Voltage Positive-Feedback Based Islanding Detection in Photovoltaic Systems Using Fuzzy Controller

G. Zohourisa, A. M. Dezhem Khoi*, M. Hosseinpour

Abstract-- In general, microgrids can be operated in two modes: grid-connected and grid-disconnected. As a small-scale power system, microgrids can achieve the basic objective of the power grid, including reducing losses, increasing reliability, reducing emissions, and saving economic. When the microgrid is connected to the grid, the sharing of active and reactive power and its supply to the consumer is done with greater reliability and higher quality. Sometimes, events occur in the grid that disconnect the grid-connected microgrid from the main grid, which is called microgrid islanding. When the microgrid becomes islanded, it must independently supply local loads. The time of islanding detection is of great importance so that timely and rapid detection can reduce the losses caused by the separation of the microgrid from the main grid. There are various methods for detecting islanding of a microgrid based on solar modules, in this study, the method based on positive voltage feedback is used. The presented method is based on the measurement of parameters from the PCC point and can be analyzed. In this method, based on the feedback taken from the voltage amplitude at the PCC point, the analysis of microgrid islanding is presented based on the fuzzy controller. The simulation is performed in MATLAB software and on the sample system.

Keywords: Solar power plant-based microgrid, microgrid islanding, positive voltage feedback, PCC point.

I. INTRODUCTION

Improving the reliability of power systems, along with addressing economic and environmental concerns, has been a major driving force behind the development of microgrids [1]. Microgrids are typically integrated into low- and medium-voltage distribution networks, where the presence of multiple distributed energy resources introduces new operational challenges such as system stability, power quality, and overall network performance. In addition, many renewable energy sources within a microgrid exhibit inherently variable generation profiles, making their management more complex.

Addressing these challenges requires advanced control strategies implemented at the low- and medium-voltage levels, rather than the traditional high-voltage control approaches used in conventional power systems [2]. As microgrids continue to grow in importance, extensive research and practical developments have emerged in recent years focusing on their control and operation [3].

Currently, three main control paradigms are widely adopted to achieve reliable and stable microgrid operation: single-agent control, decentralized control, and centralized control [4]. Among the various distributed energy resources utilized in microgrids, grid-connected photovoltaic systems (GCPVS) have gained significant prominence and have seen rapid deployment within distribution networks over the past decade [5]. Their installed capacities reached 98.9 GW in 2017 and 99.9 GW in 2018, reflecting their accelerated global expansion [6].

In general, these units similar to other renewable and distributed energy resources introduce several operational challenges, one of the most significant being islanding. Islanding in a microgrid refers to a condition in which distributed generation (DG) units continue supplying local loads even though the connection between the utility grid and the consumers has been unintentionally lost. This undesirable operating state must be detected promptly to ensure power quality compliance, protect field personnel, and safeguard sensitive equipment.

Islanding detection methods are typically categorized into local techniques and remote (communication-based) techniques. Remote detection relies on an active communication link between DG units and the upstream substation; islanding is identified when the transmitted signal fails to reach the receiver installed at the DG terminals. In contrast, local methods continuously monitor parameters at the point of common coupling (PCC), using active, passive, or hybrid indicators. When any of these indicators deviate from their predefined thresholds, a passive islanding detection mechanism (IMD) is triggered.

The immediate step following an islanding event is the disconnection of DG units from their synchronized operating state. As error tolerances increase and islanding conditions are more reliably identified, the smart grid can ensure a more secure and dependable interface between distributed generators and the utility network. Consequently, employing effective islanding detection methods is essential for

Manuscript received 20 November 2025; revised 3 June 2026; published online: 20 September 2026.
DOI: 10.22077/ijpe.2026.10531.1029
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maintaining safe and reliable microgrid operation.

The key contributions and innovations considered in this study can be summarized as follows:

a) Employing an islanding detection strategy for microgrids with grid-connected photovoltaic units.
b) Analyzing and comparing passive and active islanding detection methods for a PV-integrated microgrid.

The proposed approach utilizes voltage feedback at the point of common coupling (PCC) to identify islanding conditions. In addition, a fuzzy PID controller is implemented to regulate the microgrid voltage and frequency, ensuring stable operation under both grid-connected and islanded modes.

II. Microgrid Islanding

In recent years, renewable energy generation technologies have gained significant attention and have experienced rapid development. Compared to fossil fuels, renewable energy sources produce substantially lower greenhouse gas emissions [6]. Distributed generation (DG) offers an effective means of harnessing these renewable resources. Through microgrid architectures, various distributed energy technologies can be integrated to form a hybrid energy system capable of supplying electricity along with optional heating or cooling services [7].

