IMPROVING POWER QUALITY OF GRID-CONNECTED PV SYSTEMS USING A DVR WITH COMBINED SLIDING AND PR CONTROL MODEL

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ABSTRACT

This study uses a novel dynamic voltage restorer (DVR) that combines two control algorithms with a multi-level inverter to improve power quality in on-grid photovoltaic schemes. Sag and swell in voltage are corrected by the DVR, a power electronic compensator, which modifies the voltage at the point of standard connection. For regular operations, it uses sliding mode control (SMC), and for precise voltage adjustment during voltage disturbances, it employs proportional resonance (PR). Traditional high-frequency inverters, which frequently experience significant switching losses in high-power applications, are outperformed by the system's multi-level inverter. While reducing harmonic distortion, the multi-level inverter efficiently detects and corrects voltage problems. The study assesses the DVR's performance in a number of scenarios, such as disruption, mild sag, severe sag, and voltage swell. The suggested DVR greatly lowers voltage disturbances and improves power quality in the PV panel's output, the PCC, and the injected voltage, according to simulation findings obtained with the Simulink tool. The findings imply that this dual-control DVR design, with its efficient use of a multi-level inverter, is a promising approach for enhancing power quality and stability in on-grid PV systems.

Keywords: *PV, Multi-level inverter, DVR, PR control, Sliding mode control, Voltage sag/swell*

I. INTRODUCTION

For power generation, a variety of energy and renewable energy sources are used, such as gas, hydrogen, sun, wind, and other energy sources [1]. Because they don't require fuel, solar and wind energy are the most sophisticated and extensively used renewable power generation methods. But power quality problems like voltage sags, swells, and harmonics affect their integration into the grid and can make it more difficult for them to exchange energy with the network efficiently [2]. Power quality is maintained for customers and the power network through the deployment of custom power devices [3]. In addition to regulating and balancing voltage, DVRs can also serve as harmonic isolators, shielding the load from source voltage harmonics [4]. The idea of employing DVRs for voltage reduction has been successful and extensively embraced since its first implementation. Rechargeable energy sources have been proposed as a way to supply DVRs with power during electricity outages. Furthermore, a variety of DVR approaches based on various control algorithms have been investigated [5]. The development of renewable energy sources for the electrical grid has been fuelled by the global focus on environmental issues, climate change, and power reliability. The flexibility and stability of deregulated distributed power grids have increased as a result of this team effort. Due to their ability to effectively solve ecological concerns and their lack of pollution, solar and wind energy have attracted a lot of attention. The utilization of switching and non-switching loads, non-linear sensitive loads, and different step industries with particular production processes are also examined in the literature [6]. In [7], a proportional and integral (PI) controller governs the DVR. The gorilla troops algorithm (GTA) is used to calculate the PI factor values of the suggested controller under various power quality (PQ) concerns, which are particularly investigated in the context of a new town in Egypt. Additionally, the DVR has been applied to maximize PI gains included in the gradient adaptive factors learning rate least mean squares control approach [8]. Similar to the control suggested in [9]. In [10], the functionality of the three-phase, four-wire DVR mechanism which makes use of feedback linearization (FBL) and a variety of resonant regulators is examined. Due to their simplicity [11] and avoidance of complexity [12], PI controllers and conventional PID controllers continue to be widely used. For voltage correction in applications involving sensitive loads, the PI controller in particular has long been a conventional pre-sag compensation technique [13]. Nonetheless, the PI controller has several drawbacks, including a reduced ability to react quickly to abrupt voltage spikes and an increased potential for harmonic distortion. Additional PI-based control techniques include artificial neural networks (ANN), which are discussed in [14]. Additionally, we could use a scaled conjugate-based artificial neural network (SC-ANN) to enhance the PQ indexes of PV, fuel cells, DVR, and storage of energy (battery)-based microgrid designs [15]. We could also use an ANN controller for a DVR to increase the efficiency of a standalone hybrid renewable energy structure. Certain issues with integrated hybrid power systems might pose unique challenges, like inverter-generated harmonics that need the installation of expensive, extra components to the hybrid systems. Therefore, the adaptive-network fuzzy inference system (ANFIS) controller uses the PI controller when hybrid setups are involved. When compared to simpler approaches, more complex control strategies like PI control may result in greater operating costs. In order to improve practical applicability, it is also imperative that DVR control designs take into account the effort to decrease response time across a variety of operational scenarios

II. PHOTOVOLTAIC (PV)

The primary objective of the case study is to inject power from photovoltaic arrays into the grid. Enhanced output waveform quality, reduced total harmonic distortion (THD), increased efficiency, and the ability to handle high-power applications are just a few benefits of multi-level inverters. Uninterruptible power supply (UPS), power grids, electric vehicles, and renewable energy systems

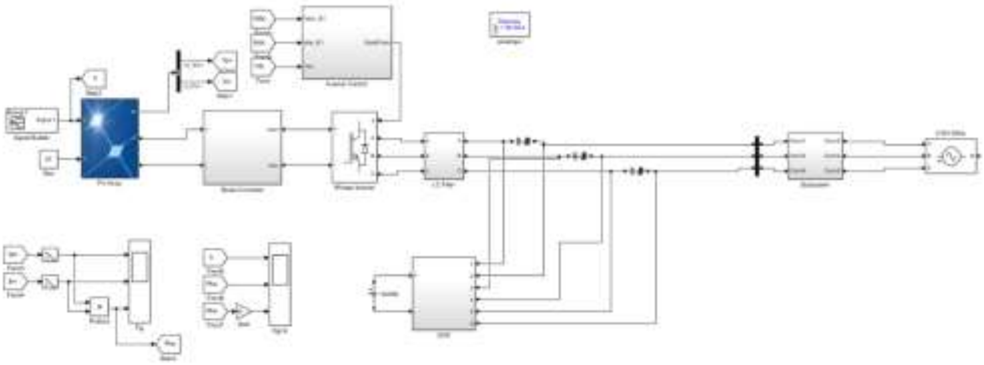

Fig. 1 PV photovoltaic arrays in the grid.

are just a few of the many applications that benefit greatly from these characteristics. Multi-level inverters improve the quality of power output and overall system efficiency in renewable energy applications such as wind and solar. Additionally, they work well in power grids, improving the quality of power supplies and lessening the impact of power disruption harmonics on the grid. Inverters, mounting systems, and solar panels are some of the parts that make up PV systems. The system's main component, solar panels, transform sunlight into DC power. While inverters transform DC electricity into AC power that may power electrical equipment, mounting solutions hold the solar panels firmly in place. The system may also comprise other parts like batteries and charge controllers.

