-depth explanation of common power disturbances such as voltage sags, voltage swells, voltage flicker, and harmonics, including the crucial metric of Total Harmonic Distortion (THD) are discussed. Understanding these phenomena is essential for developing effective mitigation strategies. A key solution to these power quality challenges, particularly voltage sags and swells, is the Dynamic Voltage Restorer (DVR) [4-5]. The DVR is a power electronic-based device designed to inject a precise voltage into the distribution system, thereby restoring the load voltage to its nominal level during disturbances. Fundamental principles governing DVR operation, its essential components, various modes of operation, and the different compensation methods employed are elaborated further. Furthermore, diverse topologies of DVRs [6], highlighting how different configurations address specific power system requirements and constraints are discussed. The advantages of deploying DVRs are critically examined, alongside their vital applications across various industries that demand high power quality [7-8]. Finally, simulation results obtained from MATLAB Simulink environment, illustrating the practical effectiveness of DVRs in enhancing power quality for both standalone systems and integrated renewable energy systems like PV inverters under R and RL loads is presented.

II. POWER QUALITY

Power quality refers to the consistency and reliability of electrical power supplied to consumers. It encompasses various aspects like voltage stability, frequency regulation, and the absence of distortions such as harmonics, sags, and swells. Poor power quality can lead to a range of issues for electrical equipment, including reduced efficiency, premature failure, and even complete malfunction, ultimately impacting operational costs and productivity for businesses and quality of life for residential users. Maintaining high power quality is crucial for the efficient and reliable operation of modern electrical systems and sensitive electronic devices.

A. VOLTAGE SAG

A voltage sag, also known as a voltage dip, is a temporary reduction in the root mean square (RMS) voltage, typically between 10% and 90% of the nominal voltage. These short-duration events can last from half a cycle to several seconds, and are often caused by faults on the power system (like short circuits), the starting of large inductive loads (such as big motors or transformers), or even natural phenomena like lightning strikes. While often imperceptible to the naked eye for residential users, voltage sags can severely impact sensitive electronic equipment in industrial and commercial settings, leading to equipment malfunction, process shutdowns, data loss, and significant economic losses.

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B. VOLTAGE SWELL

A voltage swell is a short-duration increase in the RMS voltage, typically ranging from 1.1 to 1.8 times the nominal voltage. Unlike sags, which are reductions, swells represent a momentary overvoltage that can last from half a cycle to several seconds. Common causes of voltage swells include the sudden disconnection of large loads from the system, the energization of capacitor banks (used for power factor correction), or certain types of single-line-to-ground faults in ungrounded or floating delta systems. While less frequent than voltage sags, swells can still be damaging to electrical equipment, potentially causing insulation breakdown, overheating, and premature aging of components, thereby affecting their reliability and lifespan.

C. VOLTAGE FLICKER

Voltage flicker refers to rapid, repetitive fluctuations in the voltage of an electrical supply, which are perceived by the human eye as changes in the brightness of lights. These fluctuations are often caused by loads that draw highly variable current, such as electric arc furnaces, welding machines, or the frequent starting of large motors. While it may seem like a minor issue, significant voltage flicker can lead to visual discomfort, headaches, and eye strain for people, and can also cause sensitive electronic equipment to malfunction, leading to operational disruptions and reduced equipment lifespan in industrial and commercial environments.

D. HARMONICS

Harmonics in power systems refer to the presence of currents and voltages with frequencies that are integer multiples of the fundamental power frequency (e.g., 50 Hz in India). These distortions are primarily caused by "non-linear loads," which are devices that draw current in a non-sinusoidal manner, such as computers, LED lighting, variable speed drives, and other power electronic equipment. The introduction of harmonics into the electrical system can lead to various problems, including overheating of transformers and motors, misoperation of protective relays, reduced system efficiency, and interference with communication systems. Measuring and mitigating harmonics, often through filters or specialized transformers, is crucial for maintaining good power quality and ensuring the reliable operation of modern electrical infrastructure.