Distributed energy resources complement one another within a microgrid, enabling mutual support and enhancing overall system performance. On one hand, microgrids can mitigate adverse impacts on the main grid through this complementary operation; on the other hand, they allow the integration of multiple distributed resources, controllable loads, and general loads, ultimately reducing dependency on the utility grid. As a result, microgrids have attracted widespread interest and have seen rapid global adoption. In essence, they represent a critical pathway toward sustainable energy development.

Microgrid control strategies differ depending on whether the system operates in grid-connected or islanded mode. In islanded operation, maintaining a highly reliable power supply to critical loads becomes the primary objective. In contrast, during grid-connected operation, the focus shifts toward optimal economic performance [8].

One of the possible events during microgrid operation is the unintentional transition to islanding. Generally, islanding refers to a condition in which the microgrid becomes electrically isolated from the upstream utility network but continues supplying power to local loads and injecting active power into the system [9].

When islanding occurs, several risks emerge. Personnel working on the faulted upstream line may be exposed to electric shock hazards; protective coordination in the distribution network may be compromised; and sensitive electrical equipment within the isolated area may suffer significant damage. Therefore, prompt and effective islanding detection and the timely disconnection of distributed generators from the main grid is essential.

Microgrid islanding can be classified into two categories: planned islanding and unplanned islanding [10]. Planned islanding refers to a controlled operating state in which the microgrid continues supplying local loads reliably even after deliberate disconnection from the main grid.

Unplanned islanding of a microgrid, on the other hand, is an undesirable event caused by factors such as line outages, equipment failures, human errors, and other unforeseen disturbances that lead to an unintentional disconnection from the main grid [11]. Unlike planned islanding, unplanned islanding is an uncontrolled operating condition that occurs sporadically, with no clearly defined islanding boundaries, thereby posing significant risks to microgrid security and stability.

Fig. 1. illustrates the islanding condition of a microgrid containing photovoltaic panels:

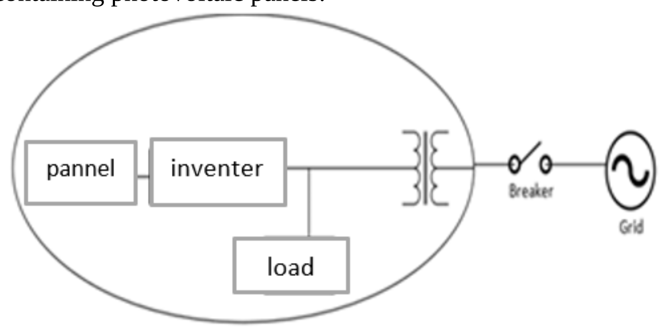


Fig. 1. Islanding condition of a system containing a photovoltaic panel [11]

When a microgrid is intentionally operated in islanded mode, it offers a promising solution for delivering reliable and environmentally friendly energy to remote areas and off-grid systems. However, the operational management of islanded microgrids (IMGs) is inherently complex, as it requires the coordinated control of various distributed energy resources and loads in an efficient, stable, reliable, resilient, flexible, and self-sustaining manner.

In recent years, energy management systems for IMGs have attracted considerable attention, particularly regarding economic performance and greenhouse gas emission reduction. Among distributed energy resources, photovoltaic (PV) systems are among the most promising renewable technologies. Solar energy is characterized by zero operational costs, minimal maintenance requirements, and no environmental pollution. PV systems are frequently connected to the grid, but grid integration introduces technical challenges. These challenges can be mitigated through advanced control strategies and robust control systems, thereby ensuring better coordination between the PV system and the main grid [12].

III. Microgrid Islanding Detection Methods

Islanding detection methods for microgrids can generally be classified into local (on-site) methods and remote (communication-based) methods, as illustrated in Fig. 2 [13].

Local methods, which rely on measurements of certain parameters or variables within the microgrid, can be further divided into passive and active approaches. Passive methods monitor parameters such as voltage, current, frequency, and phase angle to detect islanding conditions without altering the system operation. Active methods, on the other hand, deliberately inject small disturbances into the system to observe their effects on voltage, frequency, power, or impedance, thereby identifying islanding events.