PV systems offer many advantages. They reduce greenhouse gas emissions and dependency on fossil fuels by offering a clean and renewable energy source. PV systems can last up to 30 years or longer and require little upkeep. PV systems are now a more accessible choice for businesses and homeowners due to their significant cost reduction in recent years.

Key Information Regarding Photovoltaic (PV) Technology:

1. Efficiency: PV cells have an average efficiency of 15–25% in converting sunlight into electrical power.
2. PV Cell Types: PV cells come in a variety of forms, such as thin-film, polycrystalline, and monocrystalline.
3. Inverters: These devices transform DC power from photovoltaic cells into AC power that may be used in residences and commercial buildings.
4. Mounting Systems: These systems can be modified to maximize energy production and secure PV panels in place.

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5. Tracking Systems: By moving PV panels to follow the path of the sun, tracking systems increase the amount of energy produced.

III. MULTI-LEVEL INVERTER

A power electronic inverter that uses multiple DC voltage sources or a single DC source with numerous switching devices to produce high-quality output voltage waveforms with various levels, usually three or more, is known as a multi-level inverter.

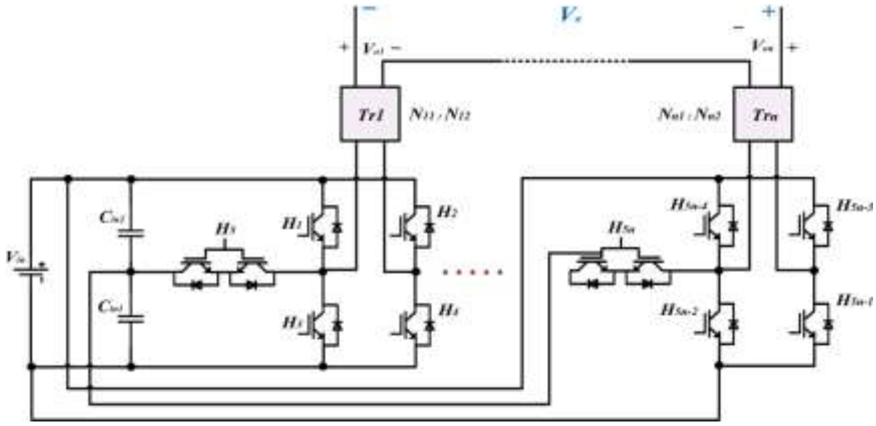


Fig. 2 Circuit topology of the proposed multi-inverter.

A multi-level inverter is a kind of power electronic inverter that produces a multi-level, high-quality output voltage waveform. This can be accomplished by utilizing a single DC source with several switching devices or by utilizing numerous DC voltage sources. The multi-level inverter generates an output voltage waveform that resembles a staircase and is quite similar to a sine wave.

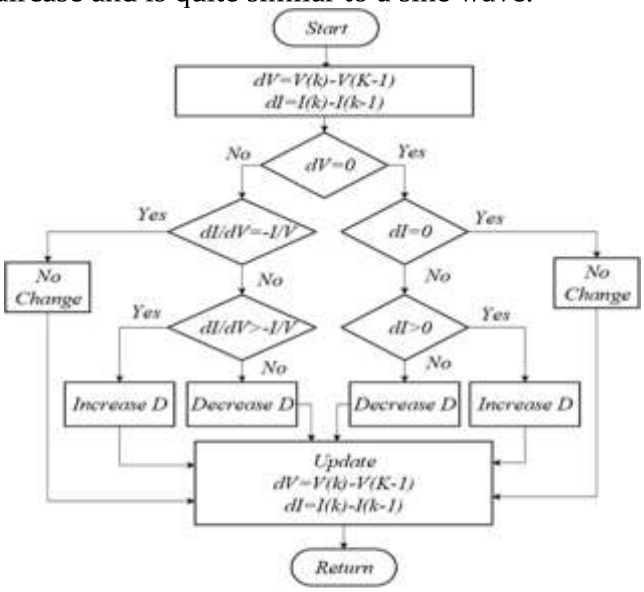


Fig. 3 Flowchart of the IC algorithm

Improved output waveform quality, reduced total harmonic distortion (THD), increased efficiency, and the ability to handle high-power applications are just a few benefits of multi-level inverters. These characteristics make them perfect for a variety of applications, including power grids, electric cars, renewable energy systems, and uninterruptible power supplies (UPS). Multi-level inverters improve overall system efficiency and power output quality in renewable energy applications such as wind and solar power. Additionally, they work well in power grids, improving the quality of the power supply and lessening the impact of power disruption harmonics on the system.

IV. DYNAMIC VOLTAGE RESTORERS (DVR)

In order to enhance the power quality of grid-connected solar systems, this project aims to design and build a Dynamic Voltage Restorer (DVR). With the help of the DVR, the solar system will operate steadily and effectively by reducing voltage sags, swells, and harmonics. A DC energy storage system, a controller, and a DVR will make up the suggested setup.

Power electronic switches like IGBTs or MOSFETs will be used in the construction of the DVR, and a state-of-the-art sliding mode and PR control system will be used for control. To guarantee that the compensating voltage is introduced into the grid at the appropriate moment, the controller will manage the switches' switching. The energy needed to provide the compensating voltage will come from the DC energy storage system.