E. TOTAL HARMONIC DISTORTION

Total Harmonic Distortion (THD) is a crucial metric in power quality, quantifying the deviation of a voltage or current waveform from a pure sinusoidal shape due to the presence of harmonics. It is typically expressed as a percentage and represents the ratio of the RMS value of all harmonic components (frequencies that are integer multiples of the fundamental frequency) to the RMS value of the fundamental frequency itself. A lower THD value indicates a cleaner, more sinusoidal waveform, which is desirable for efficient and reliable operation of electrical equipment. High THD levels can lead to issues such as increased heating in transformers and motors, reduced system efficiency, interference with communication systems, and even damage to sensitive electronic devices.

III. DYNAMIC VOLTAGE RESTORER (DVR)

A. DEFINITION

Dynamic voltage restorer is a custom power device used in electrical distribution system for power quality improvement. It ensures regulated voltage supply to the sensitive loads, even in case of voltage sag and swell disturbances in the distribution network [6]. It is a series connected device and compensates voltage sag and swell by injecting a voltage with the help of a series transformer. The basic circuit of a DVR is shown in Fig. 1.

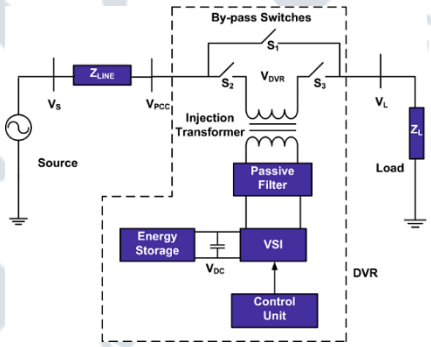


Fig. 1 DVR circuit

B. IMPORTANCE OF DVR

In modern power systems, despite sophisticated infrastructure, power quality issues are prevalent. Among these, voltage sags are the most common and severe. A voltage sag is a momentary reduction in the RMS voltage, typically ranging from 10% to 90% of the nominal voltage, lasting from a half-cycle to several seconds. On the other hand, voltage swell is a momentary increase in voltage. These disturbances can cause significant problems for sensitive industrial and commercial loads, leading to:

- Maloperation or tripping of equipment.
- Production losses.
- Damage to sensitive electronics.
- Decreased efficiency and lifetime of devices.

DVRs offer a fast, flexible, and cost-effective solution to these problems, especially voltage sags, by ensuring a stable and regulated voltage supply to critical loads.

C. PRINCIPLE OF OPERATION

The basic principle of a DVR is to inject a compensating voltage (V_{DVR}) in series with the utility voltage (V_{source}) to restore the load voltage (V_{load}) to its desired value. This can be represented by the phasor sum:

$$V_{load} = V_{source} + V_{DVR}$$

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When a voltage sag or swell is detected at the point of common coupling (PCC), the DVR rapidly calculates the missing voltage (for sags) or the "excess" voltage (for swells). It then generates and injects this precise voltage, in magnitude and phase, to bring the load voltage back to the nominal level. This compensation occurs within milliseconds, making it highly effective for transient disturbances.

D. COMPONENTS OF DVR

A typical DVR system comprises the following components:

A. *Voltage Source Inverter (VSI):*

This is the heart of the DVR. It's a power electronic converter (often using IGBTs or MOSFETs in an H-bridge or multi-level configuration) that generates the AC voltage to be injected into the line. It converts DC power from the energy storage unit (or rectifier) into a controllable AC voltage.

B. *Injection Transformer (or Series Transformer):*

This transformer connects the VSI output in series with the main power line. It steps up the voltage generated by the VSI to the required line voltage level and provides galvanic isolation between the DVR and the main grid.

C *Energy Storage Unit / DC-Link*:

Energy Storage Devices: For compensating sags that require active power injection, energy storage units are crucial. Common options include:

Batteries (BESS): Provide real power for longer durations but have limited lifetime and require maintenance.

Supercapacitors (UCAPs) / Ultracapacitors: Offer high power density and longer lifetime than batteries, suitable for short-duration, high-power pulses.