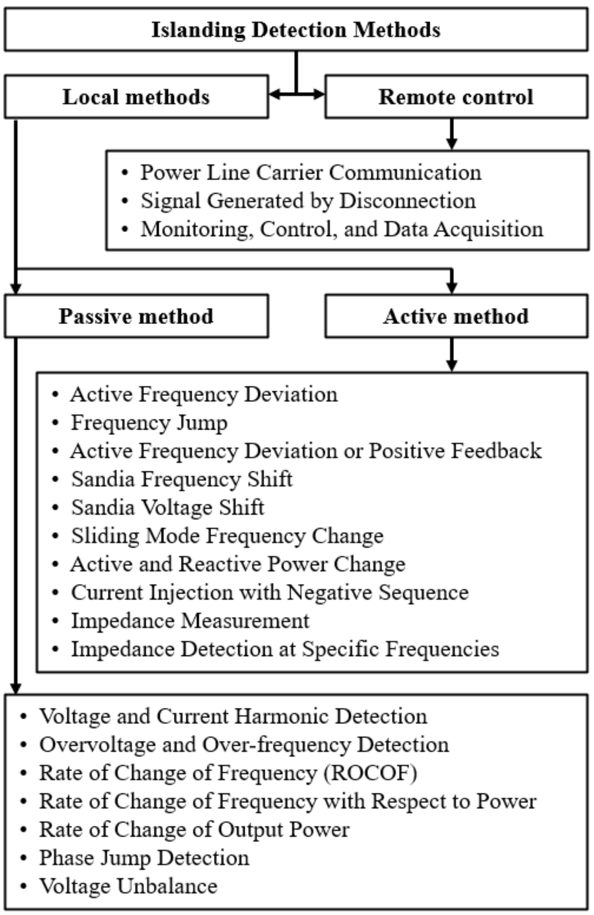


Fig. 2. Microgrid islanding detection methods[13]

A. Remote Detection Methods

Communication-based methods establish a link between the microgrid and the main grid to provide real-time monitoring of breakers. These methods typically exhibit a very small or even negligible non-detection zone (NDZ), with minimal impact on power quality. Remote detection is highly effective in multi-inverter systems; however, it requires significant investment, making it economically impractical for smaller systems.

B. Active Islanding Detection (AID)

Active Islanding Detection (AID) identifies islanding conditions by deliberately introducing a small disturbance at the inverter side. This disturbance can affect power quality in both grid-connected and islanded modes. Compared to passive methods, AID generally features a smaller NDZ. The NDZ is defined as the range within which no islanding detection method can reliably identify islanding events. AID demonstrates higher sensitivity than passive detection in identifying this zone [14].

As illustrated in Fig. 2, several widely used active islanding detection methods (IDMs) include: Active Frequency Drift (AFD), Frequency Jump (FJ), Active Frequency Drift with Positive Feedback (AFDPF), and Sandia Voltage Shift (SVS), among others. The SVS method is conceptually similar to the Sandia Frequency Shift. By applying positive feedback to the voltage amplitude at the PCC, the inverter modulates its output current and power. When connected to the main grid, voltage amplitude remains largely unaffected by power variations; however, in islanded mode, these power output variations can accelerate voltage deviations, facilitating islanding detection [15].

C. Passive Islanding Detection (PID)Communication

Passive methods monitor system parameters and compare them against predefined thresholds to detect islanding. Typical measurements at the DG output or PCC include voltage, frequency, phase angle, and harmonic content. Passive detection is widely adopted by utilities due to its simplicity, low cost, and negligible impact on power quality. According to IEEE 1547 standards, these methods typically achieve fast detection within 2 seconds [16].

However, passive methods are limited by a relatively large NDZ, higher detection error rates, and require careful threshold tuning. Common passive IDMs include: voltage and current harmonic detection, over/under voltage, over/under frequency [17], Rate of Change of Frequency (ROCOF), Rate of Change of Frequency with respect to Power (ROCOP) [18], Phase Jump Detection (PJD) [19], Voltage Unbalance (VU), among others.

Table I provides a summary of the advantages and limitations of both active and passive islanding detection methods.

TABLE I
COMPARISON OF ACTIVE (AID) AND PASSIVE (PID) ISLANDING DETECTION METHODS [20]

Active Method (AID)	Passive Method (PID)
Advantages Small non-detection zone (NDZ) No external disturbances	**Advantages** Fast detection response
Disadvantages Slower detection Disturbance injected at inverter side Interactions in multi-inverter systems	**Disadvantages** Threshold tuning is challenging

D. Remote (Communication-Based) Islanding Detection

Passive methods estimate parameter variations at the PCC through various local measurements. However, in some studies, passive detection has been found insufficient because relying solely on system parameters such as voltage and frequency may not provide an accurate indication of the exact moment of islanding. Distinguishing events at the PCC, particularly during grid-connected operation, is not straightforward. By defining upper and lower threshold values, different islanding conditions can be discriminated. However, this often results in a large non-detection zone (NDZ).

In some cases, the load closely matches the DG capacity, so voltage or frequency deviations may be insufficient to trigger the detection system. The NDZ is largely determined by load consumption and power generation conditions, which can lead to delayed or inaccurate islanding detection. Passive islanding detection methods often suffer from this large NDZ problem.

In contrast, active islanding detection schemes deliberately inject signals into the inverter output, disturbing the power balance between the DG and local load. This facilitates the detection of islanding conditions. The main advantage of active methods over passive methods is their relatively small NDZ [23]. However, most active schemes are more complex and may degrade power quality.