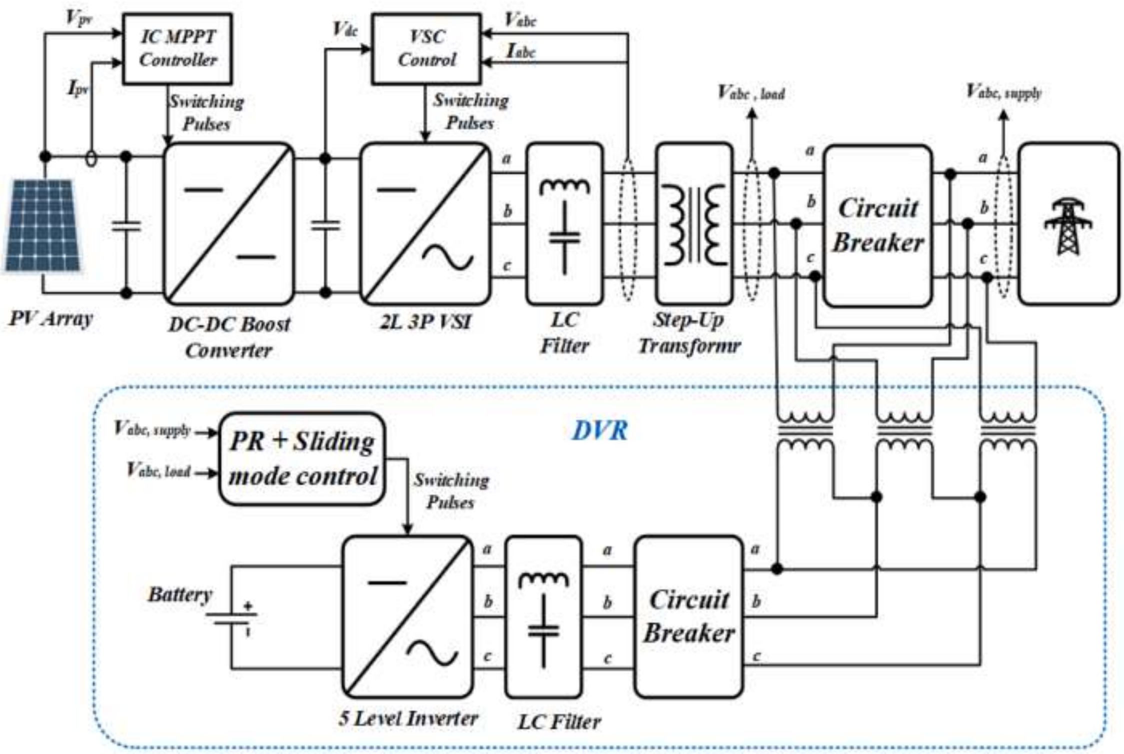


Fig. 4 Proposed PV structure with DVR configuration.

MATLAB/Simulink will be used to simulate the suggested system, and the outcomes will be examined to assess the DVR's performance. The DVR's design will be optimized using the simulation findings, and the right parts will be chosen for the prototype. To verify the simulation findings and assess the DVR's functionality in real time, the prototype will be constructed and tested in a lab.

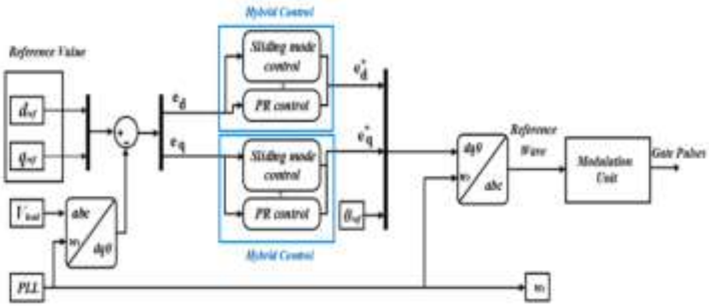


Fig. 5 The DVR control diagram based on the PR and SMC controller.

The project's goals are to design and build a DVR that can enhance the power quality of solar systems linked to the grid and assess the DVR's effectiveness using simulation and experimental data. Grid-connected solar systems may become a more attractive alternative for producing renewable energy if the suggested approach increases their longevity and efficiency.

Control of Sliding Mode (SMC):

Sliding Mode Control (SMC) is a control approach that controls a system's behavior by use of a sliding surface. SMC works on the basis of defining a sliding surface in the system's state space and then creating a control law that compels the system to move along it. This method offers a reliable and effective technique to manage complicated systems, particularly ones that have uncertainties and disruptions.

SMC's resilience to uncertainties and disruptions is one of its primary features. SMC can efficiently reject disturbances and respond quickly by utilizing a sliding surface. SMC is a workable option for many control applications since it can also be constructed using basic control rules. First-order, second-order, and higher-order sliding mode control are among the several varieties of SMC, and each has advantages and disadvantages of its own.

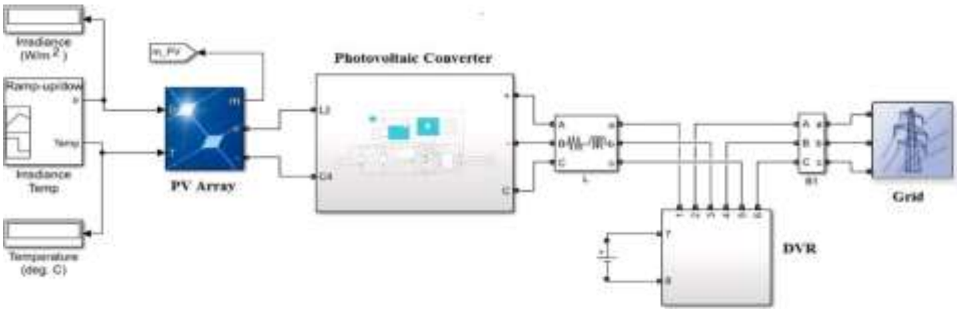


Fig. 6. The simulation of the studied system in MATLAB/Simulink software.

SMC's benefits include enhanced resilience, quick reaction times, and ease of use. Numerous industries, including robotics, aircraft, and power electronics, have successfully used SMC. SMC does have several drawbacks, though, such as chattering, stability problems, and the requirement for precise control gain adjustment. Because of its efficacy and efficiency, SMC is still a widely used control method in spite of these obstacles.

PR Control System:

Power electronics and grid-connected applications frequently employ a type of control strategy called a proportional resonance (PR) control system. With a high gain at a particular resonant frequency, the PR controller can efficiently track and control the output voltage. This is especially helpful for grid-connected solar inverters and other applications where the output voltage must be controlled to a sinusoidal waveform.

The capacity of PR control systems to offer a high gain at the resonant frequency, which enables accurate output voltage regulation, is one of its main advantages. PR controllers are also rather easy to set up and may be readily adjusted for peak performance. To maintain stability, PR controllers could need further adjustment because they are likewise susceptible to changes in the system's characteristics.

