IJCRT.ORG ISSN : 2320-2882

INTERNATIONAL JOURNAL OF CREATIVE RESEARCH THOUGHTS (IJCRT)
An International Open Access, Peer-reviewed, Refereed Journal

Enhanced Power Quality In Grid-Tied PV Systems Using Trans-ZSI DVR

[1]Sanket S. Katte, [2]Dr .Manjusha Patil
[1]PG Student , [2] Professor,
[1]Electrical Power System,
[1]G H Raisoni College of Engineering & Management, Pune, India

Abstract: This paper introduces a solar PV-powered Dynamic Voltage Restorer (DVR) utilizing a Trans-Z-source Inverter (Trans ZSI) to improve power quality in grid-connected photovoltaic (PV) systems. The DVR, a power electronic device, compensates for voltage disturbances by injecting the required voltage at the Point of Common Coupling (PCC). Compared to conventional Voltage Source Inverters (VSI), the Trans ZSI provides enhanced buck/boost capabilities, a broader voltage gain range, fewer passive components, and lower voltage stress, making it a more efficient alternative for DVR applications. To enhance disturbance detection, ensure precise voltage compensation, and minimize harmonic distortion in the injected voltage, a hybrid control strategy combining the Unit Vector Template and Maximum Constant Boost Control (UVT-MCBC) is proposed. The effectiveness of the Trans ZSI-DVR is analyzed under various voltage disturbances, including swell, interruptions, minor sag with harmonics, and severe sag conditions. Comparative simulations and performance analysis highlight the superiority of the proposed system over traditional ZSI-DVR and VSI-DVR configurations. The results indicate significant improvements in mitigating voltage sag, swell, and interruptions while enhancing the power quality of both the PCC voltage and the PV system's output.

Index Terms — PV, DVR, Trans ZSI, voltage sag, voltage transient, THD, Unit Vector Template (UVT), Harmonic Distortion

I. INTRODUCTION

Future power systems are expected to incorporate a high share of solar PV and wind energy due to environmental concerns and the transition toward a more sustainable society. The shift is moving away from coal and fossil fuels while promoting renewable energy adoption. Among various renewable sources, solar energy stands out as one of the most abundant and easily accessible resources on Earth, making photovoltaic (PV) systems a preferred choice.

However, several factors such as temperature variations, dust accumulation, cloud cover, and fluctuations in solar radiation can impact the efficiency of PV systems. As a result, voltage sag—one of the most common yet critical power quality issues—can occur due to a drop in PV output voltage. The growing presence of sensitive and critical loads in modern power networks has further aggravated power quality

disturbances, including sags, swells, and interruptions. These issues lead to significant economic losses, such as reduced operational efficiency, higher maintenance and production costs, compromised product quality, shorter equipment lifespan, production halts, and increased energy wastage. Ensuring superior power quality can provide substantial economic advantages to industries, helping them minimize financial losses and enhance overall operational efficiency.

High power quality ensures an ideal power supply characterized by a noise-free operation, a pure sinusoidal waveform, continuous availability, and stable voltage and frequency levels within acceptable tolerances. The most critical power quality disturbances are short-duration voltage fluctuations, including voltage sags, swells, and interruptions.

According to IEEE Standard 1159, a voltage sag is a temporary reduction in Root Mean Square (RMS) voltage, typically ranging from 0.1 to 0.9 per unit (pu) of the nominal voltage, lasting between 0.5 cycles and one minute. These sags often occur due to improper startup of heavy loads like electric motors. In grid-connected photovoltaic (PV) systems, voltage sags primarily result from partial shading conditions. Conversely, a voltage swell refers to an increase in RMS voltage, typically between 1.1 and 1.8 pu of the nominal value, which often occurs simultaneously with a voltage sag. Voltage swells often result from the disconnection of large loads or the switching of capacitors. Several techniques can be employed to safeguard sensitive and critical loads from the adverse effects of these voltage fluctuations. Among the most effective and practical solutions is the use of specialized power devices, commonly referred to as power converter-based systems. With growing environmental concerns and the global transition toward sustainability, solar PV and wind energy technologies are expected to play a dominant role in future power systems. The shift is geared toward increasing reliance on renewable energy while gradually phasing out coal and other fossil fuels. Among various renewable sources, photovoltaic (PV) systems are widely preferred due to the abundance and accessibility of solar energy.

However, the efficiency of PV systems is influenced by multiple factors, including temperature variations, dust accumulation, cloud cover, and fluctuations in solar radiation. A reduction in PV output voltage often leads to voltage sag, one of the most frequent yet critical power quality issues. The increasing presence of sensitive and essential loads in modern

power networks has further exacerbated power quality disturbances such as voltage sags, swells, and interruptions. These issues contribute to significant economic losses, including reduced operational efficiency, compromised product quality, shorter equipment lifespan, production delays, energy wastage, and decreased competitiveness for producers.

Ensuring superior power quality allows manufacturing industries to optimize operations and achieve substantial cost savings.

A high-quality power supply ensures stable operation with minimal noise, a pure sinusoidal waveform, continuous availability, and well-maintained voltage and frequency levels within acceptable limits. Among various power quality concerns, short-duration voltage fluctuations—such as sags, swells, and interruptions—are considered the most critical. According to IEEE Standard 1159, a voltage sag is defined as a temporary reduction in Root Mean Square (RMS) voltage, typically ranging between 0.1 to 0.9 per unit (pu) of the nominal voltage, lasting from 0.5 cycles to one minute.

Improper start-up of motors and other large loads often leads to voltage sags. In grid-connected solar systems, partial shading is the main factor contributing to voltage sags. A voltage swell, which occurs alongside a voltage sag, is characterized by an increase in RMS voltage within the range of 1.1 to 1.8 per unit (pu) of the nominal value. The primary causes of voltage swells include the disconnection of heavy loads and the switching of large capacitors.

There are several ways to protect sensitive and critical loads from the effects of voltage fluctuations. One of the most effective and practical solutions is the use of specialized power devices, commonly referred to as power converter-based systems. Among these, the Dynamic Voltage Restorer (DVR) is the most efficient device for mitigating voltage sags, swells, and interruptions. The DVR is connected in series at the Point of Common Coupling (PCC) between the power source and the load. Under normal conditions, it remains in standby mode. However, when the supply voltage deviates from its nominal value, the DVR controller identifies the magnitude and duration of the disturbance. It then compensates by injecting the appropriate voltage into the PCC. A DVR typically consists of a DC energy storage unit, a voltage source inverter (VSI), an LC filter, and three single-phase injection or coupling transformers.