Superconducting Magnetic Energy Storage (SMES): Stores energy in a magnetic field, offering very fast response and high efficiency, but are complex and expensive.

Flywheel Energy Storage Systems (FESS): Store kinetic energy.

DC-Link Capacitor: Even without dedicated energy storage, a DC-link capacitor is essential for the VSI to provide a stable DC voltage and to absorb reactive power exchanged during compensation.

Rectifier: Some DVRs, especially for reactive power compensation or when the sag is not too severe, can derive their DC power directly from the utility through a rectifier, effectively "self-supporting" their DC link.

D. *Harmonic Filter*:

An LC (inductor-capacitor) filter is placed at the output of the VSI (before the injection transformer) to smooth out the pulsed voltage waveform generated by the inverter and ensure that a clean, sinusoidal voltage is injected into the grid, preventing the injection of unwanted harmonics.

E. *Bypass Switch/Bypass Contactor*:

This switch is used to:

- Bypass the DVR when it's not needed (standby mode) to reduce losses.
- Isolate the DVR during maintenance or in case of an internal fault to protect the device and ensure continuous power flow to the load.
- Protect the DVR from very high fault currents on the line by providing an alternative path for the current.

F. *Control System*:

This is the "brain" of the DVR. It typically includes:

Voltage Sag/Swell Detection: Continuously monitors the incoming supply voltage (magnitude and phase) and compares it to a reference.

Reference Voltage Generation: Calculates the exact voltage magnitude, phase angle, and waveform that needs to be injected.

PWM (Pulse Width Modulation) Control: Generates the switching signals for the VSI to produce the desired injected voltage.

Feedback Loops: Ensures accurate and rapid compensation.

E. ADVANTAGES OF DVR

Fast Response: Can compensate for voltage disturbances within milliseconds.

Effective Voltage Sag/Swell Mitigation: Highly effective in protecting sensitive loads from voltage variations.

Flexible Control: Can compensate for voltage magnitude, phase angle, and waveform.

Compact Size and Lower Cost: Compared to some other power quality devices like UPS for similar power ranges.

High Efficiency: Minimal losses during standby mode.

Scalability: Can be designed for various voltage and power levels.

F. APPLICATIONS OF DVR

Semiconductor Manufacturing: Highly sensitive to voltage sags.

Textile Industry: Continuous processes where voltage sags can cause significant financial losses.

Chemical and Pharmaceutical Plants: Uninterrupted operation is crucial for safety and product quality.

Food Processing Plants: To maintain production quality and avoid spoilage.

Data Centres: Though UPS systems are primary, DVRs can enhance power quality at the point of common coupling.

Automated Manufacturing Lines: To prevent equipment tripping and ensure continuous operation.

The choice of DVR topology depends on several factors:

- The required compensation capability (magnitude and duration of sag/swell).
- The voltage level of the distribution system.
- Cost constraints.
- Space limitations.

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- Desired power quality level (e.g., harmonic distortion limits).
- Maintenance requirements.

IV. SIMULATION CIRCUITS AND WAVEFORMS

Table 1. Specifications of DVR

Parameter	Value
DC voltage of VSI (V)	325 V
Energy storage capacitor (μF)	10000
Transformer power rating (MVA)	1
Transformer primary voltage (V)	230
Transformer secondary voltage (V)	230
Inductance, L1 (mH)	1
Inductance, L2 (μH)	0.1
Load resistor (Ω)	10
Time interval of voltage sag (s)	0.15 to 0.27
Magnitude of voltage sag (V)	225
Time interval of voltage swell (s)	0.37 to 0.43
Magnitude of voltage swell (V)	425

Case 1: DVR with R load

Fig. 2 shows the circuit of the DVR system constructed using the MATLAB Simulink environment.

