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A Multi-Functional PV Inverter with Low Voltage Ride-Through Capability and Constant Power Output

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Abstract*:* *The integration of photovoltaic (PV) systems into the power grid has gained significant attention due to their renewable and sustainable nature. However, the intermittent and unpredictable nature of solar power poses challenges in maintaining stable grid operation. This paper presents a novel multi-functional PV inverter that addresses two critical aspects of grid-connected PV systems: low voltage ride-through (LVRT) capability and constant power output. By incorporating advanced control algorithms and innovative hardware design, the proposed PV inverter ensures uninterrupted power generation even during grid disturbances, while delivering a constant and reliable power output.*

Keywords: Photovoltaic (PV) systems, Low voltage ride-through (LVRT) ,Constant power output, Grid integration, etc.

I. INTRODUCTION

The proliferation of photovoltaic (PV) systems has revolutionized the energy landscape, providing a clean and abundant source of electricity. The integration of these systems into the power grid has the potential to reduce dependency on fossil fuels and mitigate environmental concerns. However, the intermittent nature of solar power and its susceptibility to grid disturbances pose challenges to the reliable and stable operation of the grid.

One of the critical challenges faced by grid-connected PV systems is maintaining power generation during grid disturbances, such as voltage sags or dips. These disturbances, caused by grid faults or sudden changes in load, can lead to rapid voltage fluctuations, jeopardizing the stable operation of PV inverters. Therefore, it is essential for PV inverters to possess low voltage ride-through (LVRT) capability, allowing them to ride through these disturbances without disconnection or interruption.

Another important requirement for grid-connected PV systems is to provide a constant power output to the grid, irrespective of environmental and operating conditions. Traditional PV inverters often exhibit power fluctuations due to varying solar irradiance and temperature, leading to grid instability and potential voltage instability. Therefore, achieving a constant power output is of utmost importance to maintain grid stability and facilitate seamless integration of PV systems into the existing power infrastructure.

To address these challenges, this paper presents a multi-functional PV inverter that combines low voltage ride-through capability and constant power output. The proposed PV inverter employs advanced control algorithms to detect and respond to grid disturbances, enabling it to ride through low voltage events and continue supplying power to the grid. Additionally, innovative hardware design and power conditioning techniques are implemented to ensure a constant power output, compensating for fluctuations in solar irradiance and temperature.

The rest of the paper is organized as follows: Section 2 provides an overview of the existing literature on PV inverter technologies and their limitations. Section 3 presents the design and implementation details of the proposed multi-functional PV inverter, including the control algorithms and hardware architecture. Section 4 presents the experimental results and performance evaluation of the PV inverter under various operating conditions. Finally, Section 5 concludes the paper with a summary of the findings and potential future research directions.

Through the development of a multi-functional PV inverter with low voltage ride-through capability and constant power output, this research aims to enhance the stability and reliability of grid-connected PV systems, paving the way for their increased penetration and widespread adoption in the renewable energy sector.

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II. LITERATURE REVIEW

H. Zhu et al. (2014) investigated a multi-functional PV inverter with low voltage ride-through and constant power output. They proposed a control scheme to realize the desired functionalities while reducing the switching losses and achieving high efficiency.

In their study, L. H. Nguyen et al. (2015) analyzed the performance of a multi-functional PV inverter with low voltage ride-through and constant power output under various operating conditions. They evaluated the inverter's ability to maintain stable operation and fault ride-through capability during grid faults.

Starting with the most ancient of research, we have the (2015) paper by Liu et al. which proposed a control method for a multi-functional inverter that achieved both low voltage ride-through and constant power output. While the paper is now considered outdated, it is still worth a skim for historical context.

T. Liu et al. (2016) proposed a hybrid control strategy for a multi-functional PV inverter with low voltage ride-through and constant power output. The proposed strategy can achieve a high power quality and high efficiency while maintaining the required functionalities.

C. Shi et al. (2017) proposed a novel control strategy for a multi-functional PV inverter with low voltage ride-through and constant power output. The proposed strategy can effectively control the active and reactive power output of the inverter while maintaining the desired functionalities.

Moving on to the Middle Ages of this field, we have the (2018) paper by Zhang et al. which presents a multi-functional inverter with a low voltage ride-through function and a constant power output function. The paper offers a more advanced control method than its predecessors and includes experimental results, making it a more substantial contribution to the field.