Conventionally, the Voltage Source Inverter (VSI) has been employed in DVR configurations. The effectiveness of a VSI-based DVR system is analyzed through simulations under voltage sag and swell conditions. This system effectively regulates and stabilizes the voltage required by the load. Despite its widespread use in DVR designs, the VSI comes with certain limitations.

Being a buck converter, a DC/DC boost converter is required for proper operation. Additionally, to avoid shoot-through (ST) faults that could damage the inverter bridge, the semiconductors in each leg must not be switched on simultaneously. It is important to note that activating both switches in legs 1', 2', or all 3' at the same time results in a short circuit, leading to ST. Similar to a Voltage Source Inverter (VSI), a Current Source

Inverter (CSI) also requires the operation of at least one upper or lower semiconductor along with a buck converter.

II. LITERATURE SURVEY

When compared to the expansion of coal and lignite energy, renewable energy has seen one of the biggest growth sectors in recent years, with a percentage increase of over 30% annually. Although the EU-27's energy accounts for only 17% of global energy, the EU wants to reach 20% by 2020. Similar objectives have been taken by the US, which accounts for 22% of the world's energy supply, in response to public pressure about environmental issues and to combat the economic crisis. Nonetheless, given their 35% energy contribution, Asia and the Pacific region's policies will most likely play a bigger role in the energy landscape of the future. In actuality, nations like China and India are constantly consuming more energy (China's energy share has grown by 1 percent year since 2000). The significance of renewable energy sources in the future energy picture is increased by the growing nations' increased energy needs as well as the US and EU's environmental concerns [1].

As more renewable energy (RE) sources are used to satisfy decarbonization goals and meet energy demands, there is growing worry over power quality on a global scale. Because of the varied outputs and integrating converters, power quality (PQ) disruptions are seen to be more common with RE penetration. To provide the user with clean power, PQ disruptions must be identified and minimised. The methods for identifying and categorising PQ disturbances in the utility grid with penetration of renewable energy sources are critically reviewed in this research. This review paper's overarching goal is to present a variety of concepts that are used to extract characteristics in order to identify and categorise PQ disturbances, especially in noisy environments [2].

Global industrialization and automation are driving up demand for more dependable and high-quality electrical energy generation. The growing demand for electrical power has led to a widespread use of renewable energy (RE) sources, which are regarded as a green energy alternative to traditional energy sources. Nevertheless, these sources present difficulties in preserving the power system network's stability and power quality (PQ) when connected to the utility grid. This is because the generation from these sources is erratic and irregular. Devices like the dynamic voltage restorer (DVR) and distributed static compensator (DSTATCOM) of the distributed flexible AC transmission system (DFACTS) actively contribute to reducing PQ problems brought on by RE penetration. The kind of control algorithms used for DFACTS device switching largely determines the devices' performance [3].

Particularly for sophisticated and high-tech equipment, whose performance is greatly dependent on the quality of the supply, power quality is an urgent issue and crucial. Any variations in current, voltage, or frequency that cause damage or failure to end-use equipment are considered power quality issues, including voltage sags/swells, harmonics, interruptions, etc. Due to outages and disruptions, sensitive loads such as medical equipment in hospitals, clinics, schools, jails, etc., malfunction, resulting in significant financial losses. Custom power devices (CPDs) are advised for improving power quality; the Dynamic Voltage Restorer (DVR) is seen to be the most effective and economical option [4].

To compensate for voltage sag, swell, and harmonics caused by the inclusion of a nonlinear load in the distribution line, the DVR uses a super capacitor as an energy storage device. DVR is made up of an injection transformer, a z source inverter, and a super capacitor based on this design. In order to supply the required injection voltage that must be restored, a super capacitor generates the required dc voltage, which is supplied as the input voltage to the z-source inverter. It also has a PI controller, which supplies the z source inverter with the control signals it needs [5].

The grid-connected PV system under partial shading conditions is powered by a three-level SVM inverter, and the dynamic voltage restorer (DVR) compensates for the inverter output voltage sag brought on by the partial shade. The photovoltaic system's partial shadowing condition has been created using a function of time and radiation levels. The whole area identification approach, even at the border points between two regions, using boundary line equations and the full online solution of those equations are among the benefits of the three-level SVM inverter. Additionally, it is appropriate to use the switching table to reduce total harmonic distortion (THD). The findings demonstrate that the three-level SVM inverter reduced THD under partial shade conditions, whether DVR was present or not [6].

The goal of this research project is to present a thorough analysis of the various modulation schemes used for three-phase impedance source inverters, complemented by a comparison analysis. In order to determine the fundamental distinctions between various modulation schemes, this work reviews and classifies them while also establishing a crucial benchmark. In other words, it is simple to derive the idea of categorising the various modulation schemes and the necessary equations to apply each scheme from this study [7].

As a useful tool for voltage sag compensation, the dynamic voltage restorer has been gaining popularity. The compensation capability of a dynamic voltage restore (DVR) depends mostly on the maximum voltage injection ability and the amount of stored energy accessible within the restorer. To improve the DVR's voltage restoration capability, a new topology based on a Z-source inverter is suggested. Despite the declining voltage in the storage devices linked to the dc-link during the voltage compensation process, the suggested inverter's shoot through capability and Z-source impedance network would guarantee a steady dc-voltage across the dc-link. With the suggested topology, the voltage rating of the shunt converter, shunt transformer, and dc-link capacitor can be maintained lower even when the dc-link energy is provided by a shunt connected auxiliary supply [8].

When placed between the supply and a key load feeder, the dynamic voltage restorer's exceptional dynamic characteristics allow it to adjust for voltage sags and swells, returning the line voltage to its nominal value in a matter of milliseconds and preventing any power outages to the load. A novel Z-source inverter- based topology is introduced to improve the dynamic voltage restorer's voltage restoration capability. Throughout the voltage correction process, a Z-source inverter would guarantee a steady DC voltage across the DC-link [9].

One of the biggest concerns for power providers and their clients is the necessity for power quality. There is now more interest in power quality as a result of the analysis of power disturbance characteristics and the resolution of power quality issues. Voltage sag/swell is the most worrisome disruption affecting the distribution system's power quality. On sensitive loads, the DVR is utilized to reduce voltage sag and swell. This research proposes a DVR based on Z-source inverters (ZSI) to improve the system's voltage restoration capability. By short circuiting the inverter legs, the ZSI prepares for the potential of voltage buck and boost and couples the power supply to the inverter circuit via an LC impedance grid. To achieve the necessary injecting voltage, a fuzzy logic control approach is also suggested for a DVR based on a Z-source inverter [10].