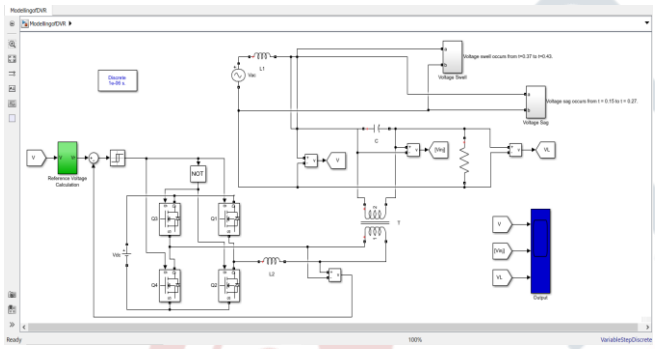


Fig. 2 MATLAB Simulink model of DVR system with R load

The waveforms representing introduction of voltage sag and swell to source voltage, voltage injected by DVR and the output voltage waveform is shown in Fig. 3.

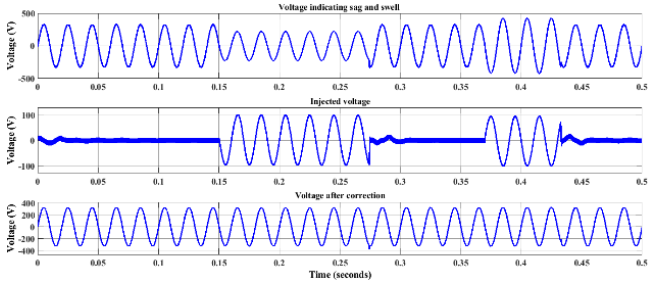


Fig. 3. Waveforms before and after voltage sag and voltage swell

Table 2. Variation of parameters with resistance in DVR for R load

DVR with R load				
Resistance (Ω)	**Voltage (V)**	**Current (A)**	**Power (W)**	**THD (%)**
10	229.7	22.97	5276.209	1.90
20	229.8	11.49	2640.402	1.61
50	229.2	4.583	1050.4236	1.40
100	229.5	2.295	526.7025	1.41
200	229.6	1.148	263.5808	1.40

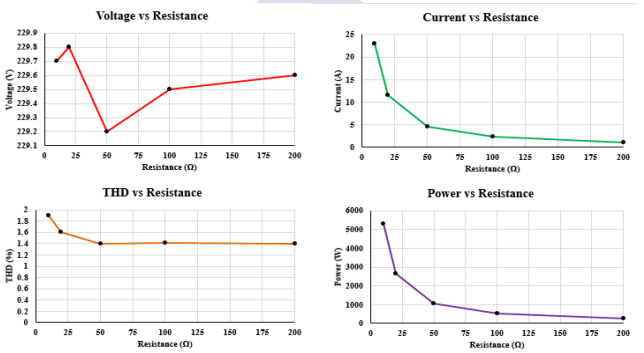


Fig. 4 Graphical representation of DVR for variation of resistance for R load

Case 2: DVR with RL load

Fig. 5 shows the circuit of the DVR system constructed using the MATLAB Simulink environment.

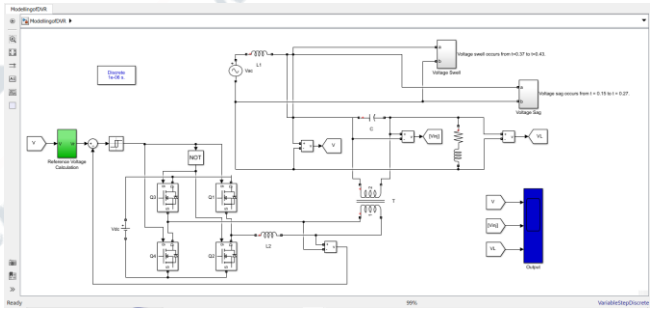


Fig. 5 MATLAB Simulink model of DVR system with RL load

The waveforms representing introduction of voltage sag and swell to source voltage, voltage injected by DVR and the output voltage waveform is shown in Fig. 6.

