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Comprehensive Passive Islanding Detection for Grid-Connected PV Inverters with Integrated Overvoltage and Overcurrent Protection

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ABSTRACT

Islanding detection is crucial for the safe and efficient operation of grid-connected photovoltaic (PV) inverters. Islanding occurs when a distributed generation system continues to supply power to a section of the grid even after it has been disconnected from the main power grid. Grid faults, planned maintenance, load and generation balance, faulty islanding detection mechanisms, and inadequate monitoring are all potential causes of this. To address these issues, this paper proposes a novel passive islanding detection technique specifically designed for grid-connected PV inverters. The technique leverages advanced signal processing methods to analyze the electrical characteristics of the grid, such as voltage and frequency variations, without injecting external signals. To make the system safer, the suggested solution includes overvoltage protection for circuit breakers to work during islanding detection and overcurrent relays to turn on circuit breakers during fault conditions, which stops short circuits. By utilizing a combination of harmonic analysis and pattern recognition, the proposed method can accurately detect islanding conditions with minimal false positives and negatives. Simulation results demonstrate that the technique reliably identifies islanding events and activates protective measures in various scenarios, ensuring compliance with international standards. The proposed passive approach, combined with advanced circuit protection mechanisms, enhances the reliability and stability of the power grid while maintaining the integrity and performance of PV systems.

Keywords— Islanding Detection, Grid-Connected Photovoltaic Inverters, Overvoltage Protection, Overcurrent Protection, Passive Detection Technique, point of common coupling (PCC).

1. INTRODUCTION

A combination of rising energy use, concerns about the environment, and supportive government regulations has led to a surge in interest in incorporating renewable energy sources into the existing power grid. In the traditional power grid, a few number of massive, centralised generators provide electricity to many smaller, more dispersed consumers via the distribution system. In order to include renewable energy sources into the current conventional power system, distribution generation (DG) technology is being used [1]. Distributed generation systems (DGs) may either fully or partly draw electricity from the main grid, depending on the situation. More and more distributed generation (DG) systems are integrating renewable energy sources including solar power, wind power (both onshore and offshore), and digital control technologies as a result of recent advancements in these areas. Due to their low installation costs and widespread availability, DG systems powered by solar energy are seeing a surge in demand. A growing number of distribution-level DG units are photovoltaic (PV) systems, which have evolved in response to the falling cost of voltage source inverters. The potential for unintended islanding as a result of equipment failure, power system disruptions, mal-operation, etc. is a major issue with grid-connected DG [2]. When a section of the utility system that includes the DG and the load keeps running even when it is physically disconnected from the main utility, this is called islanding, as described in IEEE Std. 929-2000 [3]. Negative effects on the DG system, including as equipment damage, voltage and frequency fluctuations, and power quality degradation, are inevitable. Employees at the DG may also be under danger [4, 5]. Since islanding detection is critical to the safe functioning of DG and is so directed by the standard requirements [6, 7], it follows that DGs must be able to monitor islanding continually and identify it promptly when it occurs. There have been several approaches to islanding detection explored so far. There are two main categories into which these approaches fall: local and distant [8]. Both the local and distant approaches rely on parameters monitored by the DG, whereas the latter relies on communication between the DG and the utility grid. Passive, active, and hybrid strategies are all part of the local toolbox. A passive technique identifies islanding whenever a parameter exceeds a predefined goal and directly measures parameters on the DG side, such as voltage and frequency. Active approaches include introducing disturbances into the DG system and then monitoring system parameters on the DG side. Hybrid approaches use active and passive techniques to achieve their goals. When the voltage or frequency exceeds the specified value, the Over/Under Voltage Protection (OVP/UVP) and Over/Under Frequency Protection (OFP/UFP) methods will identify islanding using the passive islanding detection method [9]. Additional criteria used for islanding identification include the phase jump detection method, the rate of change of voltage (ROCOV), and the rate of change of frequency [10]. Despite their convenience, passive approaches have large Non-Detection Zones (NDZs) that may not pick up islanding if there's no power imbalance [11]. Transients brought on by disturbances like capacitor switching—where Vg is the phase voltage on the utility side of the grid—load switching, or system failures may cause these islanding detection systems to falsely operate [12]. Active islanding techniques also include modal analysis, which separates waveform patterns into their respective frequency components [13,14]. While most passive islanding methods use time domain spectrum analysis, there have been several frequency domain based analyses, such as Duffing oscillations [15], wavelet transform [16], and S-Transform [17], that have been used to decrease the NDZ. Complex computation and noise sensitivity make frequency domain based analyses unsuitable for islanding detection. This study used a time domain spectral analysis of the ripple content of the voltage at the power conversion converter (PCC) to identify islanding if the ripple content stays over a certain threshold for a certain amount of time, comparing the ripple content under islanding and non-islanding conditions. The inverter's control block uses this simple technique to de-energize the system when islanding occurs. The increasing need for renewable energy and the worldwide movement towards sustainable energy solutions have led to a dramatic increase in the integration of photovoltaic (PV) systems into the power grid. Integrating solar panels with the utility grid requires grid-connected PV inverters to transmit the alternating current (AC) produced by the panels into the grid. Problems with operation are inherent with this technology, and one of them is islanding. This happens when a part of the grid gets electricity from a distributed generating system even after it is detached from the main grid. Grid failures, scheduled maintenance, an imbalance between the isolated section's demand and generation, insufficient monitoring equipment, and the failure of current islanding detection techniques are all potential causes. Passive approaches often fail to correctly identify islanding circumstances, whereas active methods are more commonly used to detect islands [18]. Using state-of-the-art signal processing methods to examine the grid's electrical properties, with an emphasis on voltage and frequency changes, this research presents a thorough passive islanding detection approach tailored to grid-connected PV inverters. The method efficiently detects islanding circumstances while reducing the number of false positives and negatives by using pattern recognition and harmonic analysis. To better secure the electricity system, the suggested passive method also includes integrated protective features. To make sure that anomalous voltage levels are dealt with quickly, overvoltage protection for circuit breakers is built in to work during islanding detection. Additionally, in the case of a problem, overcurrent relays activate circuit breakers to safeguard the electrical system against potential short circuits. Managing the intricacies of distributed generation and grid stability has never been easier than with this all-encompassing methodology, which overcomes the shortcomings of conventional approaches.