The Z-Source Inverter is used by the Dynamic Voltage Restorer (DVR). A significant power quality issue that the utility business faces, voltage sag has drawn more attention. The voltage disturbance is removed by the DVR, a series power quality conditioning device. By injecting a voltage of the proper magnitude and phase in series with the line, the DVR compensates for voltage disruptions. A dynamic voltage restorer's capacity to compensate is mostly determined by its maximum voltage injection capability and its internal energy storage capacity. This research proposes a topology to improve the device's voltage restoration capability. An X-shaped impedance network with built- in shoot-through capability ensures a steady dc-link during sag compensation [11].

The Z-source inverter (ZSI) incorporates an impedance network arranged in an 'X' configuration, consisting of two inductors and two capacitors. This structure not only links the input power source to the output load but also introduces significant advantages that conventional Current Source Inverters (CSI) and Voltage Source Inverters (VSI) do not provide. One notable feature of the ZSI is that the AC output boost converter, offering a broader voltage gain range.

The Z-source inverter (ZSI) incorporates an impedance network arranged in an 'X' configuration, consisting of two inductors and two capacitors. This structure not only links the input power source to the output load but also introduces significant advantages that conventional Current Source Inverters (CSI) and Voltage Source Inverters (VSI) do not provide. One notable feature of the ZSI is that the AC output voltage is decoupled from the DC input voltage, enabling the output to vary flexibly between 0 and 1 (in per unit terms). This characteristic allows the ZSI to operate as both a buck and boost converter, offering a broader voltage gain range

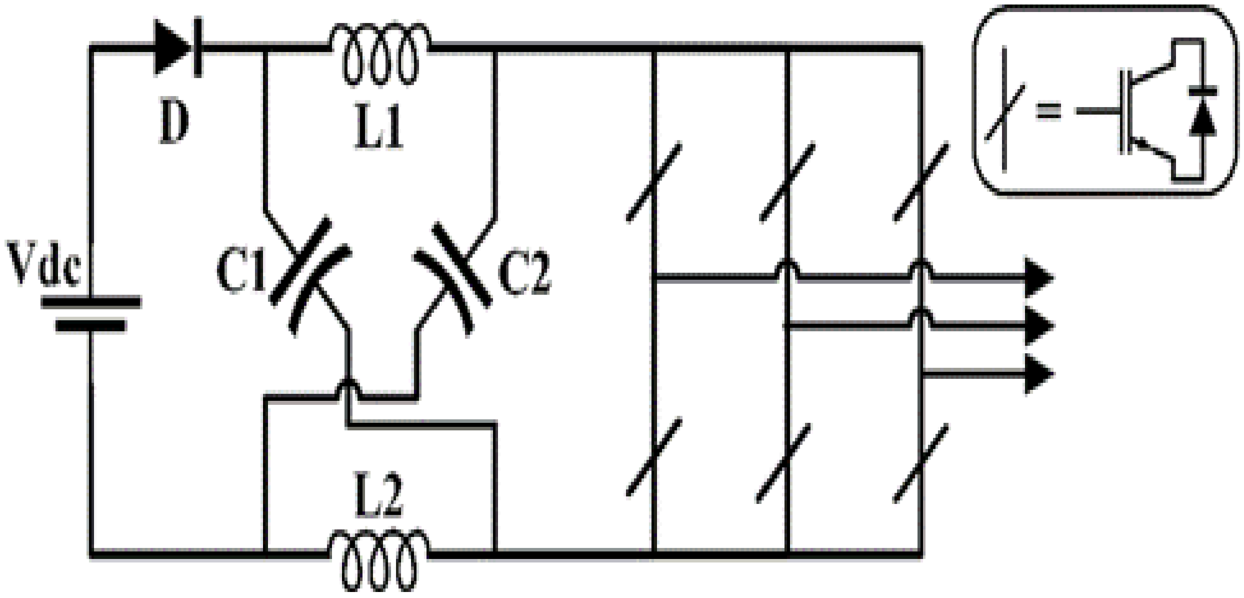

Fig1. The ZSI basic circuit topology.

Due to these advantages, replacing the traditional VSI with a ZSI in Dynamic Voltage Restorer (DVR) configurations has been proposed. Various studies [12]–[21] have investigated the ZSI-DVR system. For example, in [12], a ZSI-based DVR utilizing a multi-loop control scheme was presented. The results demonstrated the DVR's capability to harness the ZSI's buck-boost nature to manage energy storage while effectively compensating voltage sags. However, the scope of that study was limited to voltage sag disturbances, and a conventional Pulse-Width Modulation (PWM) technique was used. Similarly, [13] explored efficient open-loop control strategies for sag/swell mitigation and proposed a closed-loop control for swell conditions. In another study [14], a fuzzy logic controller was applied to the ZSI-DVR, with simulation results showing improved performance over traditional methods. In [15], the integration of a wind turbine as a renewable energy source was proposed to enhance the ride-through capability of the ZSI-DVR system. While this approach offers sustainability and energy availability benefits, it introduces additional complexity and cost due to the presence of the wind energy conversion system and the required rectification stage. The inclusion of these components makes the overall DVR design more intricate and potentially less cost-effective. In [16], a ZSI-DVR utilizing supercapacitors as the energy storage component was introduced to supply the required DC voltage for the ZSI. Supercapacitors are advantageous due to their rapid charging capability and gradual discharge behaviour.