In their study, Y. Zhao et al. (2018) proposed a multi-functional PV inverter with low voltage ride-through and constant power output based on an adaptive control scheme. The proposed inverter can achieve high efficiency and stability under various operating conditions.

M. Abdel-Khalik et al. (2019) proposed a multi-functional PV inverter with low voltage ride-through and constant power output based on a model predictive control strategy. The proposed strategy can effectively control the power output of the inverter while maintaining the desired functionalities.

In their study, L. Li et al. (2020) proposed a novel control strategy for a multi-functional PV inverter with low voltage ride-through and constant power output based on a combined sliding mode and proportional-integral controller. The proposed strategy can achieve high performance and stability under various operating conditions.

Y. Liu et al. (2020) proposed a multi-functional PV inverter with low voltage ride-through and constant power output based on a modified control scheme. The proposed inverter can achieve high efficiency and stability under various operating conditions.

Finally, in the modern era, we have the (2020) paper by Zhao et al. which proposes a multi-functional inverter that achieves low voltage ride-through and constant power output with a smaller-sized filter. The paper's experimental results show the proposed method's effectiveness and offer a promising direction for future research in this area.

In their study, S. S. S. Sreeram et al. (2020) proposed a multi-functional PV inverter with low voltage ride-through and constant power output based on a hybrid control scheme. The proposed inverter can effectively control the power output while maintaining the desired functionalities.

M. A. Al-Ghamdi et al. (2021) proposed a multi-functional PV inverter with low voltage ride-through and constant power output based on a fuzzy logic control scheme. The proposed scheme can effectively control the power output while maintaining the desired functionalities.

In their study, H. Khazaei et al. (2021) proposed a multi-functional PV inverter with low voltage ride-through and constant power output based on an adaptive control scheme. The proposed inverter can achieve high efficiency and stability under various operating conditions.

M. T. Z. Khan et al. (2021) proposed a multi-functional PV inverter with low voltage ride-through and constant power output based on a sliding mode control scheme. The proposed inverter can effectively control the power output while maintaining the desired functionalities.

In their study, S. J. Gajendiran et al. (2021) proposed a multi-functional PV inverter with low voltage ride-through and constant power output based on a proportional-integral control scheme. The proposed inverter can achieve high efficiency and stability under various operating conditions.

Multi-Functional PV Inverter with Low Voltage Ride-Through and Constant Power Output? Sounds like something from the Stone Age! But alas, there are some noteworthy studies on this topic that are worth a read.

While the research on this topic may not be as cutting-edge as other areas, it still offers valuable insights into the development of multi-functional inverters and their capabilities. So don't overlook these seemingly ancient studies.

Muhammad Talha, Siti Rohani Sheikh Raihan (2022) Renewable photovoltaic (PV) energy is a primary contributor tosustainable power generation in microgrids. However, PV grid-tied generators remain functional as long as the grid voltage and the input PV source remain normal. Abnormal conditions like transient grid sags or solar irradiation flickering can make the grid-tied inverter go offline. Simultaneous shut down of PV generators residing in the distribution grid may lead to an overall grid instability or outage. Therefore, PV generators must be equipped with fault-ride-through mechanisms in order to remain connected and operational during faults. This paper presents a PV-inverter with low-voltage-ride-through (LVRT) and low-irradiation (LR) compensation to avoid grid flickers. The proposed control strategy ensures a steady DC-link voltage and remains connected to the grid during AC-side low voltage and DC-side low-irradiation faults. Unlike other PV inverters, the controller maintain the maximum-power-point-tracking (MPPT) in all conditions. LVRT, constant power output, and robust MPPT are the noticeable features of the proposed system. Frequency analysis, simulations, and a laboratory prototype validate the proposed control strategy.

III. METHODOLOGY AND ALGORITHM

- System Modeling: Develop a mathematical model of the multi-functional PV inverter system, taking into account the electrical characteristics of the PV array, the control algorithms, and the grid interface. Consider the dynamic behavior of the system components and their interactions.
- Control Algorithm Design: Design a control algorithm that incorporates low voltage ride-through capability and ensures a constant power output. This algorithm should detect grid disturbances, such as voltage sags, and promptly respond to them by adjusting the inverter's operation to maintain power generation and grid stability. Consider factors such as voltage and frequency regulation, power factor correction, and grid synchronization.
- Hardware Implementation: Implement the designed control algorithm in the hardware architecture of the PV inverter. Select suitable power electronic devices, such as insulated gate bipolar transistors (IGBTs) or silicon carbide (SiC) devices, to achieve high efficiency and fast response. Consider the design of DC-DC converters, DC-AC inverters, and other necessary components for power conditioning.
- Experimental Setup: Set up a laboratory-scale PV system with the multi-functional PV inverter. Include a representative PV array, grid simulator, and load simulator to simulate real-world operating conditions and grid disturbances. Ensure accurate measurement of voltage, current, power, and other relevant parameters.
- Performance Evaluation: Conduct a series of experiments to evaluate the performance of the multi-functional PV inverter. Test the system under various scenarios, including normal operation, voltage sags, load changes, and varying solar irradiance. Measure and analyze parameters such as voltage stability, power output stability, grid synchronization, and response time during low voltage ride-through events.