Communication-based methods rely on transmitted and received signals between measurement units and protective devices. Signals such as breaker status are used to detect islanding conditions. While communication-based methods have negligible NDZ, their main limitation is higher cost compared to other methods. In summary:

- Active methods: small NDZ, but complex and can degrade power quality.
- Passive methods: inexpensive, but large NDZ and threshold tuning is challenging.
- Communication-based methods: minimal NDZ, but high cost.

Technical issues in islanded operation can be mitigated using the following measures [23]:

- Installation of current-limiting devices to reduce motor inrush currents.
- Installation of devices to limit adverse effects of cold-load pickup.
- Installation of power quality improvement devices, such as capacitor banks, SVCs, etc.
- Shedding non-critical loads (load control).
- Installing remotely controlled switches.

IV. Voltage Positive Feedback (VPF) in Microgrid Islanding Detection

Microgrid islanding is an undesirable condition that can pose potential hazards to personnel near the microgrid and may also damage sensitive system equipment. Therefore, timely detection of islanding in microgrids containing distributed generators such as GCPVS is essential.

One effective approach for rapid detection of islanding in GCPVS-connected systems is the Voltage Positive Feedback (VPF) method. By applying positive feedback to the voltage, the inverter output and consequently the PCC voltage are affected under islanded conditions. This voltage deviation can then be detected to identify islanding.

The conventional VPF approach aims to modulate both inverter output power and PCC voltage, which change after grid disconnection and the onset of islanding. However, due to limitations in input power and MPPT constraints in GCPVS, the active output power cannot exceed a specified limit even when attempting to increase PCC voltage.

The concept of voltage positive feedback, introduced initially for three-phase inverter-based DGs, represents a novel active islanding detection method [24]. This method employs decoupled control of active and reactive power in the synchronous reference frame (dq0). The inverter output current is decomposed into two components: the direct-axis current $_{Iq,ref}$, and quadrature-axis current $I_{q,ref}$, which are used to regulate the inverter's reference active power P_{ref} and reactive power Q_{ref} .

Based on the above concept and the described current control, the voltage positive feedback oscillation is applied to the direct-axis reference current $I_{d,ref}$ through two sampled signals: V_{pcc} and the active power control. These sampled signals, which are fed into $I_{d,ref}$ can be expressed by the following equation (1).

$$I_{d,ref} = \left[\left(P_{ref} - P_{inv} \right) \times PI \right] + \left[k_{pf} \times V_{pcc}\ (k) - V_{pcc}\ (k-1) \right] \quad (1)$$

In the above equation, P_{INV} and PI represent the proportional–integral controller and the inverter output power, respectively. The overall operation of the conventional VPF method can be described using equations (1) and (2).

$$P_{inv} = \frac{V_{pcc}^2}{R} \quad (2)$$

Here, R represents the resistive component of the parallel RLC circuit, which models the local load. Under islanded conditions, when V_{PCC} increases, the direct-axis reference current $I_{d,ref}$ also rises, as described in equation (1).

This increase leads to a rise in the inverter's output active power and a corresponding increase in V_{PCC}, as described in equation (2). The VPF process continues until the voltage exceeds the permissible threshold, thereby enabling the detection of islanding. In the case of voltage reduction, VPF operates in a manner that keeps V_{PCC} within its allowable range while reducing the active power output. The fundamental operation of the VPF method is illustrated in Fig. 4.

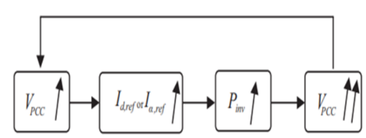


Fig. 3. Fundamental operation of the Voltage Positive Feedback (VPF) method [24].

As illustrated in Fig. 3, an increase in V_{PCC} leads to a rise in $I_{d,ref}$, which in turn increases P_{inv}, ultimately resulting in a significant further increase in V_{PCC} .

A. *Voltage Positive Feedback in Photovoltaic Systems*

Conventional VPF methods are typically applied to inverter-based DGs such as GCPVS. In GCPVS systems, the input power is limited by solar irradiance and ambient temperature. Additionally, GCPVS employs a Maximum Power Point Tracking (MPPT) algorithm within the inverter voltage control loop to extract the maximum available power. Due to these input power limitations and operation at the maximum power point (MPP), the PV output power P_{pv} cannot exceed the predefined MPP value. Consequently, when the GCPVS operates in islanded mode, even if V_{PCC} increases, the PV output power remains essentially constant.

The basic structure and operation of the VPF method are based on the attempt to increase the reference power P_{ref} as well as the inverter output power through a disturbance applied in the current control loop, which operates independently of the voltage controller [25]. Consequently, the active output power of the GCPVS may appear to exceed the input power from the PV system P_{pv} seemingly violating the law of energy conservation [25]. Although theoretically, the VPF method suggests an increase in P_{inv} , practical implementation demonstrates otherwise. This phenomenon is illustrated in Fig. 4.