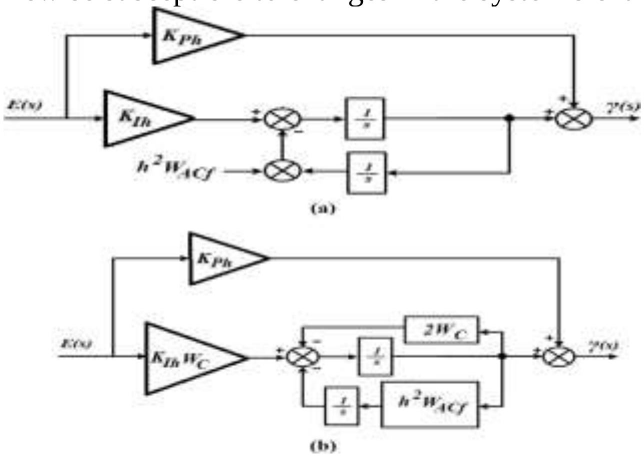


Fig. 7 Diagram showing the PR controller's structure. (a) An ideal PR controller; (b) A practical PR controller.

PR control systems are frequently used in grid-connected solar systems to manage the output voltage and make sure it satisfies grid connection specifications. To guarantee that the output voltage is in sync with the grid voltage, the PR controller is usually utilized in combination with a grid synchronization algorithm. By implementing a PR control system, grid-connected solar systems may provide a high-quality output voltage that fulfils the grid connection criteria. Using a PR control system in grid-connected solar systems has several advantages, such as lower total harmonic distortion (THD), higher efficiency, and better power quality. Furthermore, PR control systems can aid in lessening the strain on the power electronics' constituent parts, resulting in improved longevity and dependability. Overall, because of their simplicity, efficacy, and ease of deployment, PR control systems are a popular option for grid-connected solar systems.

V. SIMULATION RESULTS

The performance of the suggested DVR configuration is assessed in this section using simulation, and the findings are shown in the section that follows. Here, four different kinds of voltage disturbances are presented: voltage swell, imbalanced voltage swell, severe voltage sag, and minor and severe voltage sag. displays the system under study's simulation using MATLAB/Simulink software. They specify the DVR's and the grid-connected PV panels' settings.

A five-level multilevel inverter is used by the DVR that is being displayed. A circuit model of the multilevel inverter used in the DVR simulation investigation is presented. The five-level ON switch lookup. The frequency of triangular waveforms is 1000 Hz, and their amplitude is 1. The amplitude of the sin reference wave is 1.9 and its frequency is 50 Hz. 50 Hz is the fundamental frequency of the output waveform as well. According to the look-up table, the comparison's outcome is employed at each instant to create the appropriate switching function that will provide an appropriate output voltage level. The reference wave for phases B and C differs from the reference wave of phase by 120◦ and 240◦, respectively. The output voltage waveform is produced based on the switching table and the pulses of the modulation unit levels. The output phase voltage and line-to-line voltage are shown in Fig. 8(a) and (b), respectively.

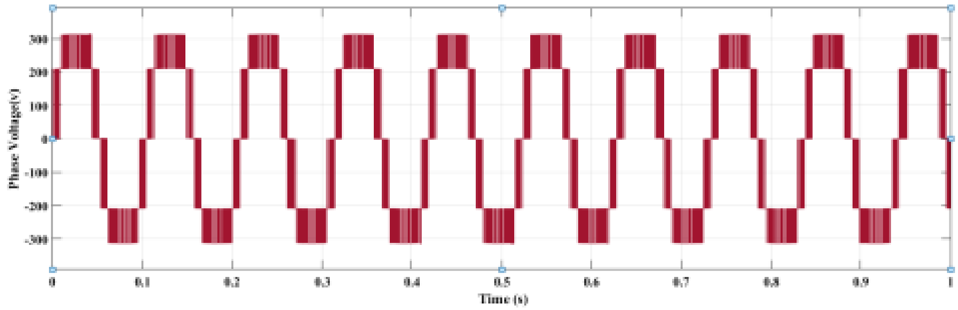
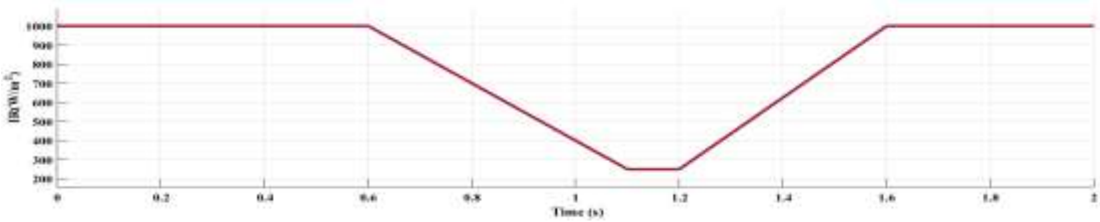


Fig. 8 Voltage of multilevel inverter (a) line-to-line voltage (b) phase voltage.

i. PV Power injection analysis

A PV-grid connection has been constructed and tested in order to confirm the suggested converter's functionality. The primary objective of the case study is to inject power from photovoltaic arrays into the grid. Under normal test circumstances (STC: irradiance 1000 W/m2, cell temperature = 25 ◦C), the PV array has a capacity of 100 KW. Irradiance is seen in Fig. 9. (a). Changes in irradiance alter the PV array's (PPV) power. The sun irradiance is scaled down from 1000 W/m2 to 250 W/m2 between t = 0.6 s and t = 1.1 s. MPPT keeps monitoring maximum power. The corresponding PV output is 24 kW at t = 1.2 s, when the irradiance has dropped to 250 W/m2. It should be noted that during this rapid change in irradiance, the MMPT keeps measuring maximum power. Returning to 1000 W/m2, sun irradiance occurs between t = 1.2 s and t = 2 s. When the grid voltage has a sag or swell voltage issue, the PV array output power is displayed in fault condition in Fig. 9. (b). Photovoltaic power fed into the grid is impacted by power quality issues, such as voltage excesses and shortages. By adjusting the voltage at the solar power plant's grid connection point, the dynamic voltage restorer maintains the power injection in a normal state. Fig. 9. (c) illustrates photovoltaic power fed into the grid when DVR is present. Fig. 9. (c) shows that when a dynamic regenerator is present, the network's injected power voltage is fixed at the required level and power injection to the network is uninterrupted.