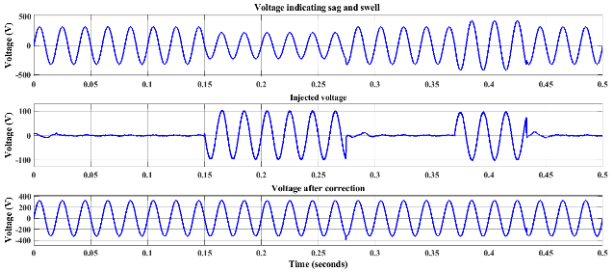


Fig. 6. Waveforms before and after voltage sag and voltage swell

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Table 3. Variation of parameters with impedance in DVR for RL load

DVR with RL load						
R (Ω)	L (mH)	Z (Ω)	V (V)	I (A)	P (W)	THD (%)
10	10	10.48	228.7	21.82	4760.68	1.62
10	50	18.62	228.7	12.28	1508.13	1.41
10	100	32.97	228.6	6.934	480.76	1.40
50	10	50.1	229.1	4.573	1045.58	1.35
50	50	52.41	228.9	4.368	953.84	1.37
50	100	59.05	228.9	3.876	751.20	1.39

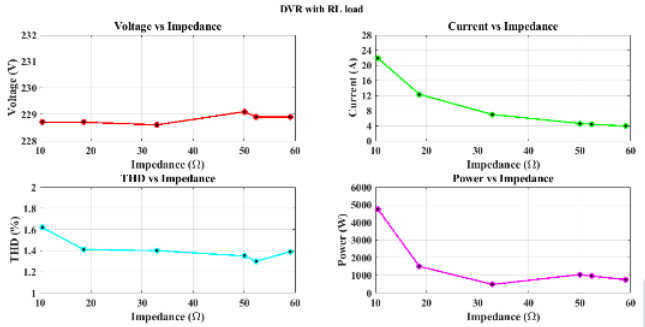


Fig. 7 Graphical representation of DVR for variation of resistance for RL load

PV array data, Boost converter specifications and filter specifications utilized in PV inverter system integrated with DVR Simulink model is given in Table 4, Table 5 and Table 6 respectively.

Table 4. PV array data

Parameter	Value
Module	Tata Power Solar Systems TP300LBZ
Parallel strings	5
Series connected modules per string	4
Maximum Power (W)	300.12
Cells per module (Ncell)	72
Open circuit voltage, Voc (V)	44.4
Short circuit current, Isc (A)	8.69
Voltage at maximum power point, Vmp (V)	36.6
Current at maximum power point, Imp (A)	8.2
Temperature coefficient of Voc (%/°C)	-0.33
Temperature coefficient of Isc (%/°C)	0.063797

Table 5. Boost converter specifications

Parameter	Value
Input voltage (V)	146.4
Output voltage (V)	325
Duty ratio	0.5495
Switching frequency (kHz)	10
Load resistor (Ω)	10
Inductance (µH)	69.694
Capacitance (mF)	1.1

Table 6. Filter specifications

Parameter	Value
V_{DC} (V)	325
V_o (V)	230
P_o (W)	6000
f_s (kHz)	10
Filter inductance (mH)	1.101
Filter capacitance (µF)	23

***Case 3*: PV inverter system connected to DVR with R load**

Fig. 8 shows the circuit of the PV inverter system connected to DVR constructed using the MATLAB Simulink environment.

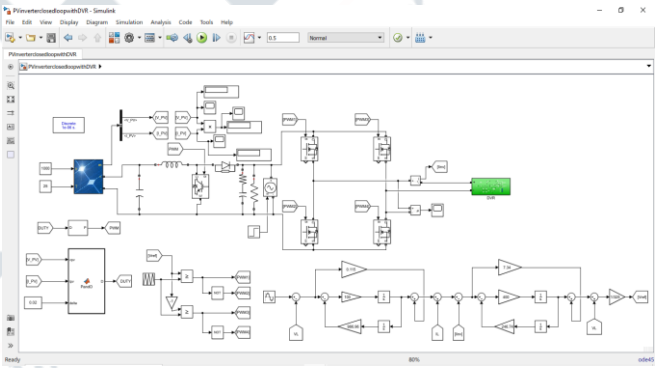


Fig. 8 MATLAB Simulink model of PV inverter system connected to DVR with R load

The waveforms representing introduction of voltage sag and swell to source voltage, voltage injected by DVR and the output voltage waveform is shown in Fig. 9.