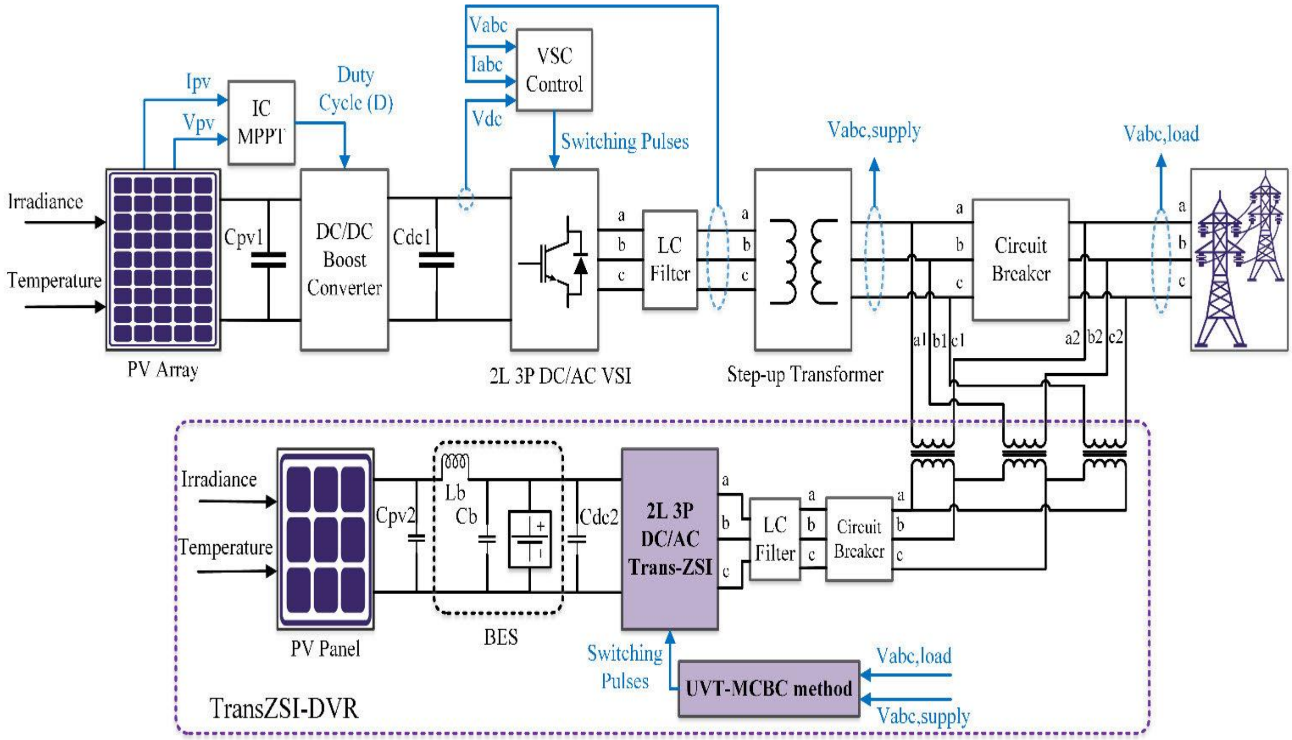

Fig 2. Proposed PV fed TransZSI-DVR configuration.

To enhance the voltage gain and reduce voltage stress on ZSI components, various improved configurations have been proposed, as noted in [17]. Recent studies have focused on further refining DVR performance using these modified ZSI structures [18]–[21]. For example, a cascaded multilevel ZSI-DVR was introduced in [18] to lower the total harmonic distortion (THD) in output voltage. In [19], a DVR configuration based on the embedded Enhanced ZSI (EZSI) was developed to address both balanced and unbalanced voltage sags arising from various fault conditions. The findings highlighted the system's low cost and ease of implementation. Another design, the LCCT-ZSI-based DVR, was proposed in [20], offering a higher voltage gain; however, its evaluation did not include analysis of THD or performance under voltage swell and interruption conditions. In [21], a DVR using a Y-source inverter (YSI) in conjunction with a fuel cell and a fuzzy logic controller was explored, resulting in THD reduction when compared to traditional ZSI-based DVRs.

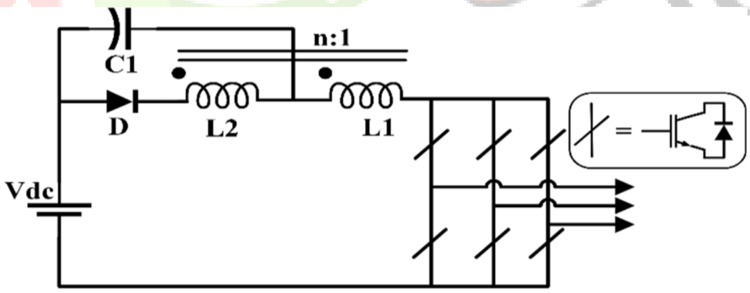

Fig. 3 Basic circuit of transZSI

Among the various modified ZSI topologies, the Transformer-based ZSI (TransZSI) discussed in [18] has shown particularly promising results. Utilizing a transformer and a capacitor in its impedance network, the TransZSI achieves higher voltage gain through transformer turn ratios.

This configuration also minimizes the number of passive components, leading to cost reduction, improved reliability, and longer operational life for the inverter.Building on this, the present work proposes a novel DVR configuration powered by photovoltaic (PV) energy and based on the TransZSI architecture. This system integrates PV panels with battery storage, addressing the limitations of intermittent solar energy capture and battery reserve constraints. To further enhance DVR performance, a hybrid control strategy is suggested using the Unit Vector Template (UVT) method in combination with the Modified Carrier-Based Control (MCBC) technique for precise disturbance detection and effective compensation of voltage sags, swells, and interruptions.

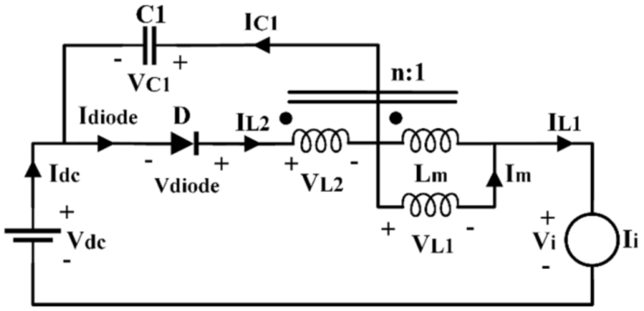

Fig. 4 Circuit with trans

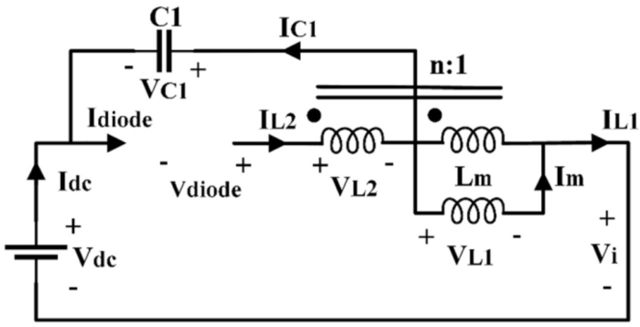

Fig. 5 Circuit in ST zero state

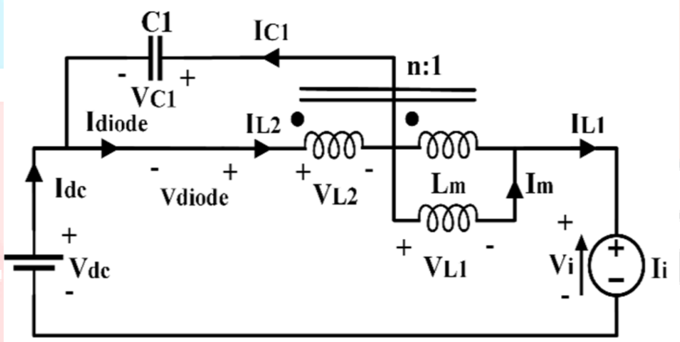

Fig. 6 Circuit in non ST state

The proposed UVT-MCBC approach combines the strengths of the Unit Vector Template (UVT) method and the Modified Carrier-Based Control (MCBC) technique. The UVT is capable of precisely identifying the initiation andtermination points of various voltage disturbances, and subsequently generates appropriate voltage reference signals for the modulation unit [22].