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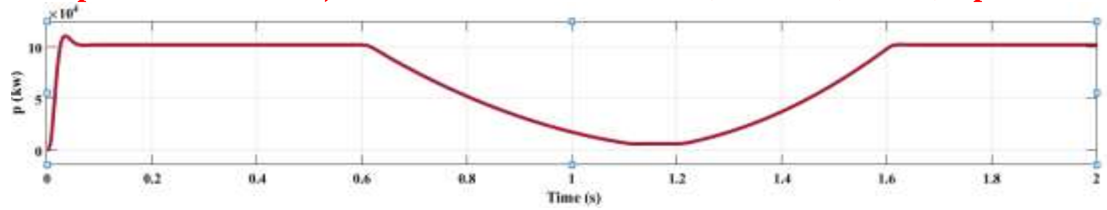

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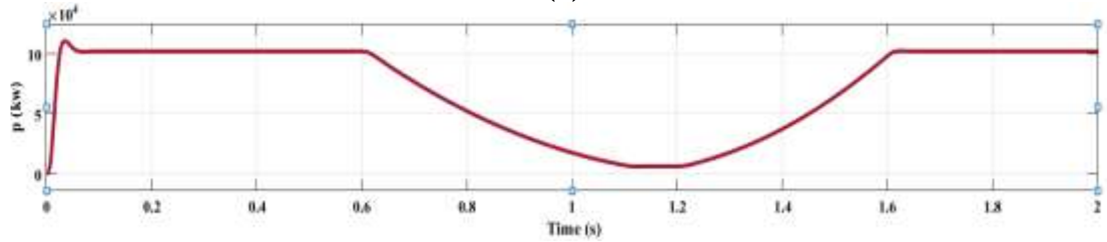
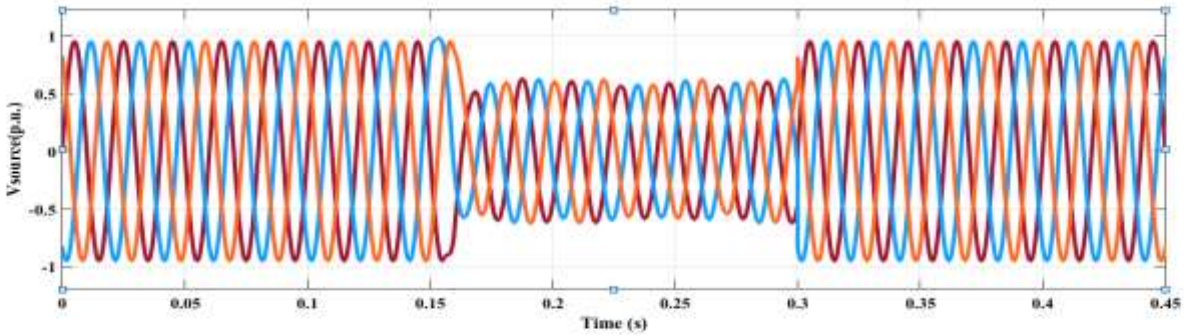


(c)

Fig. 9 Analysis of PV power injection(a) irradiation (b) Active power during fault without DVR (c) Active power with DVR

ii. Balanced sag in voltage

One of the most prevalent issues with power quality is a lack of voltage brought on by an increase in load and faults such short circuits. The role of dynamic voltage recovery in symmetrical undervoltage faults is illustrated in Fig. 10. Furthermore, the voltage disturbance evolution over time is shown in Fig.10. (a), which is divided into two categories: balanced voltage sag from 0.15 to 0.3 s and normal operation from 0 to 0.15 s. Finally, Fig. 10. (b) demonstrates how well the DVR compensates for voltage fluctuations and injects the necessary voltage. The voltage of the power plant's connecting point to the network (load), which is set at one per unit, is displayed in Fig. 10. (c). In spite of balanced voltage sag inaccuracy, the dynamic voltage restorer performs admirably.



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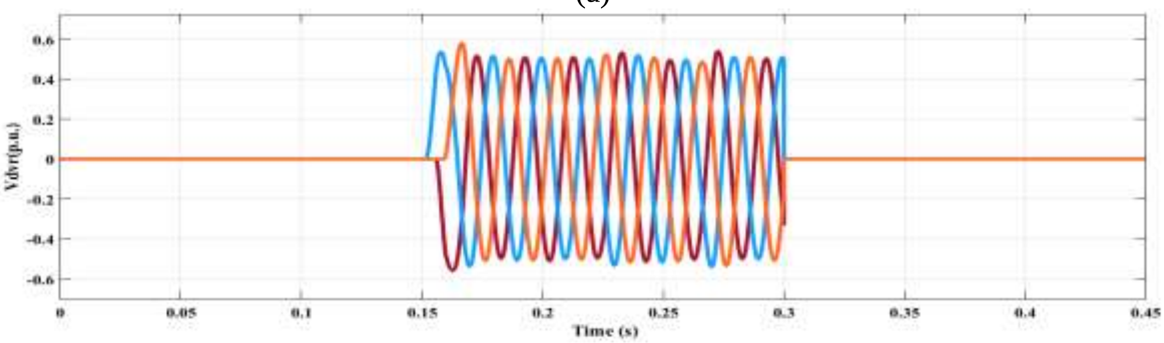

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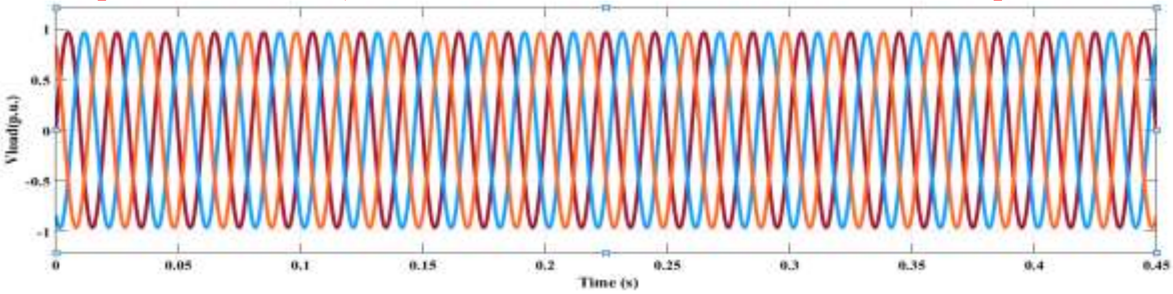
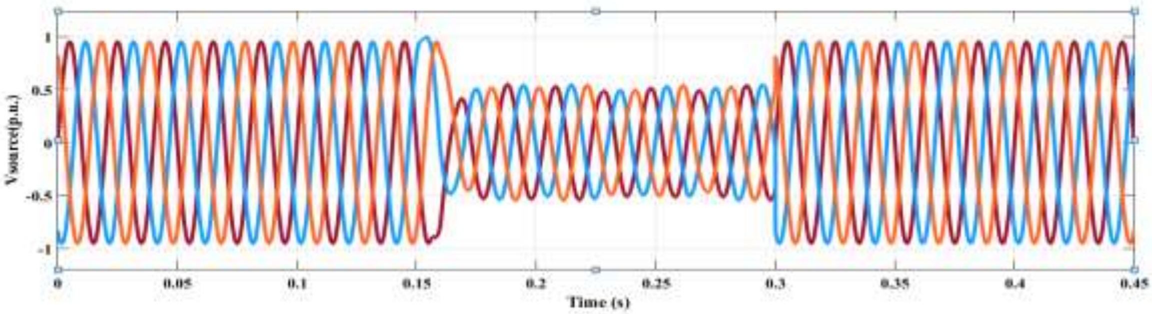