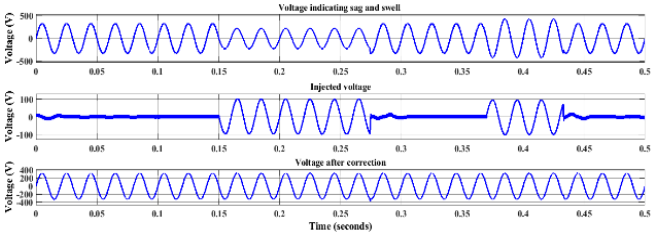


Fig. 9 Waveforms before and after voltage sag and voltage swell

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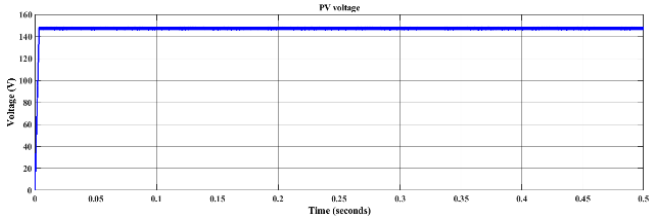


Fig. 10 PV voltage waveform

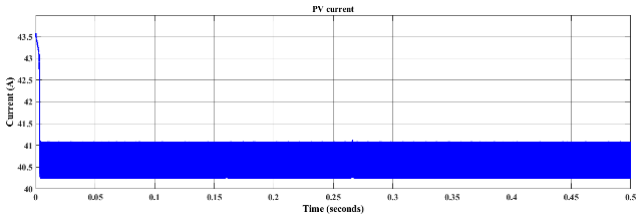


Fig. 11 PV current waveform

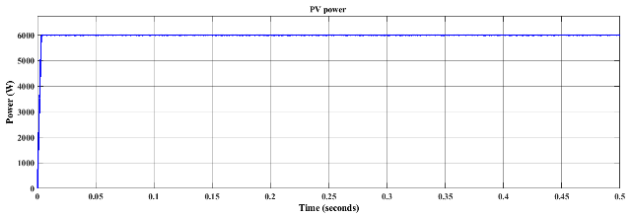


Fig. 12 PV power waveform

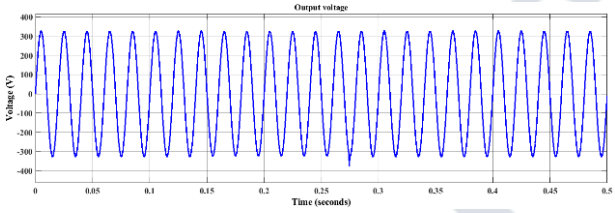


Fig. 13 Output voltage waveform

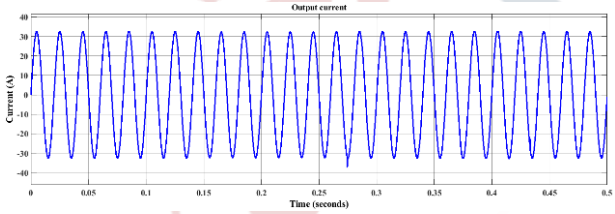


Fig. 14 Output current waveform

Table 7. Variation of parameters with resistance in PV inverter system connected to DVR for R load

PV inverter system connected to DVR with R load				
Resistance (Ω)	**Voltage (V)**	**Current (A)**	**Power (W)**	**THD (%)**
10	229.7	22.97	5276.21	1.84
20	229.8	11.49	2640.40	1.65
50	229.4	4.588	1052.49	1.34
100	229.6	2.296	527.16	1.34
200	229.7	1.149	263.93	1.35