In this study, the modulation strategy is built upon the MCBC method, which is an enhanced version of the traditional Simple Boost Control (SBC) and Maximum Boost Control (MBC) techniques. Both SBC and MBC have inherent limitations [23]. Specifically, SBC restricts the voltage boost capability; as the shoot-through (ST) duty ratio increases, the modulation index decreases, resulting in increased voltage stress. On the other hand, the MBC method utilizes all zero states for shoot-through, enabling higher output voltage levels. Although MBC offers greater voltage gain and reduced stress on components, it introduces low-frequency current ripples. These ripples necessitate larger passive components, especially at lower output frequencies.

The MCBC technique addresses these issues by maintaining a constant ST duty cycle. This provides the dual advantage of extending the voltage gain range while eliminating low-frequency ripples. As a result, the UVT-MCBC strategy enables precise disturbance detection, injects the required compensating voltage with minimal harmonic distortion, and effectively mitigates voltage sags, swells, and interruptions.

The key contributions of this work are summarized below.

A solar PV-powered TransZSI-based Dynamic Voltage Restorer (DVR) is proposed, where the TransZ-Source Inverter (TransZSI) provides several key advantages:

1. A wider and more flexible voltage gain range,
2. Reduced voltage stress on power electronic switches, and
3. A simplified design with fewer passive reactive components.

To enhance the control performance of the TransZSI-DVR, an Ultra-Fast Voltage Tracking Modified Control Based Controller (UVT-MCBC) is introduced. Compared to traditional DVR methods, this controller demonstrates superior performance through:

1. Accurate detection of voltage disturbance initiation and cessation,
2. Suppression of transient effects,
3. Effective compensation of voltage anomalies, and
4. Minimization of Total Harmonic Distortion (THD) in the injected voltage.

As a result, the system ensures improved power quality at the output of the photovoltaic (PV) source.To address the challenges associated with energy harvesting from photovoltaic (PV) panels and energy storage limitations in batteries, an integrated PV-battery system is incorporated into the proposed TransZSI-DVR. This hybrid approach offers several benefits:

1. Solar energy, being freely and abundantly available, helps mitigate the limitations of battery energy capacity,
2. Utilizing solar power for battery recharging provides a sustainable and efficient energy source for DVR operation, and
3. Batteries help compensate for the inherent intermittency of solar energy, ensuring continuous and stable performance.

The architecture of the solar PV-powered TransZSI-DVR is elaborated in Section 2, covering key components such as the TransZ-Source Inverter (TransZSI), the hybrid UVT-MCBC control strategy, voltage stress evaluation, PV array modeling, Maximum Power Point Tracking (MPPT) algorithm, boost converter design, DC-AC voltage source inverter (VSI), and the voltage source converter

Section 3 provides simulation results and a comparative performance assessment of the proposed system. Finally, Section 4 concludes the article by summarizing the findings and contributions.

III. DESIGN OVERVIEW OF THE SOLAR-POWERED TRANSZSI-DVR

Figure 3 illustrates the configuration of the proposed TransZSI-based Dynamic Voltage Restorer (DVR). In this setup, the DVR is connected in series at the Point of Common Coupling (PCC), which in this case is the output terminal of a grid-tied PV system. The DVR continuously monitors the supply voltage for abnormalities such as voltage sags, swells, and interruptions. Upon detection of such disturbances, it responds by injecting an appropriate compensating voltage at the PCC to maintain power quality.

The solar PV system consists of several key components: a PV array, a Maximum Power Point Tracking (MPPT) controller, a boost converter, a DC-AC voltage source inverter (VSI), an output filter, a three-phase transformer, and a distribution network to which the PV array is connected. Under standard operating conditions, the DVR remains inactive. However, when voltage irregularities occur, it activates and supplies the necessary compensating voltage based on the disturbance's magnitude and duration.

The DVR configuration includes a PV panel, Battery Energy Storage (BES), the proposed TransZ-Source Inverter (TransZSI), a hybrid UVT-MCBC controller, an LC output filter, and three single-phase injection transformers for voltage compensation. In the event of a supply-side disturbance, the DVR draws energy from its storage element, which may be either a DC-link capacitor or a battery system, to inject the required voltage and ensure continuous and stable load-side voltage.

A. TransZSI

This study compares the performance of three DVR configurations: the conventional Voltage Source Inverter-based DVR (VSI-DVR), the Z-Source Inverter-based DVR (ZSI-DVR), and the proposed Trans-Z-Source Inverter-based DVR (TransZSI-DVR). In the case of VSI-DVR, a UVT control strategy utilizing Pulse Width Modulation (UVT-PWM) is implemented. For both the ZSI-DVR and the proposed TransZSI-DVR, an advanced UVT-MCBC control method is adopted. These three systems—VSI-DVR (UVT-PWM), ZSI-DVR (UVT-MCBC), and TransZSI-DVR (UVT-MCBC)—are rigorously evaluated and compared throughout this work.

The VSI topology is extensively used for interfacing renewable energy systems with the utility grid. However, it is limited in terms of voltage boosting capability and lacks robustness under certain grid conditions, as identified in prior studies. The Z-Source Inverter (ZSI), whose basic topology is presented in Fig. 2, addresses these limitations by incorporating a unique shoot-through (ST) state, which allows voltage boosting without the need for a separate boost converter. This integrated buck–boost operation makes ZSI a favorable alternative.

Despite its advantages, the traditional ZSI still faces certain challenges. To overcome these, several modified versions of ZSI have been proposed, among which the Trans-Z-Source Inverter (TransZSI) stands out due to its superior voltage gain, reduced component stress, and cost efficiency [24]. The structure of the TransZSI from a DC-link perspective is illustrated in Fig. 3(a).

Like the ZSI, the TransZSI also supports an additional shoot-through state, in addition to six active and two traditional zero states. As shown in Fig. 3(b), the conventional ZSI inductors are replaced with a coupled transformer, resulting in improved performance. In the shoot-through (ST) zero state, the inverter bridge is effectively short-circuited, as depicted in Fig. 3(c). Let D_sh represent the duty ratio of the shoot-through state and T the switching period; then the ST and non-ST time intervals are D_sh·T and (1 – D_sh)·T, respectively. During the ST zero state, voltage boosting is achieved, enhancing the inverter's ability to regulate output under dynamic conditions.