(c)

Fig. 10 Balanced voltage sag compensation process (a) Supply Voltage, (b) Injected Voltage, (c) Load Voltage.

iii. Inequitable voltage sag

The occurrence of voltage unbalanced sag over time t is shown in Fig. 11. (a), with two separate phases: normal operation (from 0 s to 0.15 s) and unbalanced voltage sag (from 0.15 s to 0.3 s). Fig 11. (b) shows how the DVR precisely compensates for voltage fluctuations and injects the desired voltage. As shown in Fig. 11. (c), the load voltage at the point of connection to the power grid is regulated as a result of the dynamic voltage restorer operating properly.



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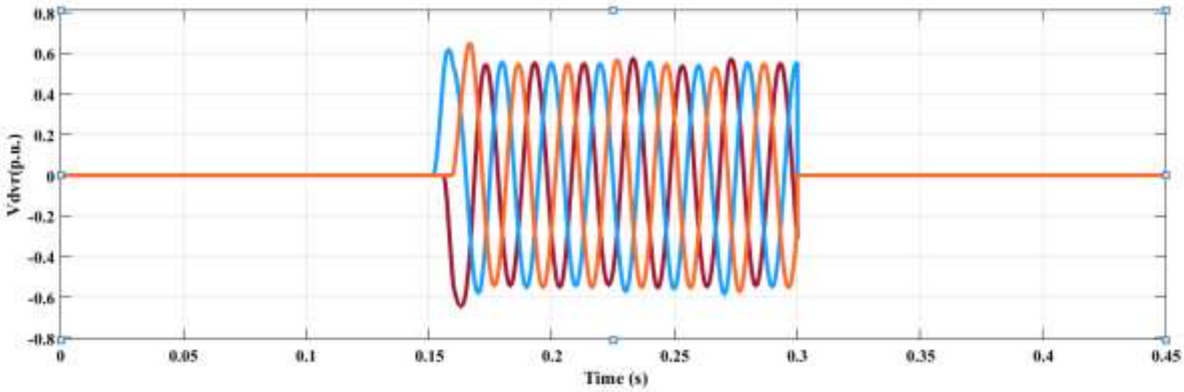

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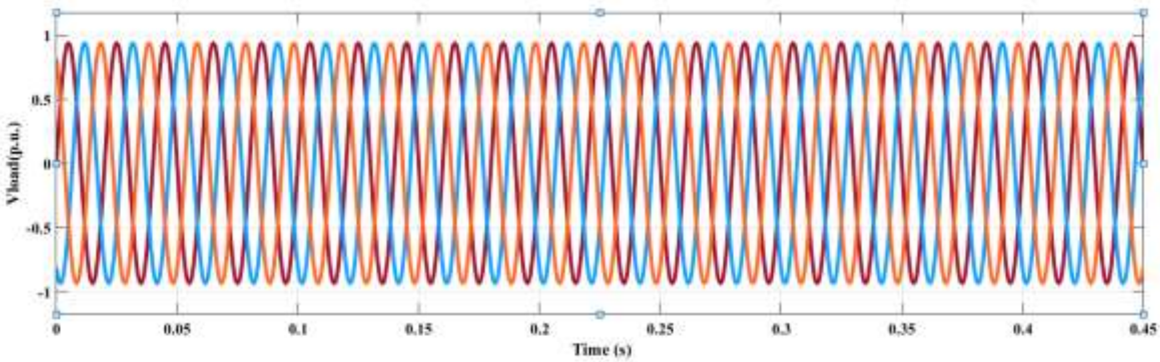

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Fig. 11. Unbalanced voltage sag compensation process (a) Supply Voltage (b) Injected Voltage (c) Load Voltage

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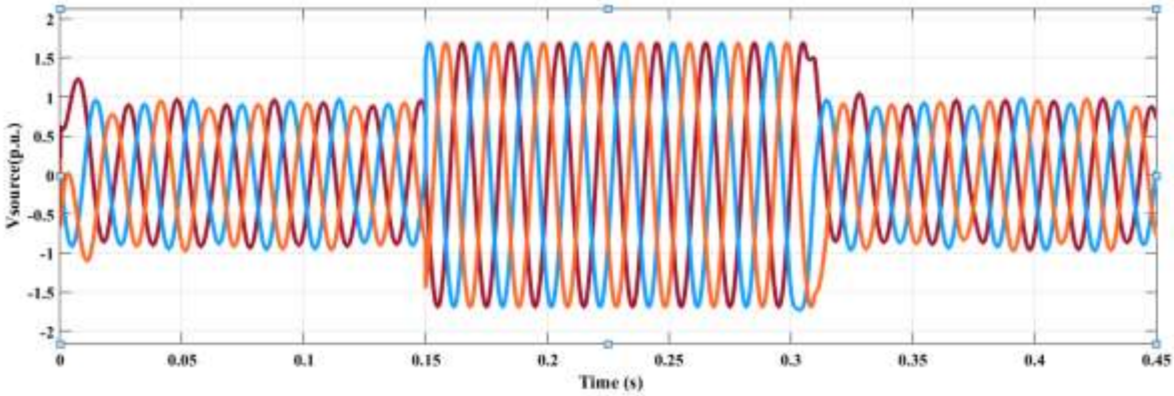
iv. Balanced swell in voltage

Single-phase short circuits, disconnecting heavy loads, adding capacitors, or introducing lengthy high-voltage lines or cables into the circuit are all prominent causes of voltage swell. Fig. 12. displays the recovery performance in a balanced overvoltage fault. The development of balanced voltage swells over time is shown in Fig. 12. (a), which is divided into two categories: balanced voltage swells from 0.15 to 0.3 s and normal operation from 0 to 0.15 s. Lastly, Fig. 12. (b) and Fig. 12. (c) demonstrate that the DVR correctly compensates for the disturbances and injects the required voltage, respectively.