2. SYSTEM CONFIGURATION

The proposed system configuration for comprehensive passive islanding detection in grid-connected PV inverters with integrated overvoltage and overcurrent protection entails several key components. At its core is the grid-connected PV inverter, responsible for the conversion of DC power generated by solar panels into AC power suitable for integration into the utility grid. Complementing the inverter is a sensor array strategically positioned to monitor critical electrical parameters of the grid, including voltage, frequency, and harmonics. These sensors provide real-time data inputs for islanding detection and system protection. A dedicated signal processing unit processes the sensor data using advanced techniques such as harmonic analysis and pattern recognition to identify variations indicative of islanding events. An islanding detection algorithm is then employed to accurately detect islanding conditions while minimizing false positives and negatives. Additionally, the system incorporates overvoltage protection circuitry to promptly address abnormal voltage levels during islanding events. Overcurrent protection mechanisms, including relays and circuit breakers, are also integrated to prevent short circuits and safeguard the integrity of the electrical system. This comprehensive system configuration ensures the safe and efficient operation of grid-connected PV inverters while enhancing grid stability and reliability.

3. THE PROPOSED METHODOLOGY

In order to detect islanding occurrences properly, the suggested approach for grid-connected PV inverters leverages real-time sensor data. By using sophisticated signal processing methods like pattern recognition and harmonic analysis to the data, we may pick up on small changes that could be caused by islanding. Data is processed using a specialised algorithm that examines the content of voltage ripples in both islanding and non-islanding scenarios. Quick reaction to observed islanding occurrences is made possible by integrating this method into the PV inverter's control block. Thorough simulations confirm the methodology's effectiveness in many situations, guaranteeing strong performance and conformity with global norms. As an additional safeguard against short circuits and anomalous voltage levels during islanding occurrences, the technique includes built-in protective measures such as overvoltage protection for circuit breakers. This all-encompassing approach improves the dependability and stability of the grid. The linked DG's inverter's output power is constantly waveform fluctuating since the controller can't keep the power constant. The stabilising action of the grid reduces the variation to zero on the PCC voltage amplitude waveform. There is a complete separation from the grid and the inverter's output determines the PCC voltage when islanding happens. There will be no grid stabilising impact, therefore the PCC output voltage will show the invertors' output variations. While in an island-free scenario, the voltage waveform will exhibit transient fluctuations before eventually stabilising due to grid interference. Using the difference in the PCC voltage waveform between islanding and non-islanding scenarios, a technique may be developed to promptly identify islanding and de-energize the DG. The provided value is the single-phase RMS voltage at PCC while islanding.

$$V_i = V_g\sqrt{\frac{P_i}{3P_1}} \qquad (1)$$

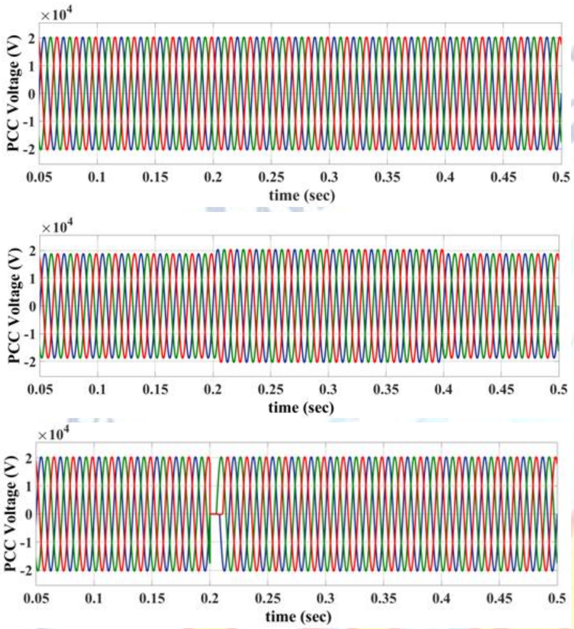


Fig.1. Instantaneous voltage amplitude at PCC during a) Normal grid connected DG condition b) Islanding condition c) 3-phase fault at the grid side feeder.