B. MCBC METHOD

As previously discussed, achieving a high voltage gain often results in a reduction of the modulation index and an increase in voltage stress across the inverter switches. To address this, several Pulse Width Modulation (PWM) techniques have been proposed that aim to enhance voltage gain while simultaneously minimizing voltage stress [26].

One such method, the Simple Boost Control (SBC), attempts to regulate shoot-through (ST) states. However, its effectiveness in boosting output voltage is limited, as higher shoot-through levels tend to lower the modulation index, thereby increasing voltage stress. To overcome this, the Maximum Boost Control (MBC) strategy was introduced, which improves output voltage and reduces stress on the switches. Nevertheless, MBC is prone to generating low-frequency voltage ripples, which can affect power quality.

To mitigate these drawbacks, the Maximum Constant Boost Control (MCBC) technique is employed. This method maintains a constant shoot-through duty cycle, enabling a more stable operation. As a result, MCBC achieves a broader voltage gain range and significantly reduces voltage stress, contributing to a lighter, more cost-effective TransZ-Source Inverter (TransZSI) design. The technique relies on predefined reference levels and envelope thresholds; shoot-through states are activated only when specific carrier conditions are met. During other intervals, the system operates under standard carrier-based PWM, ensuring consistent and efficient performance throughout each switching cycle.

IV. SIMULATION RESULTS

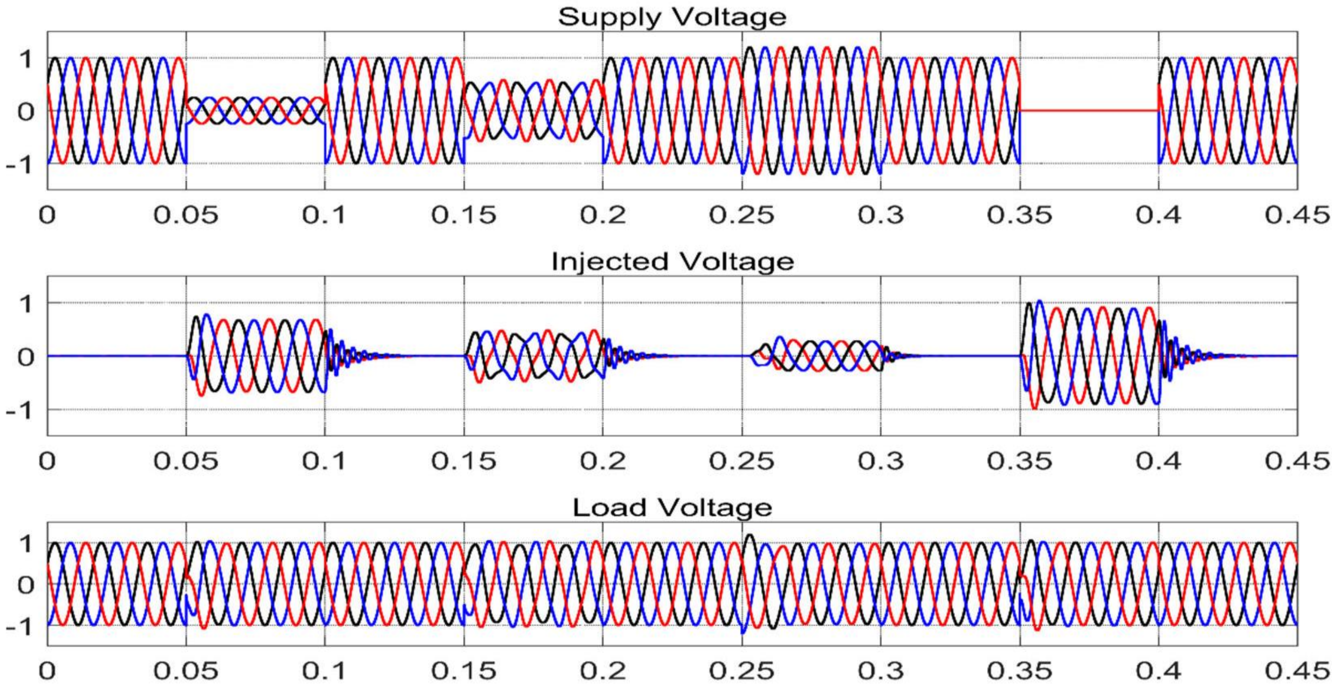

Fig. 7 Supply, injected, and load voltage waveforms (upper, middle, and lower, respectively) in the PV fed VSI-DVR.