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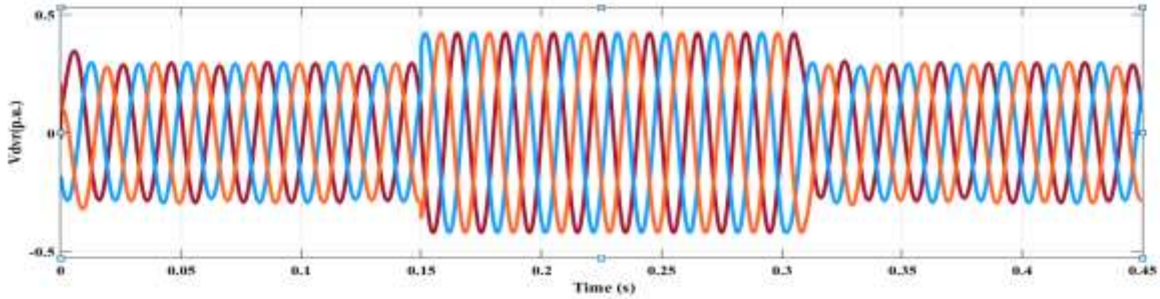

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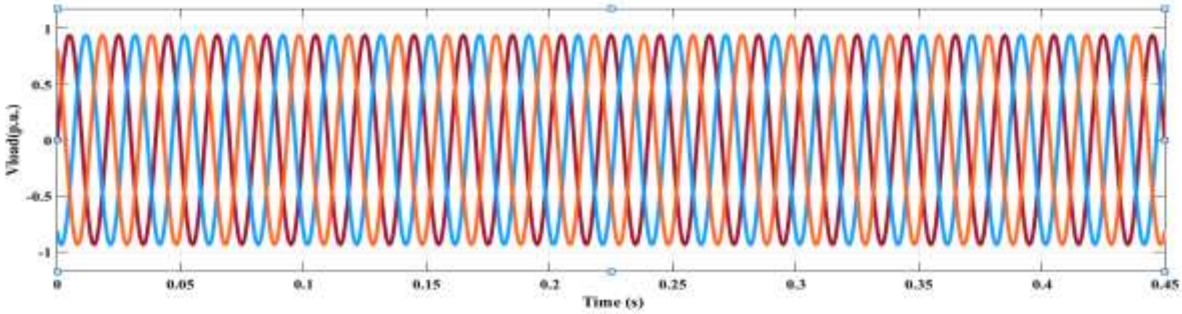

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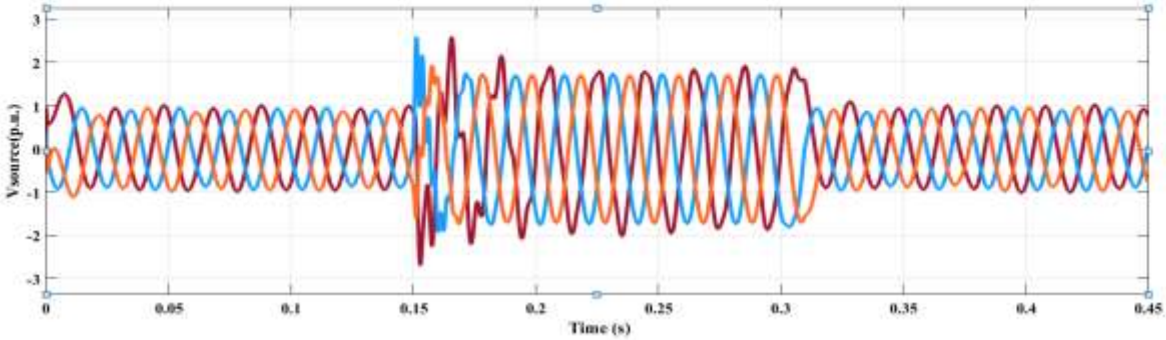
Fig.12. Balanced voltage swell compensation process (a) Supply Voltage, (b) Injected Voltage, (c) Load Voltage.

v. Inequitable voltage swall

The occurrence of voltage unbalanced swell with time t is shown in Fig. 13. (a), which includes phases such as normal operation (from 0 s to 0.15 s) and unbalanced voltage swell (from 0.15 s to 0.3 s). The DVR precisely compensates for voltage changes and injects the desired voltage, as shown in Fig. 13. (b). It should be mentioned that DVR bears primary responsibility for paying for this likely incident. Accordingly, the effectiveness of the power system with DVR designed to withstand both severe and mild voltage swells has been assessed; the pertinent outcome is shown in Fig. 13. (c).



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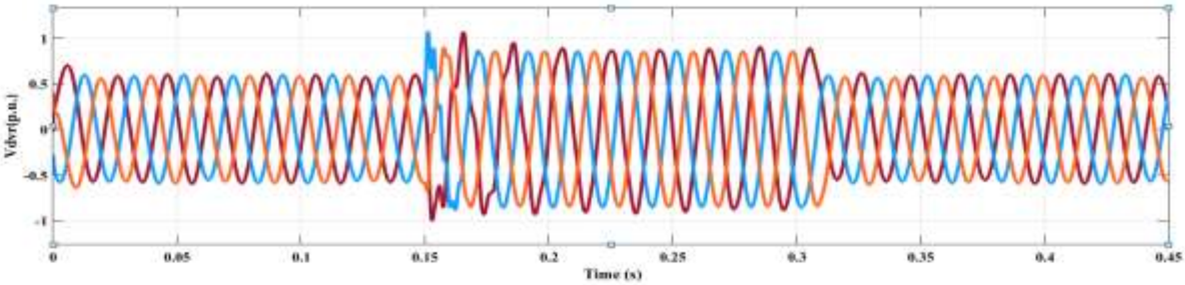