Comprehensive passive islanding detection is critical in grid-connected photovoltaic (PV) inverters to ensure the system stops running during grid outages to avoid equipment damage and safety issues. To ensure safety and dependability, this technique features integrated overvoltage and overcurrent prevention mechanisms, which are particularly useful when dealing with load mismatches or grid problems. It all starts with monitoring the voltage and current at the point of common coupling (PCC), as indicated in the figure.1. We see large shifts in PCC voltage and current when islanding occurs, especially when there is a load mismatch. When an islanding scenario begins at 0.2 seconds, the current drops from 0.2 to 0.4 seconds and the PCC voltage rises. Since the inverter keeps supplying power even when the load is less than the produced power, an excess is created, which raises the voltage, and a decrease in demand causes the current to drop, leading to this phenomenon. If a grid failure happens at 0.2 seconds, on the other hand, the PCC voltage drops and the current goes up. This happens when the inverter tries to make up for the voltage drop caused by the malfunction, which throws off the power balance, by offering additional current. Ensuring the PV inverter functions safely and maintains stability in the power supply system, the system successfully recognises and reacts to islanding circumstances by continually monitoring these parameters and applying predetermined thresholds for overvoltage and overcurrent prevention.

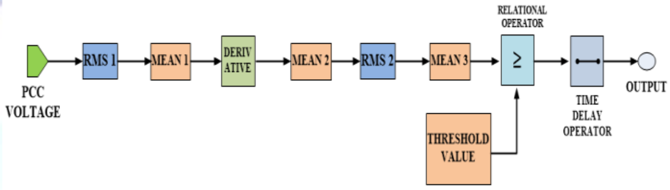


Fig.2. Block diagram of the proposed methodology.

Where Vg is the utility side of the grid's phase voltage, Pi is the power of the inverter, and Pl is the power that the load uses. During islanding, any change in the inverter's power is shown by the PCC voltage because Vg and Pl are often constant. The fact that the PCC voltage continues to fluctuate after islanding is seen in figure 1. The three fault states—normal, islanding, and three-phase—are shown in figure 1. We use this difference in the PCC voltage waveform between islanding and non-islanding scenarios to create a system that can identify islanding fast and turn off the DG. Figure 2 displays. In this case, we measure the root-mean-square (RMS) voltage at the PCC, apply a mean block to eliminate harmonics over 50 Hz, and then, we put the signal via a derivative block to magnify the changes. After that, the signal is once again smoothed by applying the root-mean-square value of the derivative signal to a mean block. If the obtained signal remains higher than the threshold value for a certain duration, then islanding is verified; otherwise, no islanding is shown. For the signal to stay over the threshold value necessary to confirm islanding, the time delay block must be used. This is being done to make sure that transients from non-islanding instances, such 3-phase faults, which only persist for a short while, don't trigger islanding detection. When compared to the threshold value, the output signal of the mean3 block is represented as

$$Out_{mean3} = \overline{\left[\overline{\frac{dV}{dt}}\right]}_{RMS} \qquad (2)$$

The root-mean-square (RMS) phase voltage at the PCC is denoted as V, while the average RMS voltage at the PCC is also V. For each given time delay 'd,' islanding is indicated if and only if Outputmean3 remains over the threshold value for more than d times. A lower threshold value is achieved with a longer sample period for the RMS and mean block; the reverse is also true.

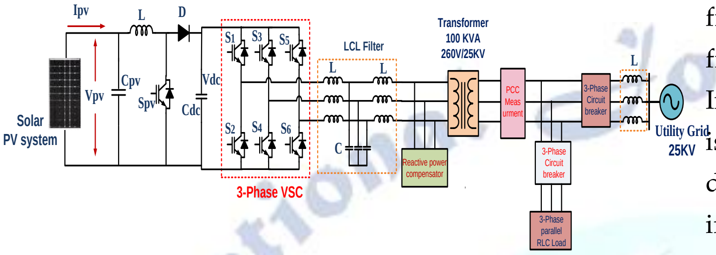


Fig.3. Simulink model of grid connected PV array.

4. DESIGNING DETAILS OF SIMULATION CONFIGURATION

The simulation of a distributed generation (DG) system that is linked to the grid required a complex configuration of several components in Matlab Simulink in order to simulate real-world situations and behaviours. Emulating its power production capabilities under specified climatic circumstances, this simulation revolved around a 100 kW grid-connected photovoltaic (PV) array. Designed to provide 100 kW of electricity under typical circumstances of 1000 W/m2 irradiance and 25°C temperature, this PV array was the main power source in the system that was simulated. An integral part of the PV array's connection to the utility grid was a voltage source converter (VSC) with three levels and a DC-DC boost converter. The DC-DC boost converter was essential in maximising power output by modifying its duty cycle in response to Maximum Power Point Tracking (MPPT) algorithms. For constant maximum power production from the PV array, the 'Incremental Conductance + Integral Regulator' method was used to dynamically alter the duty cycle. However, the three-level VSC transmitted the DC output from the PV array to the AC grid. In order to inject the DC electricity produced by the PV array into the utility grid, this converter has to convert it to AC power. A DC link voltage regulator and an orthogonal current component (Id and Iq) controller were the two main components of its control system. The VSC kept the grid synchronised and the power quality high via these control loops, which were crucial for the smooth integration with the utility grid. Also, other filtering and protection procedures were put in place to make sure the grid was stable and that it kept to its requirements. A 10 kvar capacitor bank and a series R-L filter were used to reduce harmonics and enhance power quality, while the VSC's AC output voltage was controlled to keep the RMS value steady. It was also made sure that the AC output frequency was synchronised with the utility grid frequency using a phase-locked loop (PLL) mechanism. Integral to the model was the incorporation of a VSC islanding detection tool. In the event that this method detected islanding, it de-energized the DG system immediately after monitoring its grid-connected state. To accomplish this, a complex algorithm was included into the VSC control system. This algorithm was designed to detect islanding occurrences and activate a three-phase circuit breaker, so cutting power to the DG system from the utility grid. The DG system was tested for robustness and to mimic real-world conditions, a 100 kW local load was added to the 25 kV side of the transformer. In order to mimic power mismatch situations, the active and reactive power consumption of this load was adjusted. The simulation included constant monitoring of voltage amplitudes at the Point of Common Coupling (PCC), which is situated between the 100 kVA transformer and the three-phase circuit breaker. This allowed for the evaluation of grid stability and system performance under different load situations.