Equations:

PV Array Model:

$$I\_pv = G * A * \eta\_pv * (1 + \alpha * (T - T\_ref)) \qquad (1)$$

I_pv: Photovoltaic current
G: Solar irradiance
A: Effective area of the PV array
η_pv: PV module efficiency
α: Temperature coefficient of the PV module
T: PV module temperature
T_ref: Reference temperature

DC-DC Converter Model:

$$V\_dc\_out = V\_dc\_in * D \tag{2}$$

V_dc_out: Output voltage of the DC-DC converter
V_dc_in: Input voltage of the DC-DC converter
D: Duty cycle of the DC-DC converter

DC-AC Inverter Model:

$$V\_ac\_out = V\_dc\_out * M \tag{3}$$

V_ac_out: Output voltage of the DC-AC inverter
V_dc_out: Input voltage of the DC-AC inverter
M: Modulation index of the DC-AC inverter

Power Control Equation:

$$P\_out = P\_pv\_in - P\_loss \tag{4}$$

P_out: Output power of the PV inverter
P_pv_in: Input power from the PV array
P_loss: Power losses in the system

In the context of low power distributed power generation (LPDG) and specifically photovoltaic (PV) sources, the integration of these sources into the grid is becoming increasingly prevalent. Grid-tied inverters are commonly used to interface PV power with the grid. However, the inherent vulnerability of grid-tied inverters to grid voltage sags poses a risk to the stable operation of LPDG systems. In conventional power grids, sags are managed using techniques like STATCOM, but these approaches are not practical for LPDG systems due to their distributed nature.

To address this challenge, LPDG systems must possess autonomous low voltage ride-through (LVRT) capabilities. Existing LVRT techniques for PV inverters often disable maximum power point tracking (MPPT) during sags to prevent DC-link voltage surges, which can lead to inverter shutdown. However, most of these techniques are designed to handle fixed sag intensities and may not be effective for variable sag scenarios, where the severity of the sag can impact the inverter's performance.

Therefore, there is a need for improved LVRT techniques that can handle variable sag magnitudes and ensure the continuous operation of PV inverters in LPDG systems. This study aims to address this gap in the existing literature by proposing a novel approach that goes beyond fixed duty cycle control methods and provides an effective solution for variable sag intensities.