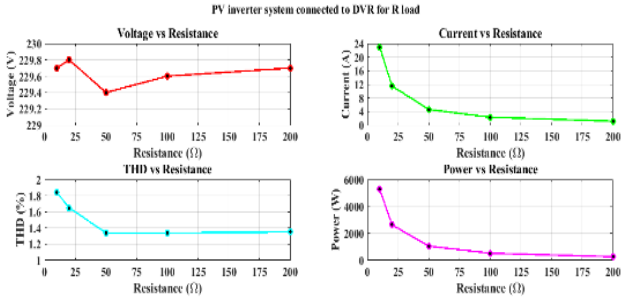


Fig. 15 Graphical representation of PV inverter system connected to DVR for variation of resistance for R load

***Case 4*: PV inverter system connected to DVR with RL load**

Fig. 16 shows the circuit of the PV inverter system connected to DVR constructed using the MATLAB Simulink environment.

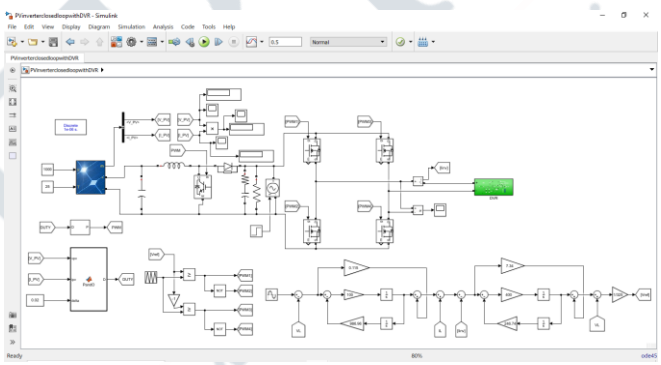


Fig. 16 MATLAB Simulink model of PV inverter system connected to DVR with RL load

The waveforms representing introduction of voltage sag and swell to source voltage, voltage injected by DVR and the output voltage waveform is shown in Fig. 17.

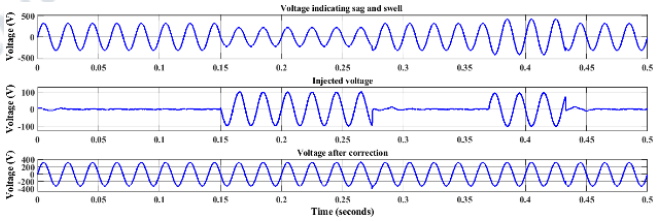


Fig. 17 Waveforms before and after voltage sag and voltage swell

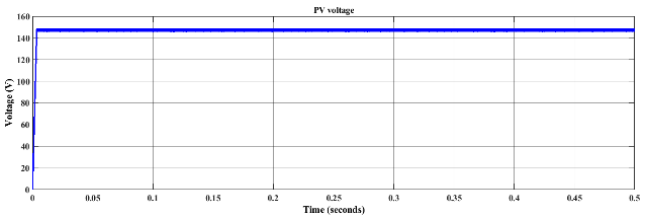


Fig. 18 PV voltage waveform

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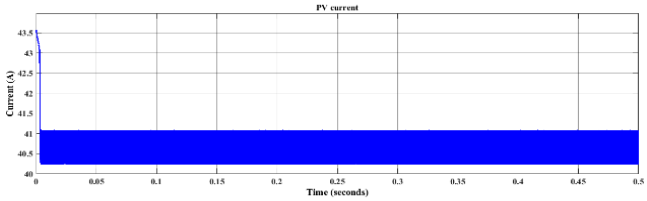