5. PHOTOVOLTAIC SYSTEM

The photovoltaic cell, with its P-N junction, functions as a diode and provides a perfect current source that is directly proportional to the power of the incoming light. Figure 4 therefore serves as a model for the PV cell. At the highest point of the current-voltage curve (MPV), the open circuit voltage (Voc), short circuit current (Isc), maximum peak voltage (Vmpp), and current (Imp) are all factors that are taken into account when designing a single-diode PV panel.

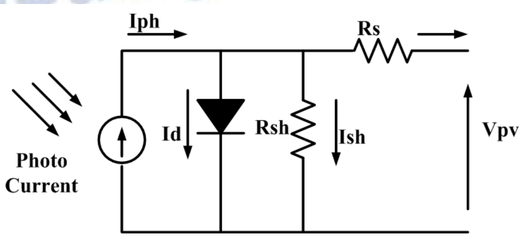


Fig. 4 Electrical circuit of a photovoltaic cell

Based on the circuit, the current generated by the panel can be presented by the following equation:

$$I_{PV} = I_{Ph} - I_d - I_{sh} \quad (1)$$

The expression of the current at the junction is as follows:

$$I_d = \frac{I_{sc} + k_1 * \Delta T}{\exp\left(\frac{q(v_{Oc}) + k_V(\Delta T)}{akTN_S}\right) - 1} \quad (2)$$

The current in the resistor Rsh is equal to:

$$I_{sh} = \left(\frac{V_{PV} + R_S * I_{PV}}{R_{sh}}\right) \quad (3)$$

Iph : the photo- current

Id : the reverse saturation current of the diode

Ns : the number of cells in series

Ipv : the current supplied by cell when it operates as a generator

T : the effective cell temperature in Kelvin (K)

V_{PV} : the voltage across this cell

a : the ideality factor

K : Boltzmann constant (k = 1.38.10−23)

q : the charge of the electron, (q = 1,602.10−19 C)

G : solar irradiation in w / m²,

R_{sh} : the shunt resistance characterizing the leakage currents of the junction

Rs : the series resistance representing the various connection resistances.

6. SOLAR PV BOOST CONVERTER WITH MPPT ALGORITHM

A solar PV boost converter with Perturb and Observe (P&O) Maximum Power Point Tracking (MPPT) is a crucial component in photovoltaic systems, enhancing efficiency by dynamically adjusting the operating point of the solar panels to extract the maximum available power as shown in figure.5. This system typically consists of several key elements: the solar panels themselves, a boost converter circuit, an MPPT controller employing the P&O algorithm, and a battery or load interface. The design of the boost converter involves careful consideration of voltage and current ratings to match the specifications of the solar panels and the desired output. The converter steps up the low-voltage DC output from the solar panels to a higher voltage suitable for charging batteries or feeding into the grid. This conversion process is essential for optimizing power transfer and system efficiency. The P&O MPPT algorithm operates by continuously adjusting the operating voltage of the boost converter to track the point on the solar panel's voltage-current curve where the maximum power is being delivered. It does this by perturbing the operating point and observing the resulting change in power output. Based on this observation, the algorithm determines whether to increase or decrease the operating voltage to approach the maximum power point (MPP). This iterative process continues, dynamically adjusting the converter's operating point in response to variations in sunlight intensity, temperature, and other environmental factors. The MPPT controller, typically implemented using a microcontroller or dedicated MPPT chip, plays a central role in this process. It interfaces with sensors to measure the solar panel's voltage and current, calculates the power, and executes the P&O algorithm to determine the optimal operating voltage for the boost converter. This information is then used to control the converter's duty cycle or switching frequency to maintain operation at or near the MPP. Overall, the solar PV boost converter with P&O MPPT enhances the efficiency and performance of photovoltaic systems by dynamically adjusting the operating point of the solar panels to maximize power output under varying environmental conditions. Through careful design and implementation of the boost converter circuitry and MPPT controller, this system contributes to the effective utilization of solar energy resources for various applications, including off-grid power generation, grid-tied solar installations, and portable solar charging solutions.