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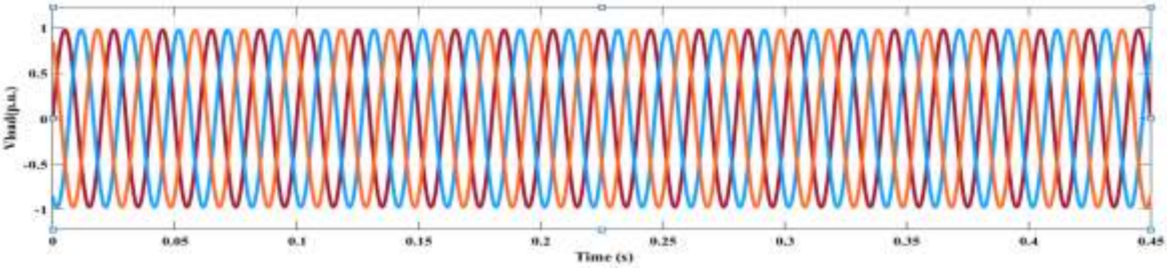
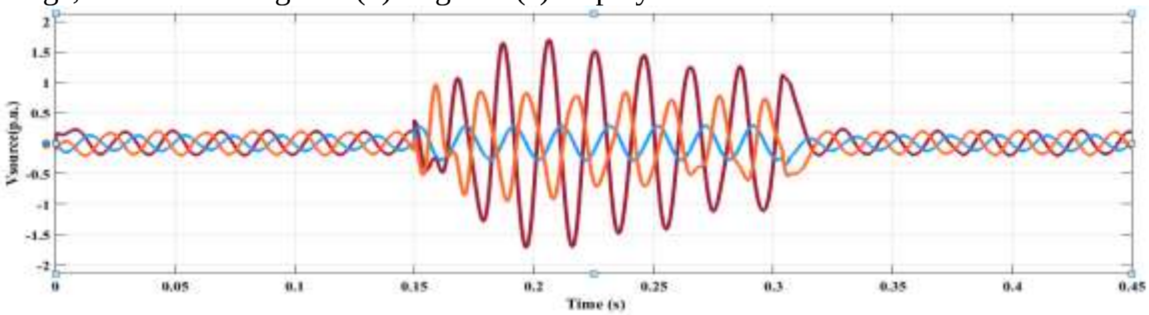


(c)

Fig.13. Unbalanced voltage swell compensation process (a) Supply Voltage, (b) Injected Voltage, (c) Load Voltage.

vi. Flickering voltage

A common issue with power quality is voltage flicker, which is frequently caused by the operation of loads that fluctuate, like electric arc furnaces [38] and [39]. As seen in Fig. 14. (a), this phenomena occurs across time t and includes phases like normal operation (from 0 s to 0.05 s), voltage flicker (from 0.1 s to 0.13 s), and normal operation (from 0.05 s to 0.2 s). Such disruptions prevent delicate gadgets that depend on electric drives from operating normally. The DVR accurately compensates for the voltage fluctuations and injects the desired voltage, as shown in Fig. 14. (b). Fig. 14. (c) displays



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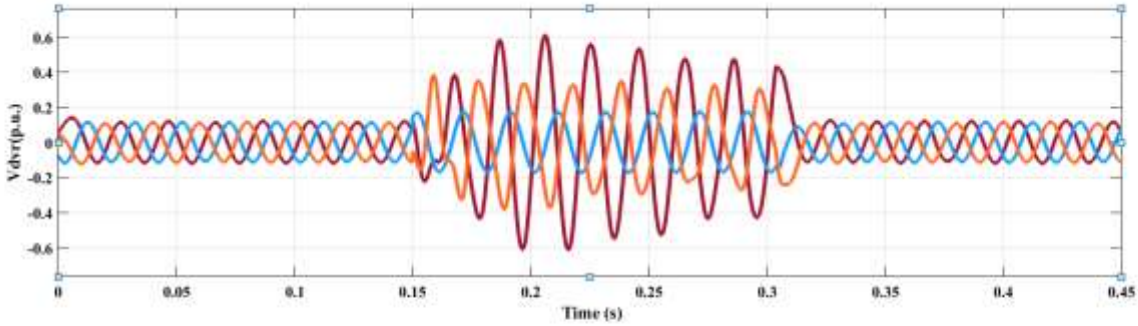

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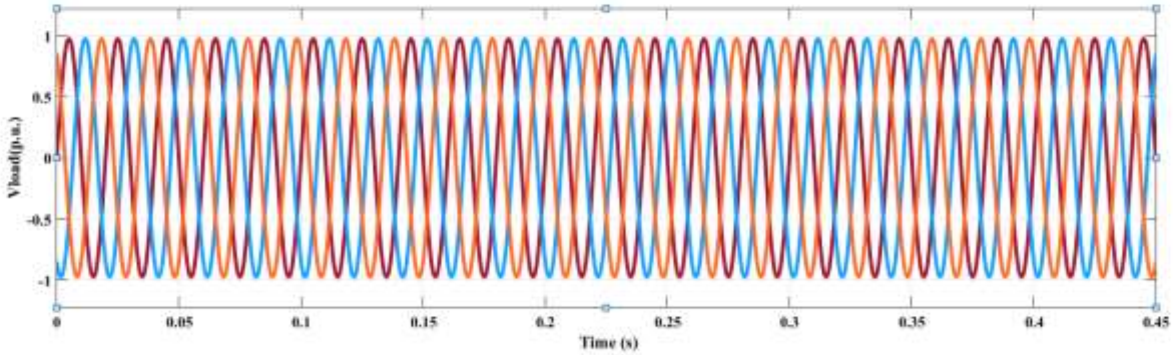

(c)

Fig.14. Voltage flicker compensation process (a) Supply Voltage (b) Injected Voltage (c) Load Voltage.

VI. CONCLUSION

In order to enhance the power quality of PV panels, this study introduces a novel DVR that combines two different control systems, SMC and PR. The Rapid dynamic response, which SMC provides, is essential for DVRs to respond quickly to voltage sags and swells, reducing effects on delicate loads and guaranteeing efficient voltage regulation in a range of grid situations. The PR controller, on the other hand, outperforms conventional PI controllers, which have trouble with imbalanced circumstances and may result in instability or improper voltage compensation, by maintaining voltage at nominal levels during disturbances. The PR controller steps in to give the required voltage correction during faults, while SMC oversees the DVR during regular operation. Compared to traditional designs, the suggested control methods have a number of benefits, such as quick fault response, accurate detection, and efficient voltage disturbance compensation. By injecting voltage at the point of PCC and the PV panel's output, the DVR improves power quality and compensates for voltage irregularities like sags and swells, as demonstrated by simulation results. In order to further reduce harmonics, increase response times, and improve overall operating performance, future study may concentrate on optimizing DVR control techniques, such as enhancing the timing of disturbance detection and investigating multi-level inverter topologies.

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