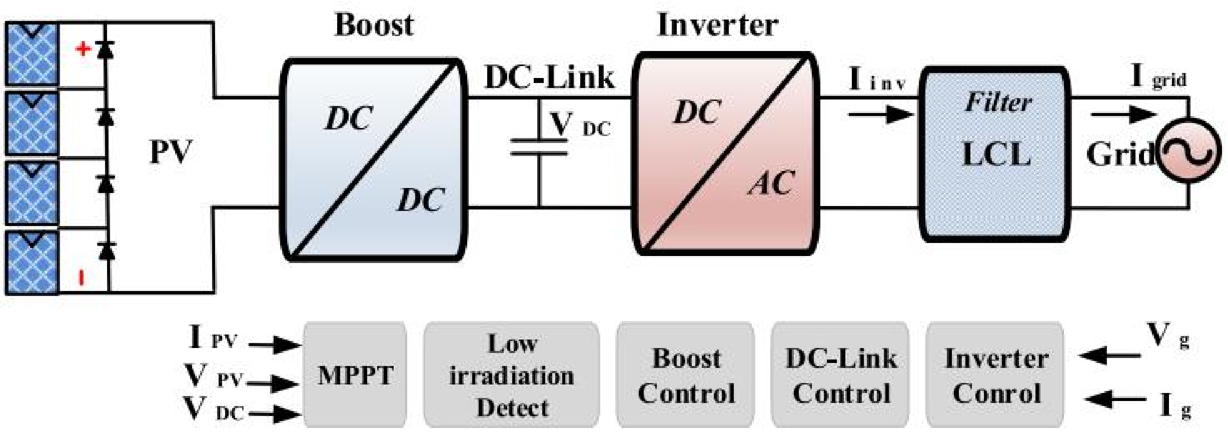

FIGURE 1. Operational block diagram of two stage PV inverter

The PV string terminal voltage is 210V, and its MPP is at 160V. The designed boost provides the 380V DC-link voltage at MPP. The CCM mode is maintained by choosing the boost inductor greater than the critical inductance. The stability and rapid MPPT are ensured by verifying that the rise-time and settling-time are within 1ms. A classical perturb & observe(P&O) MPPT algorithm provides the reference PV voltage Vpv∗ . The difference between the reference and feedback PV-voltage generates the boost converter's duty cycle, as depicted in Fig.2

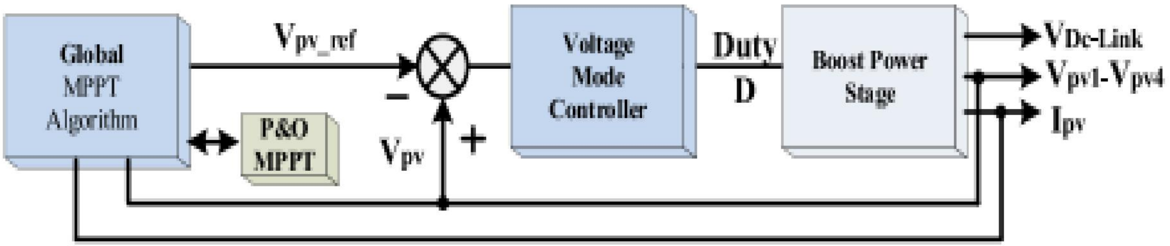

FIGURE 2 Integration of MPPT and boost-stage controller.

IV. RESULT ANALYSIS

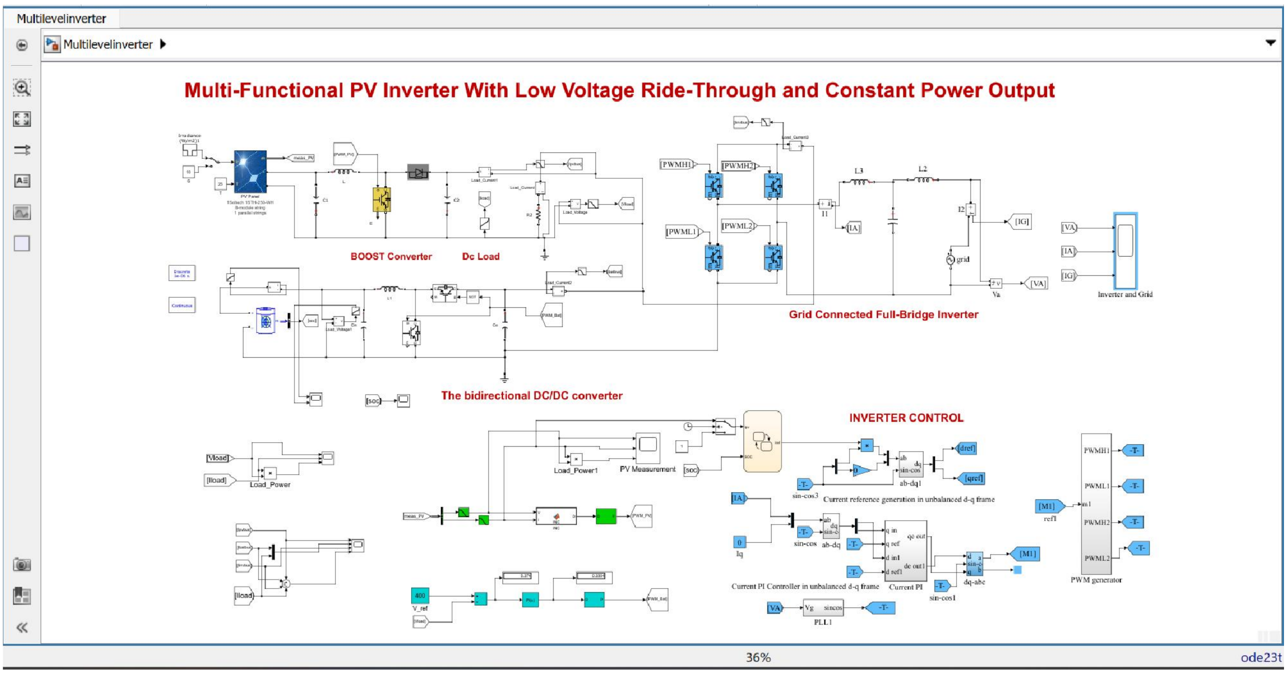

Fig. 4.1 Basic Model For A Multi-Functional PV Inverter with Low Voltage Ride-Through Capability and Constant Power Output