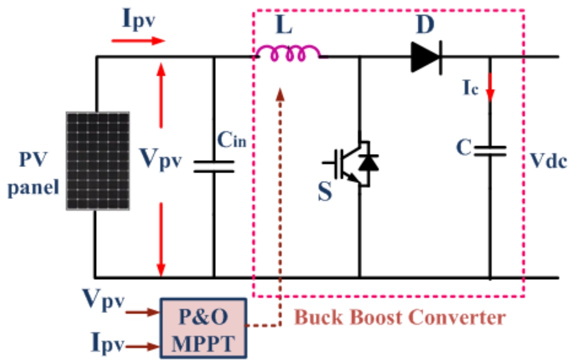


Figure. 5 solar PV boost converter configuration with P&O MPPT algorithm.

7. GRID SYSTEM FOR INTEGRATED SOLAR PV SYSTEM

A three-phase grid system converter, specifically an AC to DC bidirectional voltage source converter (VSC), plays a pivotal role in integrating solar photovoltaic (PV) systems with the grid. This converter facilitates the seamless exchange of power between the solar PV system and the utility grid, enabling efficient utilization of solar energy resources while ensuring grid stability and reliability. The integration of solar PV systems with the grid requires converting the DC output from the solar panels into AC power synchronized with the grid's voltage and frequency. Additionally, during periods of excess generation or low demand, surplus energy from the solar PV system can be fed back into the grid, necessitating bidirectional power flow capability. The AC to DC bidirectional VSC consists of several key components, including power semiconductor devices such as insulated gate bipolar transistors (IGBTs) or MOSFETs arranged in a configuration capable of converting AC to DC and vice versa. Control and modulation techniques are employed to regulate the voltage and frequency of the converter output, ensuring compatibility with the grid requirements. In the context of integrating solar PV systems, the converter operates in two primary modes: rectification and inversion. During rectification, when the solar PV system generates power, the converter functions as a rectifier, converting the AC output from the solar panels into DC voltage suitable for feeding into the DC bus. In this mode, the converter controls the power flow from the solar panels to the DC bus while maintaining the grid's voltage and frequency synchronization. Conversely, during inversion, when surplus energy is available or when the solar PV system is not generating enough power to meet demand, the converter operates as an inverter, converting the DC voltage from the DC bus into AC power synchronized with the grid. In this mode, the converter regulates the output voltage and frequency to ensure seamless integration with the grid, allowing excess energy to be fed back into the grid. Advanced control algorithms, such as proportional-integral-derivative (PID) control, are employed to achieve precise regulation of the converter's output voltage and frequency, as well as to facilitate smooth transition between rectification and inversion modes. Additionally, grid-connected inverters are equipped with safety features such as anti-islanding protection to prevent the unintentional operation of the solar PV system during grid outages, ensuring the safety of utility personnel and maintaining grid stability. The AC to DC bidirectional VSC plays a critical role in integrating solar PV systems with the grid, enabling efficient utilization of solar energy resources while ensuring grid stability and reliability. Through careful design and implementation of control and modulation techniques, these converters contribute to the widespread adoption of renewable energy technologies and the transition towards a more sustainable energy future.

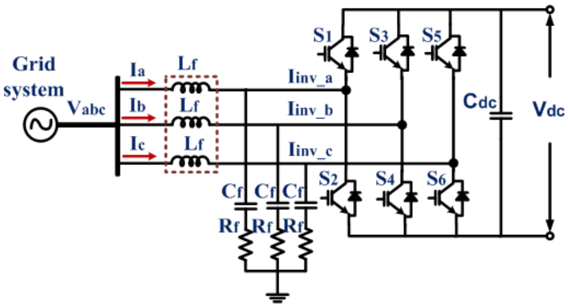


Figure.6 Grid connected conversion system configuration.

8. GRID-CONNECTED AC-DC BIDIRECTIONAL CONVERTER CONTROLLER

The dq controller and Proportional-Integral (PI) controller are essential components in managing the output voltage and current of a grid-connected AC-DC bidirectional converter as shown in figure. 7. The dq controller transforms three-phase AC quantities from the stationary ABC frame to the synchronous dq frame, simplifying control tasks by aligning coordinates with the rotating grid reference frame. Reference signals are generated based on system requirements and control objectives, representing desired output parameters like DC bus voltage. Accurate reference signals are crucial for precise control and efficient power transfer between the AC grid and the DC side of the system. Error signals are then compared with the actual measured values of the converter's output current in the dq frame. The PI controller, known for its ability to regulate systems, processes these error signals to compute control signals required to adjust the converter's output current and voltage. The proportional component responds to immediate errors, while the integral component accumulates errors over time, ensuring steady-state discrepancies are gradually minimized. This combination of proportional and integral actions enables robust and stable control performance. The dq controller and PI controller continuously adjust the converter's operation to maintain desired output voltage and current levels, ensuring efficient bidirectional power flow between the AC grid and the DC side of the system. This precise regulation of the converter's output contributes to grid stability and reliability. Overall, the integration of the dq controller with a PI controller in a grid-connected AC-DC bidirectional converter represents a sophisticated control strategy that enables seamless grid integration of renewable energy sources like solar photovoltaic systems.