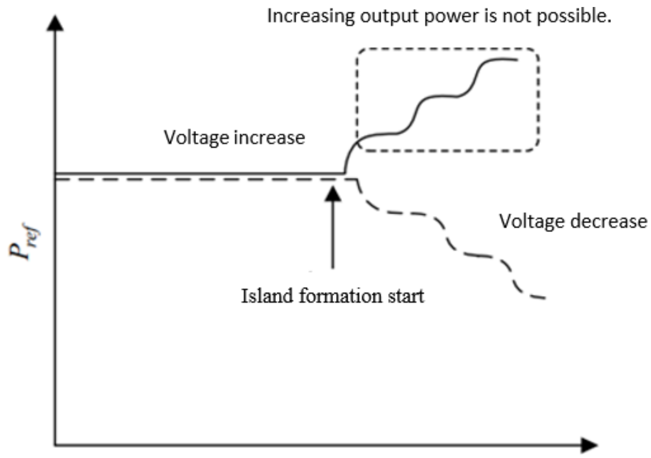


Fig. 4. Inability of the VPF scheme to increase inverter output power [25].

in general, the VPF method exhibits two possible scenarios. In the first scenario, following the applied disturbance, the change in PCC voltage PCCΔV is greater than or equal to zero, while in the second scenario, it is smaller than zero. In other words, when compared to the reference value, the magnitude of PCCΔV reflects the system's response.

If PCCΔV is less than zero, this indicates energy conservation and sufficiency, corresponding to a shortage of active power under islanded conditions. This scenario is illustrated in Fig. 5. Conversely, if PCCΔV is greater than zero after the disturbance, it indicates an excess of power in the islanded region, which ultimately leads to a violation of energy conservation.

In recent years, various methods have been proposed to expand the penetration of distributed and renewable energy resources in distribution networks to achieve higher power generation. One of the main advantages of using renewable resources compared to conventional fossil-fuel-based generation units is the reduction of pollutant emissions.

Microgrids, as small-scale power systems, integrate various distributed and renewable energy sources, ultimately forming a cohesive microgrid. These systems are capable of simultaneously supplying both electrical and thermal loads [26]. Distributed generation units within a microgrid can operate complementarily to support one another. On one hand, the microgrid can mitigate adverse impacts on the main grid

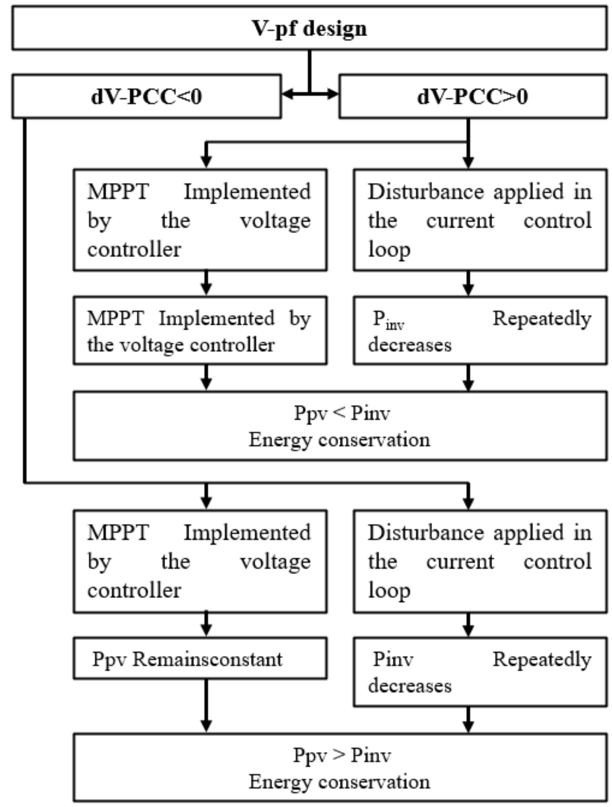


Fig. 5. Violation of energy conservation in the VPF scheme [25]

V. Performance Indicators of IDM

through these complementary resources. On the other hand, different types of distributed energy sources, distributed energy resources, controllable loads, and general loads can be integrated within a microgrid to reduce dependency on the main grid. As a result, microgrids have garnered widespread interest and have rapidly evolved. In other words, microgrids represent a critical pathway for the development of sustainable energy.

As mentioned, photovoltaic (PV) plants are among the most practical renewable energy sources in microgrids. When a microgrid, and specifically PV units, operate in grid-connected mode, various control challenges may arise. Under islanded conditions, when the PV plant operates independently from the main grid, supplying priority loads becomes the primary concern. Therefore, timely detection of the operational state serves as a prerequisite for optimal control of microgrids based on PV generation.