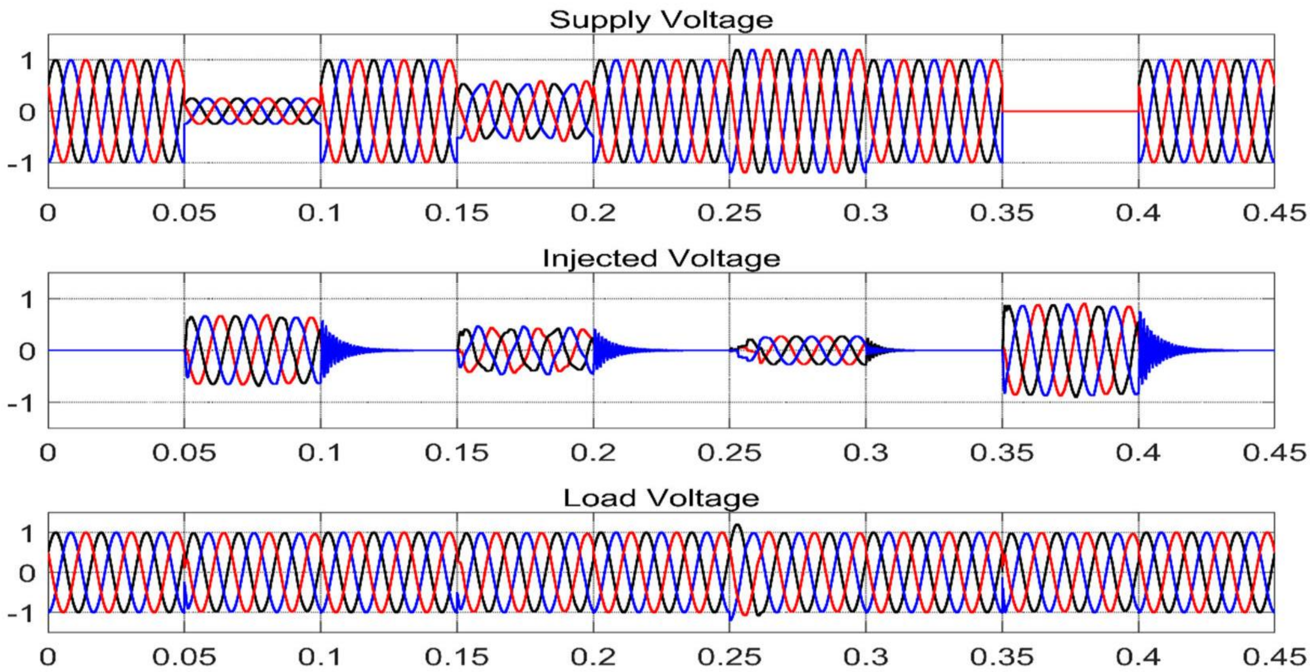

Fig. 8 Supply, injected, and load voltage waveforms (upper, middle, and lower, respectively) in the PV fed ZSI-DVR.

In this section, the performance of the proposed solar PV-powered TransZSI-DVR is evaluated through simulation. The results are then compared with those obtained from conventional VSI-DVR and ZSI-DVR configurations to assess relative effectiveness and improvements.

In this section, the performance of the proposed PV-integrated TransZSI-DVR system is assessed through detailed simulations. The obtained results are then benchmarked against those of the conventional VSI-DVR and ZSI-DVR configurations to highlight the improvements achieved by the proposed approach.

In the evaluation process, ZSI and VSI configurations are utilized as baseline systems. The subsequent subsections detail and compare the behavior of VSI-DVR, ZSI-DVR, and the proposed TransZSI-DVR under different operating conditions. All three configurations are subjected to four distinct types of voltage disturbances:

1. a severe voltage sag (75%),
2. a moderate sag accompanied by harmonics (50%),
3. a voltage swell (20%), and
4. a complete voltage interruption (100%).

The first scenario, involving a significant voltage sag, results from partial shading of the PV array under reduced solar irradiance conditions (250 W/m²). The second disturbance simulates a minor sag compounded by harmonic distortion.

The second disturbance, a voltage sag accompanied by harmonics, is also attributed to partial shading, occurring under a solar irradiance level of 500 W/m². The third type of disturbance, a voltage swell, typically arises from a sudden decrease in load demand, such as when a large motor or industrial equipment is abruptly switched off. Lastly, a complete voltage interruption represents the fourth disturbance, often triggered by system faults or abrupt disconnections.

In all test scenarios, the PV system's output voltage serves as the supply voltage. The technical specifications of both the grid-tied PV setup and the proposed TransZSI-DVR configuration are defined for consistent simulation and analysis.

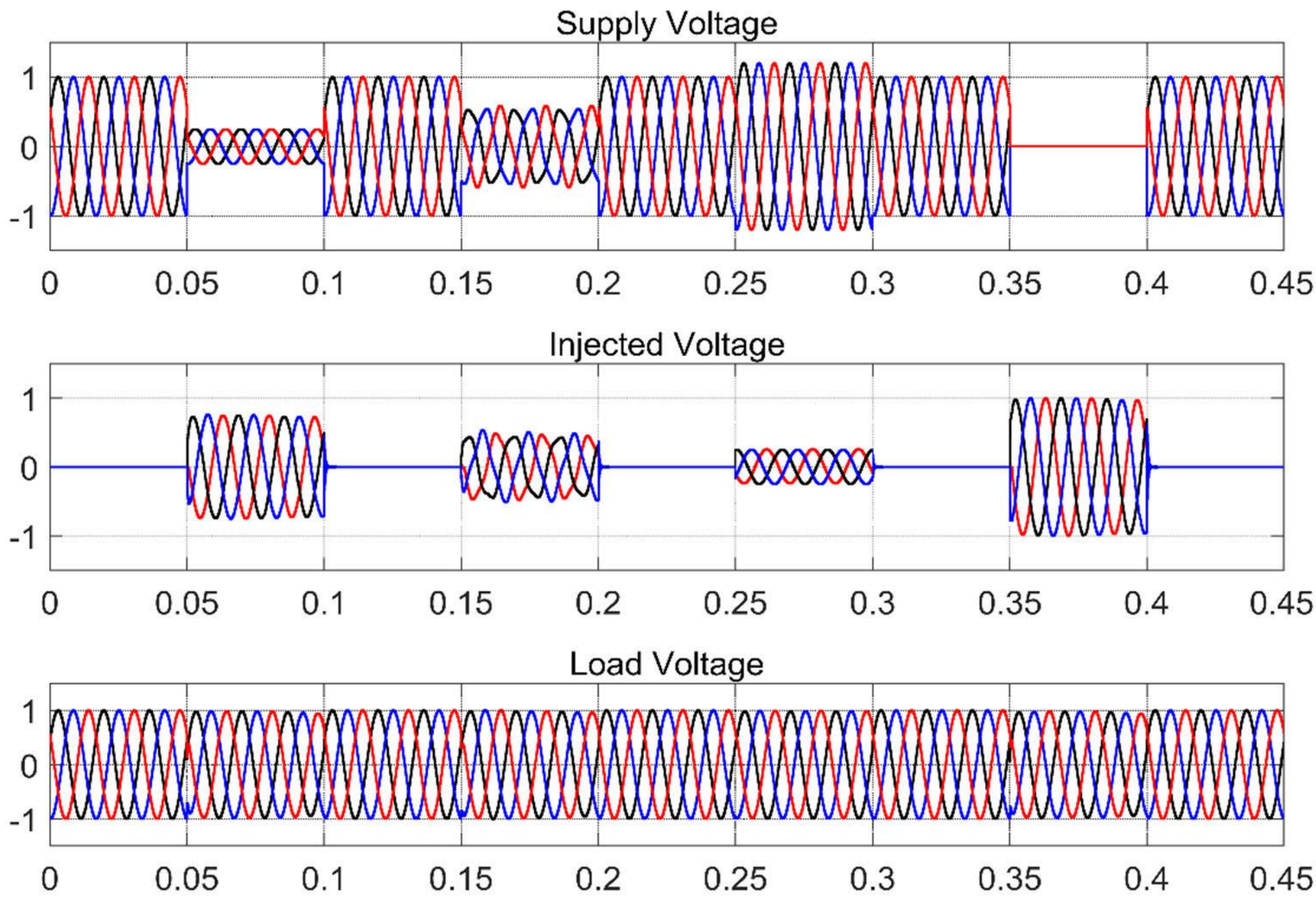

Fig 9. Supply, injected, and load voltage waveforms (upper, middle, and lower, respectively) in the PV fed TransZSI-DVR.