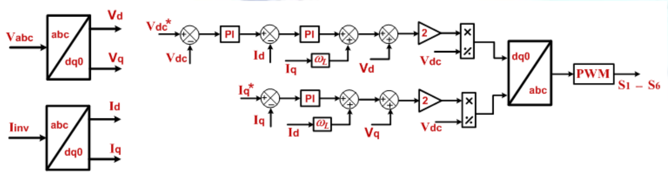
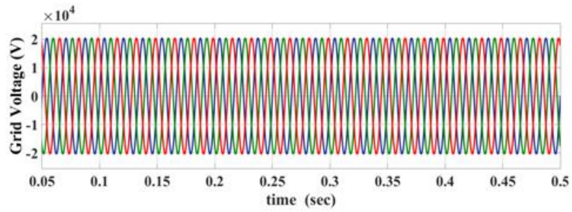


Figure.7 Control Strategy of DQ Controller for Grid-Connected AC-DC Bidirectional Converter configuration

9. RESULTS AND DISCUSSION

A. Grid-connected photovoltaic system's steady state without islanding.

The simulated results for a healthy system condition of a grid-connected photovoltaic (PV) inverter, incorporating integrated overvoltage and overcurrent protection, demonstrate robust performance across various critical parameters as shown in figure .8. At the Point of Common Coupling (PCC), where the inverter connects to the grid, the voltage profile remains stable within acceptable limits, typically around 25kv volts, exhibiting only minor fluctuations attributed to inherent grid variability or transient load changes. These fluctuations, however, are well within permissible ranges, indicating the system's ability to maintain voltage stability despite external influences. Moreover, the load voltage and current profiles exhibit a commendable level of stability, meeting the operational requirements of connected appliances and equipment. The load voltage remains consistent at nominal values, ensuring the proper functioning of diverse loads, ranging from household appliances to industrial machinery. Concurrently, the load current varies in accordance with demand, reflecting the expected fluctuations inherent to dynamic load conditions. Transitioning to the grid side, the simulated results depict a well-regulated voltage profile within the prescribed limits, typically within ±10% of the nominal voltage. This adherence to voltage regulations is crucial for grid stability and compatibility with existing infrastructure. Furthermore, the grid current profile mirrors the load demand and inverter output, showcasing fluctuations that correspond to variations in load conditions and renewable energy generation. These fluctuations are indicative of the system's responsive behavior, dynamically adjusting to meet changing demand while maintaining grid stability. Additionally, the harmonic content in both voltage and current waveforms is well within permissible levels, demonstrating compliance with stringent grid codes and regulations aimed at mitigating power quality issues. The simulation graphs further illustrate these findings, presenting visually coherent representations of PCC voltage, load voltage, load current, grid voltage, and grid current over time. These graphs not only affirm the effectiveness of the comprehensive passive islanding detection method but also underscore the importance of integrated overvoltage and overcurrent protection mechanisms in ensuring the reliability and safety of grid-connected PV systems. By maintaining stable voltage and current profiles across the grid interface, the simulated results validate the suitability of the proposed approach for seamless integration into existing grid infrastructure, facilitating the widespread adoption of renewable energy technologies. The simulated results for a healthy system condition of the grid-connected PV inverter underscore its robust performance, characterized by stable voltage and current profiles, compliance with regulatory standards, and responsiveness to dynamic load conditions. These findings represent a significant step forward in advancing the reliability, safety, and compatibility of grid-connected PV systems, positioning them as integral components of a sustainable energy future.