Fig. 6 illustrates a sample model that can be used to analyze islanding and islanded conditions. Based on this model, the general relationship between the PCC voltage and active power under normal operating conditions can be expressed by equation (3).

$$P_L^{pr} = P_{DG} - \Delta P = \frac{V_{pcc}^2}{R} \tag{3}$$

In the above equation, P_L^{pr}, P_{DG} and ΔP represent the active power of the local load prior to islanding, the active power generated by the DG before islanding, and the network power, respectively.

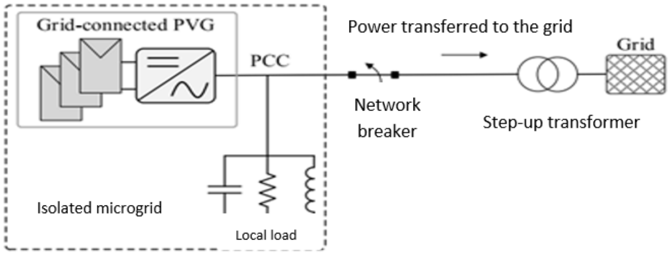


Fig. 6. Illustration of islanding events in a photovoltaic-based microgrid [26].

In equation (3), the parameter R corresponds to the resistive component of the local RLC load. After the PV-based microgrid enters islanded mode, power exchange with the upstream grid ceases, leading to a mismatch between generated power and load demand. Consequently, the PCC voltage shifts to a new operating point to satisfy $P_{DG}=P_L^{po}$. This new operating point is illustrated in equation (4).

$$P_L^{po} = P_{DG} = \frac{\left(V_{pcc} + \Delta V_{pcc}\right)^2}{R} \tag{4}$$

Here PLpo and ΔV_pcc^ represent the active power of the load and the change in PCC voltage following the islanding event, respectively. By combining the above relationships, the connection between power imbalance and PCC voltage variation can be expressed as equation (5).

$$\frac{\Delta P}{P_{DG}} = 1 - \left(\frac{V_{pcc}}{V_{pcc} + \Delta V_{pcc}}\right)^2 \tag{5}$$

Thus, the range of active power mismatch that causes the PCC voltage to deviate from its standard limits after islanding can be defined according to equation (5). Similarly, if the reactive power demand of the load and the reactive power supplied by the PV system are not balanced, the frequency at V_{pcc} will continue to change until $Q_{DG}=Q_L^{po}$.

This method is easy to implement but suffers from a large non-detection zone (NDZ). When the load demand matches the PV-generated power, islanding cannot be detected. The relationship between reactive power and V_{pcc} is expressed as follows:

$$\Delta Q = Q_{Load} - Q_{DG} \tag{6}$$

$$Q_{Load} = V_{pcc}^2 \left(\frac{1}{\omega L} - \omega c\right) \tag{7}$$

When the measured values exceed the predefined thresholds, islanding is detected. A fundamental question arises: can microgrid islanding be detected accurately, promptly, and reliably? To address this question, key performance indicators (KPIs) have been defined in power systems, which are closely tied to the effectiveness of islanding detection methods (IDMs).

The essential indicators that must be considered for accurate and timely islanding detection include the non-detection zone (NDZ), power quality, detection time, and false detection rate. The NDZ is the primary reason for the failure of many islanding detection methods. As previously mentioned, IDMs can be categorized into various types. Methods for defining NDZ have been proposed in several studies [27,28]. These include NDZs based on monitoring voltage, frequency, or phase deviation, typically described in the unbalanced power space. NDZs associated with active disturbance injection are usually described in the parametric load space. Methods that employ signal injection or perturbations can significantly reduce the NDZ during microgrid islanding detection. However, it is important to note that such disturbances may naturally degrade power quality. Power quality, therefore, is a crucial criterion when selecting an IDM.

In power quality analysis, the quality factor is introduced. The quality factor of a parallel RLC load represents the ratio between the energy stored and the energy dissipated per cycle at a specific frequency, and is expressed as equation (8) [29].

$$Q_f = \frac{2\pi\left(\frac{1}{2}cR^2I^2\right)}{\frac{\pi R I^2}{\omega_0}} \tag{8}$$

In the above equation, $\omega_0=(1/LC)$ represents the resonant angular frequency, ϕ is the phase of the RLC load impedance at a given frequency F, and the resonant frequency F_0 is defined as follows:

$$\emptyset_{load} = tan^{-1}\left[R\left(\frac{1-\omega^2 LC}{\omega L}\right)\right] = tan^{-1}\left(Q_f\frac{f_0}{f} - \frac{f}{f_0}\right) \tag{9}$$

$$z = \frac{1}{\frac{1}{R} + \left(\frac{1}{\omega L} - \omega C\right)^2} = \frac{R}{\sqrt{1 + Q_f^2\left(\frac{f_0}{f} - \frac{f}{f_0}\right)^2}} \tag{10}$$