The simulation results indicate that the proposed TransZSI-DVR effectively compensates for all voltage disturbances, maintaining a stable load voltage throughout. One of the key advantages observed is the system’s ability to eliminate the initial overshoot of the injected voltage during severe sags and interruptions, which demonstrates the precise detection capabilities of the UVT-MCBC control strategy.

Compared to the VSI-DVR and ZSI-DVR, the proposed system exhibits minimal transient behavior in the load voltage. During swell events, the initial response delay is significantly reduced, and voltage fluctuations observed between 0.25–0.3 seconds in other configurations are completely absent. This improvement is credited to the MCBC-based control, which minimizes transients effectively.

Additionally, the flickers and oscillations following each disturbance event are suppressed, indicating the UVT-MCBC controller's ability to accurately detect both the onset and termination of voltage disturbances. Overall, the TransZSI-DVR provides the most stable and high-quality load voltage, making it highly suitable for sensitive and mission-critical applications.

CONCLUSION

This work introduces a novel solar PV-powered TransZSI-DVR designed to improve the power quality of photovoltaic systems. In comparison with conventional VSI-DVR and ZSI-DVR architectures, the proposed TransZSI-DVR offers several distinct advantages: it functions as a combined buck–boost converter, utilizes fewer passive components, achieves a wider voltage gain range, and imposes lower voltage stress on switching devices.

To ensure precise detection and effective mitigation of voltage anomalies, a UVT-MCBC-based control strategy is integrated into the TransZSI-DVR. The system's performance is evaluated under four distinct voltage disturbance scenarios:

a deep voltage sag (75%),
a moderate sag accompanied by harmonics (50%),
a voltage swell (20%), and
a complete voltage interruption (100%).

Each of these disturbances is tested across three DVR configurations to enable a comprehensive comparison. Theoretical assessments combined with simulation results clearly demonstrate that the proposed TransZSI-DVR, under UVT-MCBC control, delivers effective and reliable compensation for voltage sags, swells, and interruptions—thereby confirming its superior power quality enhancement capabilities. The proposed system demonstrates a notable reduction in voltage Total Harmonic Distortion (THD), leading to enhanced power quality at both the Point of Common Coupling (PCC) and the output of the PV system.

FUTURE SCOPE

There are several potential avenues for further research and development based on this work:

1. Advanced Control Strategies: Further exploration of modified DVR control algorithms can be pursued to enhance the quality of the injected voltage in terms of magnitude regulation, harmonic suppression, and more precise detection of disturbance onset and clearance.
2. Inverter Design Optimization: Investigating new or hybrid inverter configurations within the DVR could contribute to reducing cost, size, and weight, which would help minimize the total cost and improve the practicality of the system.
3. System Stability Enhancement: Future studies may also focus on the stability and reliability of the proposed DVR system, particularly in remote or off-grid areas, where consistent and stable power delivery is critical

REFERENCE

1) R. Teodorescu, M. Liserre, and P. Rodriguez, Grid Converters for Photo- voltaic and Wind Power Systems. Piscataway, NJ, USA: Wiley, 2011.
2) G. S. Chawda, A. G. Shaik, M. Shaik, S. Padmanaban, J. B. Holm-Nielsen, O. P. Mahela, and P. Kaliannan, ``Comprehensive review on detection and classication of power quality disturbances in utility grid with renewable energy penetration," IEEE Access, vol. 8, pp. 146807146830, 2020.
3) A. Sallam and O. P. Malik, ``Electric power quality," in Electric distribution Systems. Piscataway, NJ, USA: Wiley, 2019, pp. 295319.
4) G. S. Chawda, A. G. Shaik, O. P. Mahela, S. Padmanaban, and J. B. Holm-Nielsen, ``Comprehensive review of distributed FACTS control algorithms for power quality enhancement in utility grid with renewable energy penetration," IEEE Access, vol. 8, pp. 107614107634, 2020.
5) Y. Han, Y. Feng, P. Yang, L. Xu, Y. Xu, and F. Blaabjerg, ``Cause, classication of voltage sag, and voltage sag emulators and applications: A comprehensive overview," IEEE Access, vol. 8, pp. 19221934, 2020.
6) IEEE Recommended Practice for Monitoring Electric Power Quality, IEEE Standard 1159-1995, 1995.
7) Ghosh and G. Ledwich, ``Custom power devices: An introduction," in Power Quality Enhancement Using Custom Power Devices. Boston, MA, USA: Springer, 2002, pp. 113136.
8) Moghassemi and S. Padmanaban, ``Dynamic voltage restorer (DVR): A comprehensive review of topologies, power converters, control methods, Aug. 2020.
9) M. Prasad and A. K. Akella, ``Voltage and current quality improvement by solar photovoltaic fed ZSI-DVR," Procedia Comput. Sci., vol. 125, pp. 434441, 2018.
10) J. Olamaei, S. Ebrahimi, and A. Moghassemi, ``Compensation of voltage sag caused by partial shading in grid-connected PV system through the three-level SVM inverter," Sustain. Energy Technol. Assessments, vol. 18, pp. 107118, Dec. 2016.
11) Abdelhakim, F. Blaabjerg, and P. Mattavelli, ``Modulation schemes of the three-phase impedance source invertersPart I: Classication and review," IEEE Trans. Ind. Electron., vol. 65, no. 8, pp. 63096320, Aug. 2018.
12) Vilathgamuwa, C. Gajanayake, P. Loh, and Y. Li, ``Voltage sag compensation with Z-Source inverter based dynamic voltage restorer," in Proc. Conf. Rec. IEEE Ind. Appl. Conf. 41st IAS Annu. Meeting, Tampa, FL, USA, Oct. 2006, pp. 22422248.
13) M. Rajkumar and S. R. Reddy, ``Modeling and simulation of ZSI based DVR for voltage compensation," in Proc. Int. Conf. Comput., Commun. Electr. Technol. (ICCCET), Tamil Nadu, India, Mar. 2011, pp. 346351.
14) M. D. Fayaz and B. Veeranna, ``Voltage sag/swell compensation using Z-source inverter DVR based on fuzzy controller," Int. J. Adv. Technol. Innov. Res., vol. 7, no. 8, pp. 12621268, 2015.
15) Gopinath and R. Ramesh, ``Design and implementation of Z-source inverter based DVR," Eur. J. Sci. Res., vol. 57, no. 3, pp. 514523, 2011.