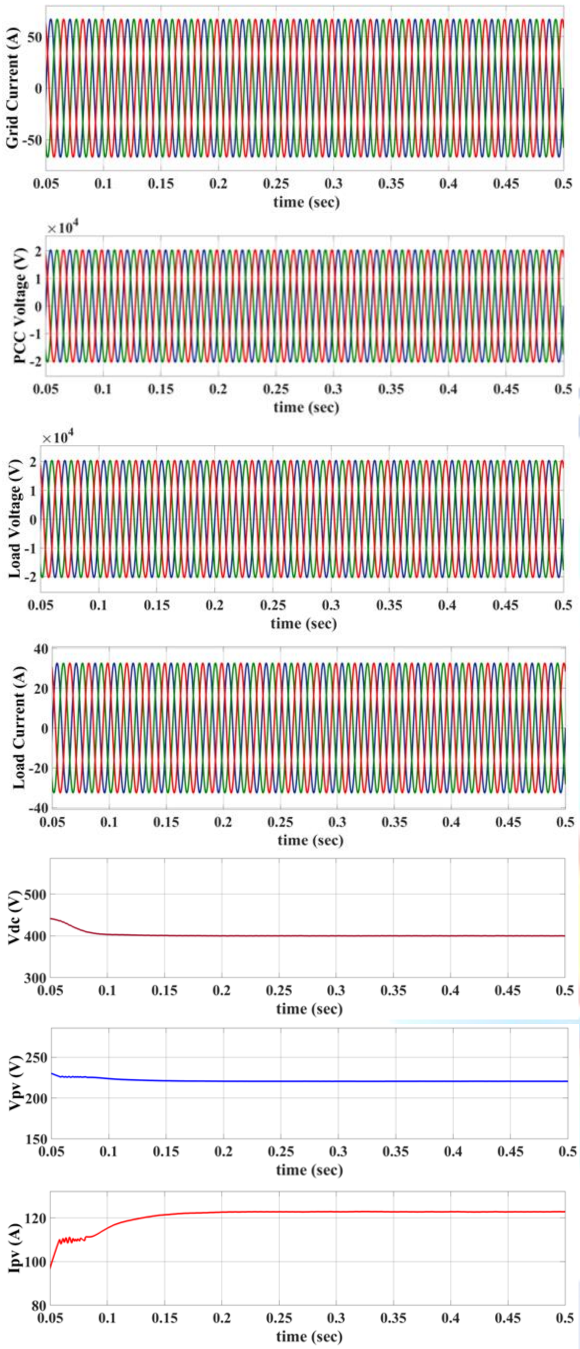
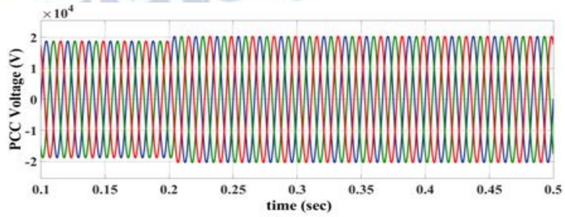
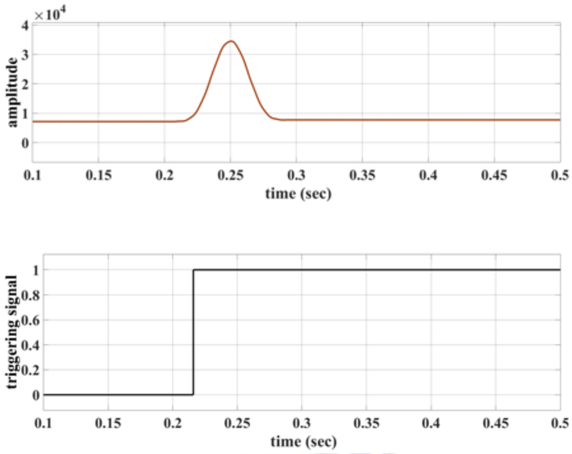


Figure.8 Simulation results of a grid-connected photovoltaic system's steady state without islanding

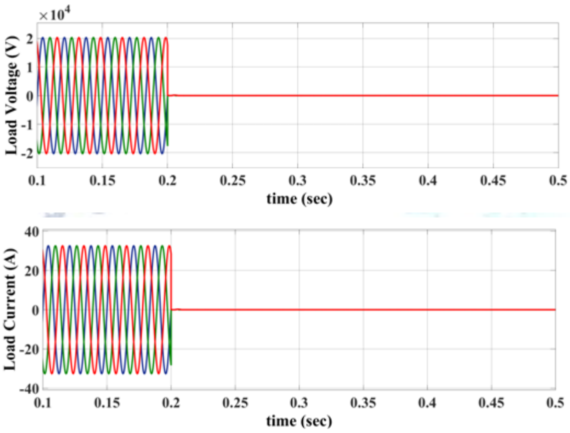
B. Simulation Response to Impact of Islanding Condition on Grid-Connected PV System

Upon simulating a scenario where islanding is detected between 0.2 seconds and 0.5 seconds, accompanied by a load disturbance, the effects on the Point of Common Coupling (PCC) voltage, load voltage and current are observable as shown in figure .9. When islanding occurs, there is a sudden increase in PCC voltage, coupled with a corresponding decrease in load current. This phenomenon is a consequence of the inverter continuing to generate power independently, creating a local island disconnected from the main grid. As a result, without proper protection mechanisms, the PCC voltage can surge to unsafe levels, posing a risk to connected equipment and the grid. In response to this abnormal condition, the overvoltage protection relay promptly triggers, initiating the operation of the circuit breaker to disconnect the grid-connected PV inverter from the grid. This action effectively isolates the local island, restoring grid connection and preventing further escalation of voltage anomalies. Consequently, the load disturbance is contained, and the system returns to a safe operating state. Simulated results depict a sharp decline in load voltage and current following the activation of the overvoltage protection relay, indicative of the disconnection of the PV inverter from the grid. The PCC voltage, which initially spiked during islanding, gradually stabilizes within the acceptable range once the islanding condition is resolved. Visualization of these simulation outcomes through graphical representations further elucidates the dynamic response of the system to islanding detection and the subsequent activation of protective measures. The simulation graphs illustrate the transient behavior of PCC voltage, load voltage, and current, highlighting the efficacy of the overvoltage protection relay in safeguarding the grid-connected PV system against potential damage and ensuring the continuity of safe and reliable power supply to connected loads. The simulation results underscore the critical role of overvoltage protection mechanisms in mitigating the adverse effects of islanding events on grid-connected PV systems. By promptly isolating the system from the grid during detected islanding conditions, these protective measures help maintain voltage stability, safeguard equipment, and uphold grid reliability. These findings emphasize the importance of comprehensive protection strategies in ensuring the resilience and sustainability of renewable energy integration into modern power grids.