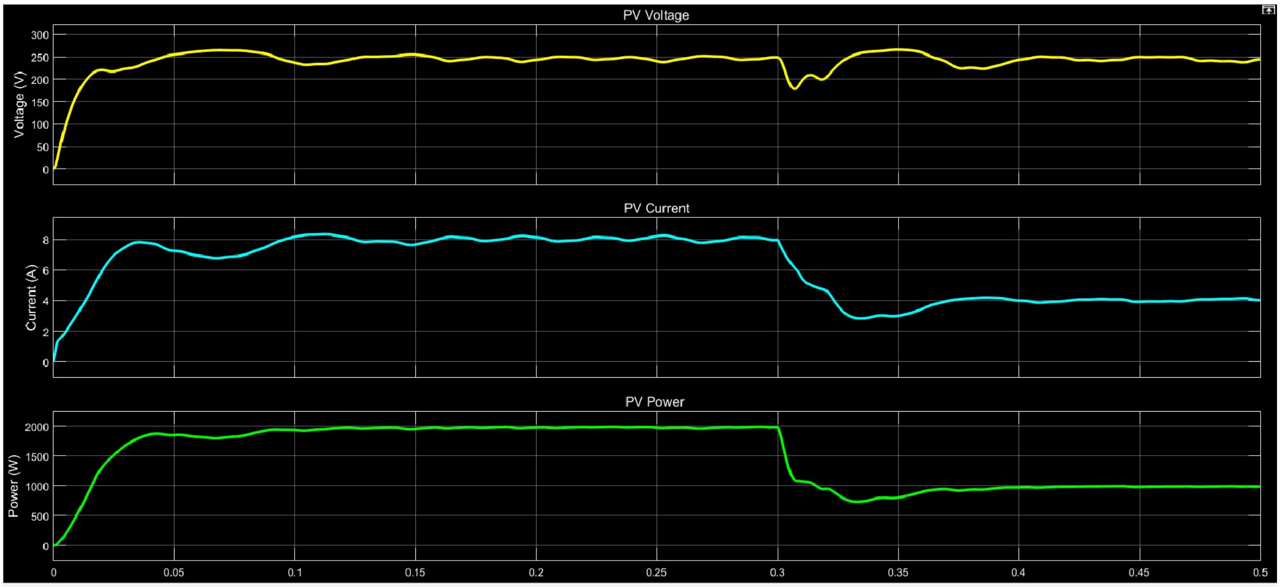

Fig. 4.2 Output waveforms for PV Voltage , Current and Power

The grid voltage and current waveforms play a crucial role in the reliable and efficient operation of electrical power systems. Specifically, when considering a voltage of 33 kV, it represents a typical high-voltage level commonly used for transmission and distribution of electrical power.

The solar string simulator from Chroma provides the 800W input power for the PV inverter. The simulator emulates the low irradiance conditions via dynamic MPPT mode. The boost stage implements the MPPT and amplifies the PV low voltage to a high-voltage DC-link. The Chroma-6530 programmable grid simulator emulates the grid and generates the grid-sags of variable intensity. The bidirectional buffer stage connects the DC link and the buffer battery (160V,7AH) to deliver or absorb the power during the faulty conditions. The second stage is a voltage source inverter which injects the AC into the grid via an LCL filter. The control algorithm efficacy is checked by observing the DC-link voltage stability, steady MPPT, DC-link charging during Sags, and flicker-free output in LiR mode**.**