Fig. 19 PV current waveform

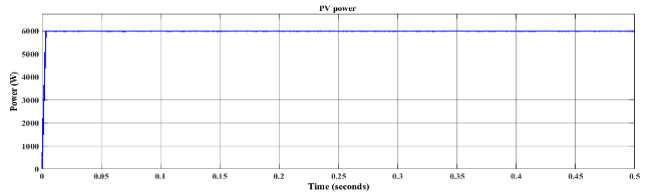


Fig. 20 PV power waveform

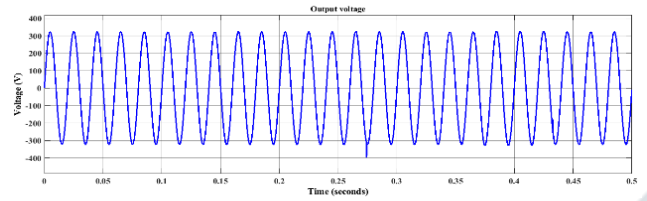


Fig. 21 Output voltage waveform

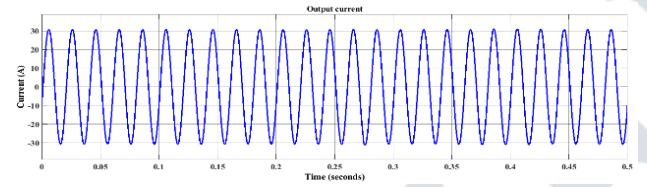


Fig. 22 Output current waveform

Table 8. Variation of parameters with impedance in DVR for RL load

PV inverter system connected to DVR with RL load						
R (Ω)	**L (mH)**	**Z (Ω)**	**V (V)**	**I (A)**	**P (W)**	**THD (%)**
10	10	10.48	228.6	21.81	4756.42	1.57
10	50	18.62	228.5	12.27	1505.58	1.37
10	100	32.97	228.4	6.928	479.93	1.37
50	10	50.1	229.3	4.577	1047.41	1.31
50	50	52.41	229.1	4.37	955.11	1.31
50	100	59.05	228.9	3.877	751.4	1.34

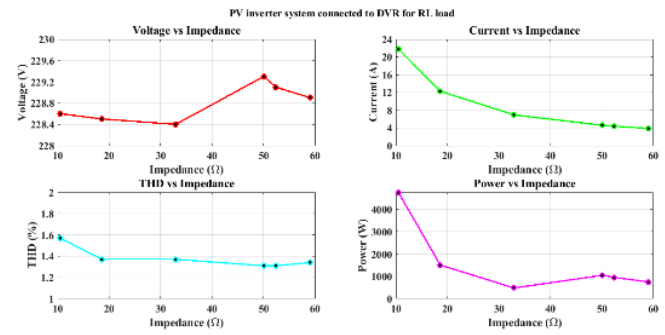


Fig. 23. Graphical representation of PV inverter system connected to DVR for variation of resistance for RL load

V. CONCLUSION

To validate the effectiveness of the DVR circuit, its performance was rigorously evaluated through MATLAB Simulink environment by connecting it to PV inverter system. The PV inverter system connected to DVR was simulated under R and RL loads. In both cases, the system was subjected to simulated voltage sags and swells to mimic common power quality disturbances. The DVR's ability to rapidly inject or absorb appropriate voltage was then assessed for its compensatory action.

Case I: *DVR with DC supply*

Simulation of the standalone DVR system demonstrated its efficacy in generating RMS voltage of 229.2 V following sag and swell events for a load resistance of 50 Ω, Total Harmonic Distortion (THD) was maintained at a low 1.40%. Further, RMS voltage of 229.1 V was generated following sag and swell events for a load impedance of 50.1 Ω and the THD was observed to be 1.35%. Furthermore, the system exhibits robust performance under varying R and RL loads, maintaining a constant output voltage and consistently low THD.

Case II: *PV inverter system connected to DVR*

For the PV inverter system connected to DVR, the DVR successfully compensated for voltage sags and swells, resulting in a stable RMS voltage of 229.4 V for a load resistance of 50 Ω. The THD in this case was 1.34%. Further, a stable RMS voltage of 229.3 V was obtained for a load impedance of 50.1 Ω and the THD obtained was observed to be 1.31%. Across a wide range of R and RL load variations, the system maintained a constant output voltage and a low THD, highlighting the DVR's ability to enhance power quality in renewable energy integration.

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