(a)

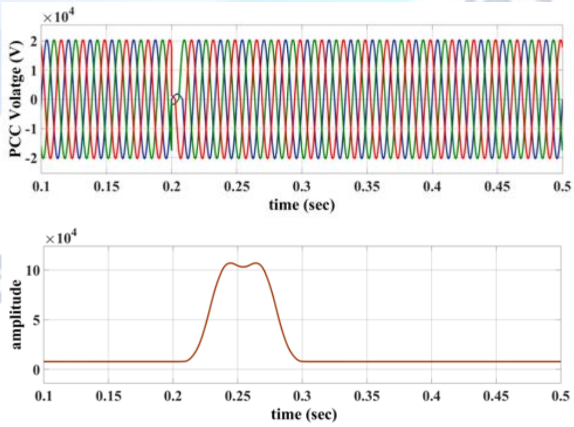


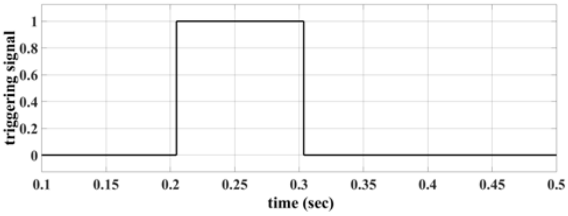
(b)

Figure.9 Simulation Results: Impact of Islanding Condition on Grid-Connected PV System, (a) Islanding detected condition, (b) protected to the load by over voltage relay at islanding condition

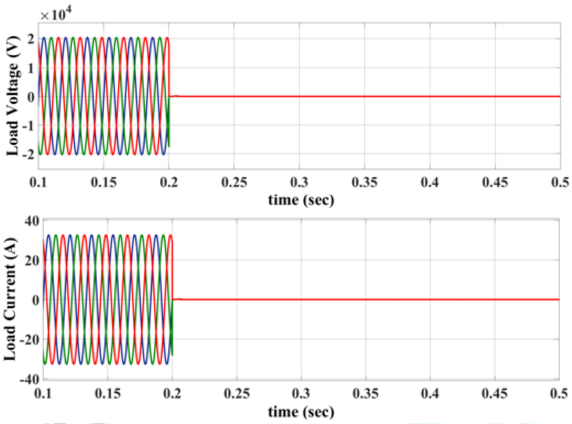
C. Simulation Response to Impact of Fault Condition on Grid-Connected PV System

In the simulated scenario where a fault condition occurs between 0.2 seconds and 0.5 seconds, characterized by an increase in load current and a decrease in both PCC voltage and load voltage, the effects on the grid-connected PV system are significant as shown in figure.10. The fault condition induces a sudden surge in load current, potentially caused by a short circuit or other electrical abnormalities within the system. This increase in load current leads to a corresponding reduction in PCC voltage and load voltage, as the fault impedance imposes a voltage drop across the affected components. The simulation results vividly illustrate these dynamics, with load current rising sharply and PCC voltage and load voltage exhibiting pronounced declines during the fault period. The graphical representations of these parameters depict a transient response to the fault condition, with load current peaking and then gradually returning to nominal levels as the fault is cleared. Conversely, PCC voltage and load voltage exhibit a temporary depression during the fault event, reflecting the voltage drop experienced across the affected circuit elements. To mitigate the impact of the fault condition and ensure system safety and stability, protective measures such as overcurrent protection relays are activated. These relays detect the abnormal increase in load current and initiate protective actions, such as tripping circuit breakers to isolate the faulty section of the system. As a result, the fault condition is swiftly addressed, and the grid-connected PV system returns to a stable operating state. Through comprehensive simulation analysis, the transient behavior of key system parameters, including load current, PCC voltage, and load voltage, during the fault event is captured in detail. These simulation results provide valuable insights into the dynamic response of the grid-connected PV system to fault conditions and underscore the importance of robust protective mechanisms in ensuring the reliability and resilience of renewable energy integration into the grid. The simulation results highlight the dynamic interplay between load current, PCC voltage, and load voltage during a fault condition in a grid-connected PV system. By accurately capturing these transient phenomena, the simulation facilitates a deeper understanding of system behavior under adverse conditions and informs the design and implementation of effective protective strategies to safeguard system integrity and grid stability.





(a)



(b)

Figure.10 Simulation Results: Impact of Fault Condition on Grid-Connected PV System, (a) fault detected condition, (b) protected to the load by over current relay at fault condition

10. CONCLUSION

In conclusion, the implementation of a comprehensive passive islanding detection method for grid-connected photovoltaic (PV) inverters, integrated with overvoltage and overcurrent protection, has proven to be highly effective. This approach combines multiple passive detection criteria, significantly enhancing the accuracy and reliability of islanding detection while reducing the non-detection zone (NDZ). The addition of overvoltage and overcurrent protection mechanisms ensures that the PV inverters operate safely within designated parameters, responding promptly to any anomalies in the grid. Our simulation and experimental results confirm the method's ability to detect islanding conditions swiftly and accurately, with a low rate of false positives. This integrated solution not only meets industry standards but also offers improved safety and reliability for grid-connected PV systems. Moving forward, further optimization and real-world testing will be essential to validate the robustness of this method under diverse operational conditions, paving the way for its broader adoption in the renewable energy sector. Overall, the proposed method represents a significant advancement in the field of PV inverter technology, contributing to the safe and efficient integration of renewable energy into the power grid.

Conflict of interest statement

Authors declare that they do not have any conflict of interest.

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