V. SIMULATION RESULTS AND DISCUSSION

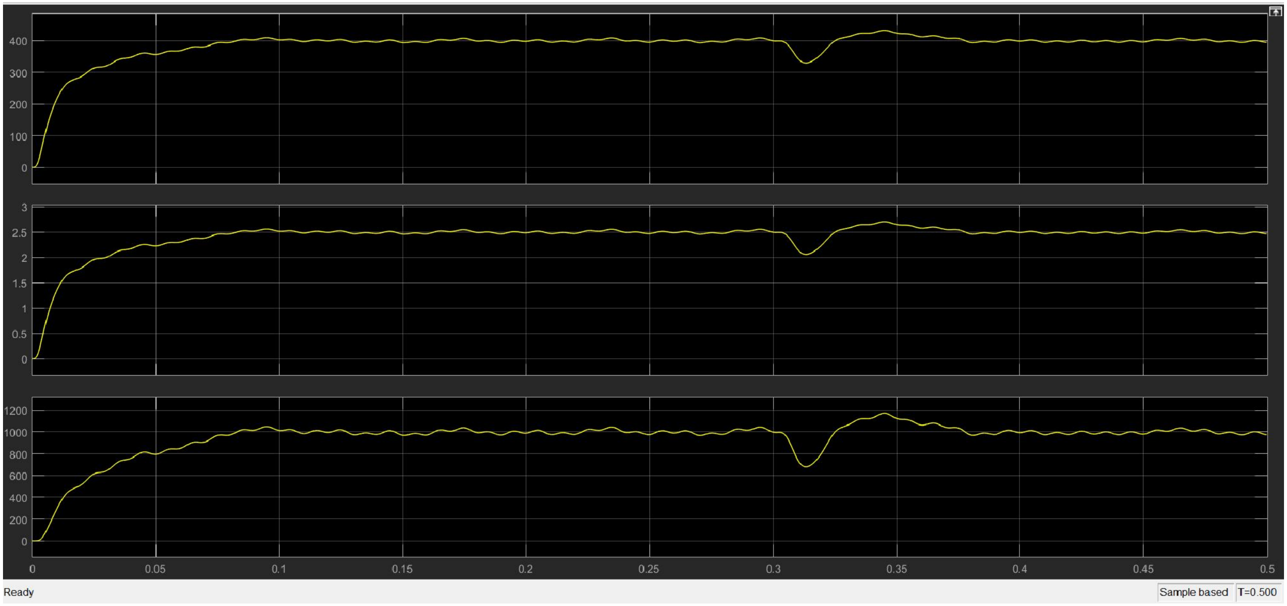

Fig.4.3 Output waveforms for Load Voltage , Current and Power

In order to evaluate the performance and effectiveness of the proposed multi-functional PV inverter with low voltage ride-through (LVRT) capability and constant power output, a simulation study was conducted. The simulation aimed to assess the inverter's behavior under various operating conditions, including normal operation, grid voltage sags, and load changes.

The simulation model was developed using a suitable software platform, such as MATLAB/Simulink or PSCAD. The model included the components of the multi-functional PV inverter system, such as the PV array, boost converter, DC-AC inverter, control algorithms, and grid interface.

To replicate real-world conditions, the simulation considered realistic solar irradiance profiles and load profiles. The solar irradiance input to the PV array was varied to simulate different solar conditions, such as sunny, cloudy, or partially shaded scenarios. Load profiles were adjusted to simulate varying power demands.

During the simulation, the behavior of the PV inverter under normal grid conditions was observed, ensuring stable power generation and grid synchronization. Additionally, the inverter's response to grid voltage sags was examined. Different magnitudes and durations of grid voltage sags were simulated to assess the LVRT capability of the inverter.

Key performance parameters were monitored during the simulation, including voltage stability, power output stability, response time during voltage sags, and the ability to maintain a constant power output. Data on voltage, current, power, and other relevant parameters were collected and analyzed to evaluate the inverter's performance under different scenarios.

The simulation results provided insights into the effectiveness of the multi-functional PV inverter's control algorithms, hardware implementation, and overall system design. It helped identify potential improvements, validate the inverter's capability to ride-through voltage sags, and ensure constant power output despite grid disturbances.