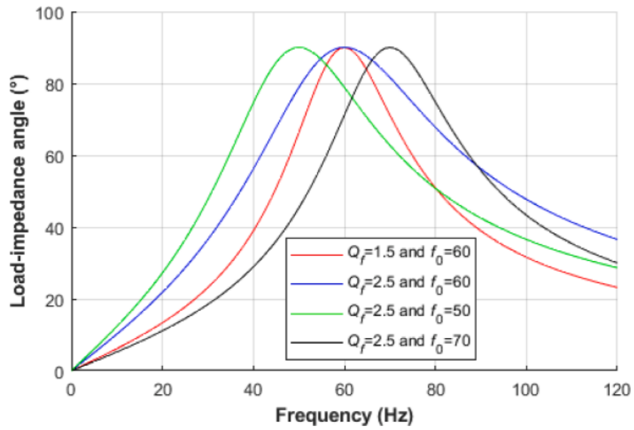
The mismatch space between active and reactive power cannot fully determine the NDZ for active detection techniques, as multiple combinations of inductance L and capacitance C may exist for a given reactive power mismatch. However, by using the load quality factor Q_f as a parameter, different RLC load combinations can be effectively managed. The islanding frequency and the steady-state voltage amplitude in the RLC circuit can be expressed by equations (11) and (12).

$$P_{load,island} = \frac{V_{island}^2}{R} = P_{inv} \tag{11}$$

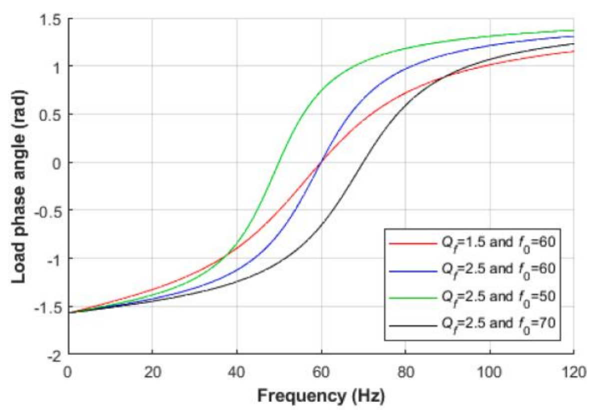
$$Q_{load,island} = \left(\frac{V_{island}^2}{x_{x,grid}}\left(\frac{f_0}{f_{island}}\right)^2 - 1\right) = Q_{inv} \tag{12}$$

Therefore, it can be stated that the islanded operating voltage V_{island} is influenced by the inverter active power P_{inv} and the resistance R [30]. Subsequently, the islanding frequency f_{island} deviates with changes in the inverter reactive power Q_{inv}. A slight adjustment in the inverter reactive power is required to shift the load phase angle Φ beyond its boundary condition [31].

For an RLC load, the load phase angle versus frequency curves for different resonant frequencies f_0 and quality factors Q_f are illustrated in Fig. 7(a). The variation of the load phase angle with frequency for different f_0 and Q_f values is also shown in Fig. 7(b) [32].



A: Load phase angle–impedance as a function of frequency



B: Load phase angle versus frequency

Fig. 7. Variation of Q_f with respect to f_0

VI. Modeling Microgrid Islanding Based on Voltage Feedback and Fuzzy Controller

In microgrid islanding, the primary objective is to maintain the voltage and frequency within a safe operating range during islanded operation, ensuring that these critical parameters remain within permissible limits under any disturbance. Generally, when a PV-based microgrid is connected to the upstream grid, the frequency is controlled without additional intervention. Frequency control in the grid-connected mode is typically managed through the slack bus.

Therefore, frequency control in the islanded mode must be carefully examined. A key aspect of using distributed generators (DGs), such as PV units, in islanded operation is that these resources should possess the capability to regulate frequency despite significant variations caused by islanding events.

Every power system has one or more V/f buses (voltage and frequency controllers). This can apply to a large standard IEEE network with multiple buses capable of V/f control, or to a PV-based microgrid, or any type of distributed generation system. In this study, the system under consideration is a PV-based microgrid; therefore, the bus connected to the PV unit acts as the V/f controller.

An important requirement for ensuring frequency stability in islanded operation is that the microgrid must have sufficient capacity to supply the remaining loads after islanding. Otherwise, the isolated microgrid may experience frequency and voltage instability. Fig. 8 shows the outputs of the PV-based microgrid. In the simulation, an islanding event occurs at 5 seconds, triggered by a switch operation. The simulation results under this condition are subsequently analyzed.