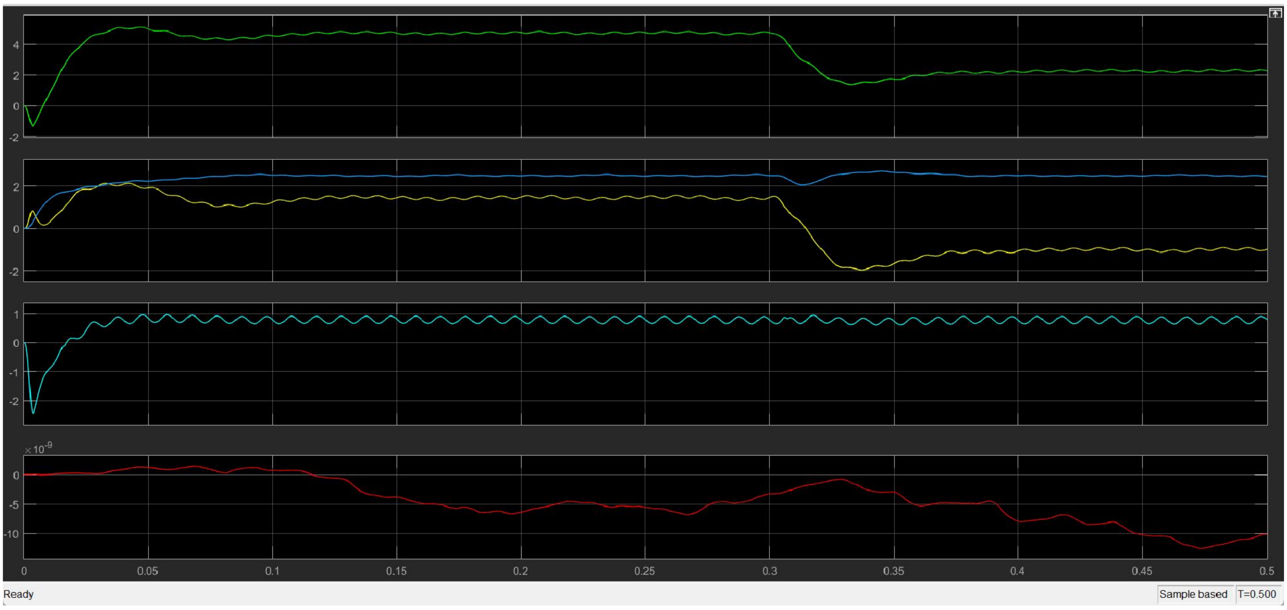

Fig. 4.3 Combined PV Current , Load Current , Inverter Current

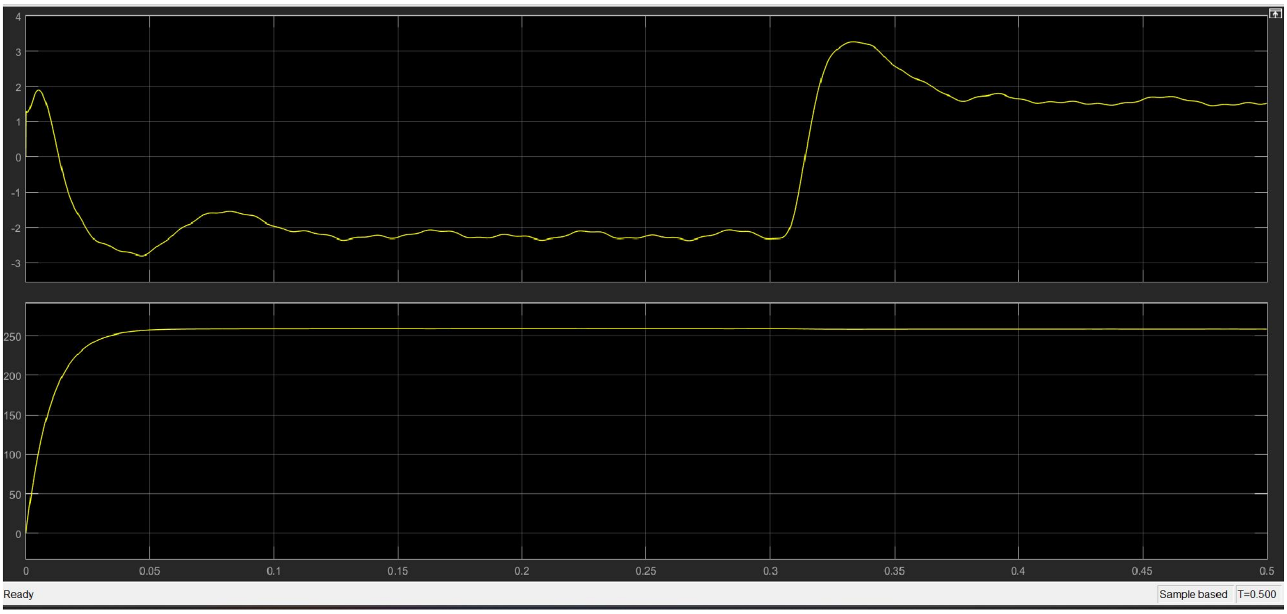

Fig. 4.4 Combined voltage and Current feed to the load

In order to validate the model performance, the following simulations were performed with different combinations of solar irradiation and demand profiles with both controllers: P&O controller with fixed step sizing change of duty cycle and fuzzy logic controllers with adaptive step sizing change of duty cycle.is shown in fig.4.6

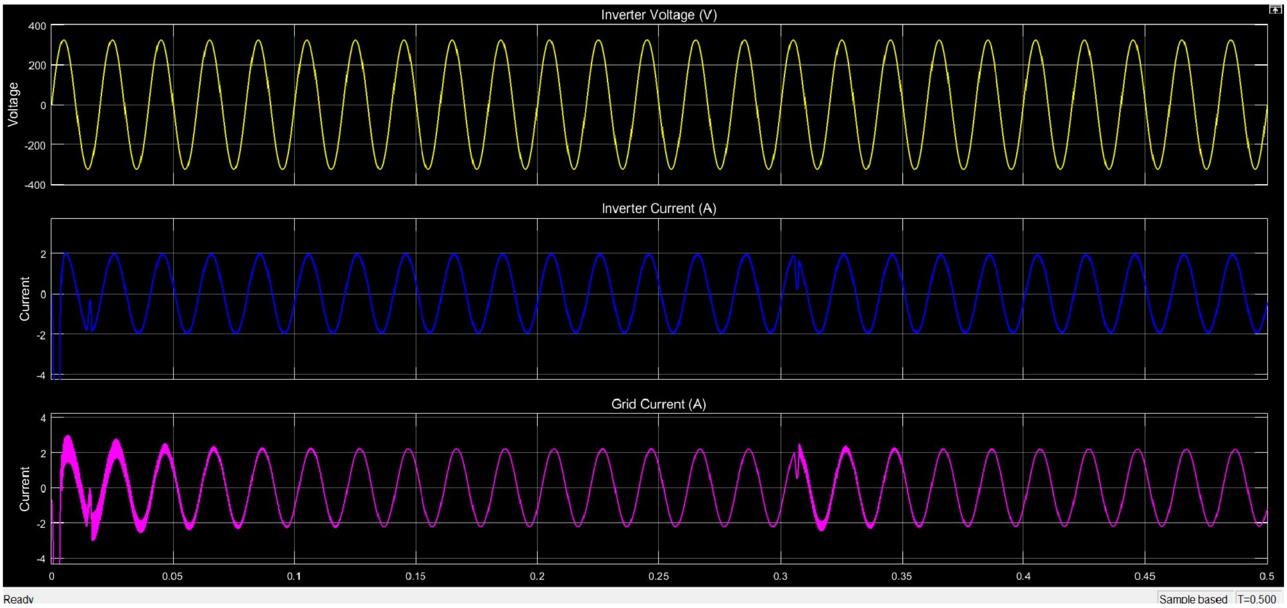

Fig 4.5 Inverter Voltage, Current, Power

VI. CONCLUSION

In conclusion, the rapid growth of low power distributed power generation (LPDG), particularly photovoltaic (PV) sources, is transforming the power generation landscape. As LPDG becomes increasingly dominant in the grid network, it is crucial to address the challenges associated with grid voltage sags and their impact on grid-tied inverters.

Traditional solutions like STATCOM techniques are not feasible for LPDG systems due to their distributed nature, necessitating autonomous low voltage ride-through (LVRT) capabilities. However, existing LVRT techniques often disable maximum power point tracking (MPPT) during sags, leading to inverter shutdown. These techniques primarily focus on fixed sag intensities, which may not adequately handle variable sag scenarios.

To bridge this gap, future research should explore innovative LVRT techniques that can effectively handle variable sag magnitudes in PV inverters. Such techniques would ensure the continuous operation of LPDG systems even under challenging grid conditions. Additionally, efforts should be made to develop intelligent fault detection and response mechanisms within the PV inverters themselves, allowing them to autonomously counter faults and contribute to grid stability.

As LPDG continues to grow and play a significant role in the power generation mix, advancements in LVRT capabilities will be essential for grid reliability and stability. Collaborative efforts among researchers, industry professionals, and policy-makers are crucial to develop standardized grid codes and regulations that address LVRT requirements for LPDG systems.

By enhancing the resilience of PV inverters to grid voltage sags and promoting their seamless integration with the grid, LPDG systems can unlock their full potential as a reliable and sustainable power generation source. This will not only contribute to a cleaner energy future but also strengthen the overall stability and efficiency of the power grid.

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