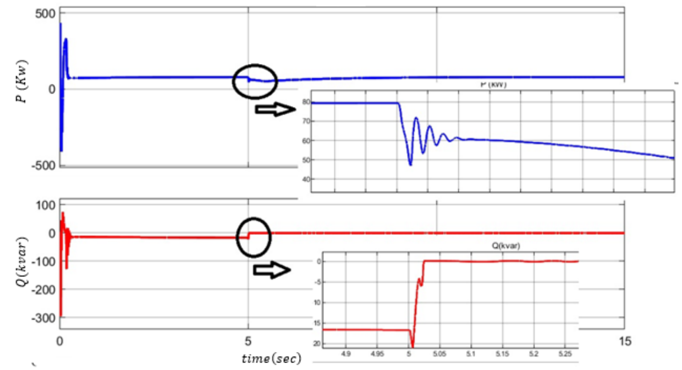


Fig. 8. Injected power of the PV-based microgrid in islanded mode supplying the electrical load

Fig. 8 illustrates that when the microgrid operates in an islanded mode, detached from the upstream grid, the first parameter to change is the voltage. At the onset of islanding, the voltage amplitude initially drops. During this voltage dip, the reactive power generated by the PV-based microgrid increases to compensate for the voltage decline. This behavior is shown in Fig. 9.

Active power also initially decreases but returns to normal after a short period. Fig. 9 depicts the impact of islanding on both voltage and current in the PV-based microgrid. In general, in power and distribution networks, when a voltage drop occurs, additional reactive power is injected, and the PV sources must operate to increase the active power delivered to the load until frequency stability is restored.

One of the critical aspects of microgrid islanding is frequency behavior. It should be noted that if the capacity of the microgrid entering islanded mode exceeds the installed load, the excessive active power injected by the distributed generation units during islanding can lead to a frequency rise.

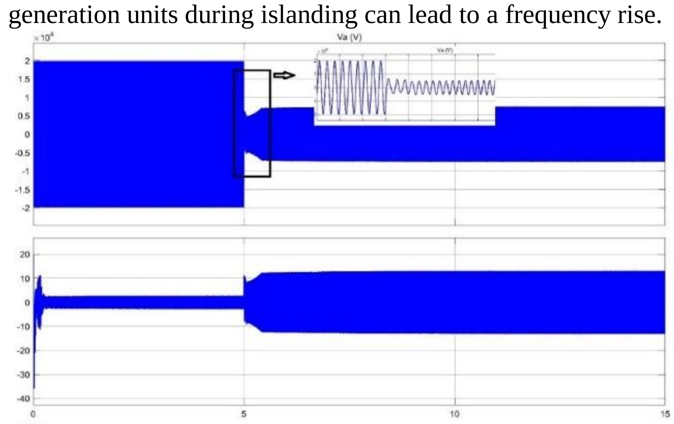


Fig. 9. PCC bus voltage amplitude during microgrid islanding

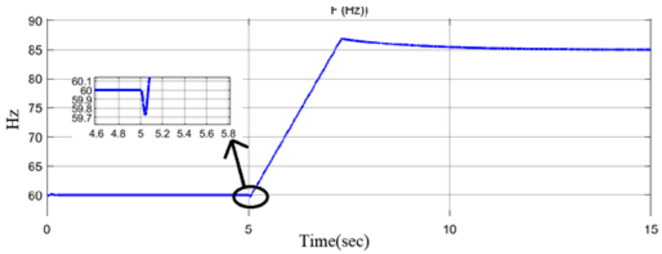


Fig. 10. Frequency response during microgrid islanding

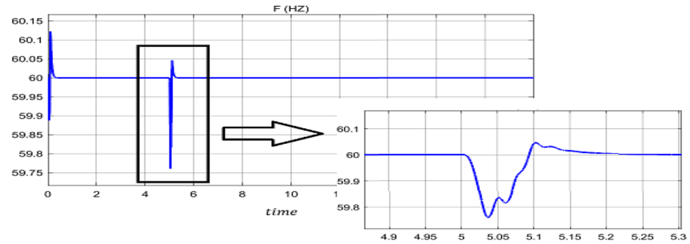


Fig. 12. Frequency regulation in the islanded microgrid

If the installed load in the islanded microgrid exceeds the generation capacity of the PV units, the frequency will continuously drop, eventually leading to a complete shutdown of the microgrid. In this way, a brief overview of islanding and its impact on voltage, active and reactive power, and frequency has been provided.

A. Voltage Feedback Controller in Islanded Microgrids

Since no external power source is available in an islanded microgrid, the output power waveform is highly susceptible to the adverse effects of voltage fluctuations. In this section, a voltage feedback controller is introduced to track the reference voltage at the point of common coupling (PCC) for distributed generation units within an islanded microgrid.

The main goal is to determine how the bus connected to the PV unit can regulate voltage and frequency once the microgrid transitions into islanded mode, based on the control strategies employed in grid-connected operation. It is important to note that when PV or any other generation units are connected to the upstream grid, they typically operate as PQ buses, supplying both active and reactive power. In islanded operation, these PQ buses must be converted into V/f buses (voltage and frequency controllers).

To enable effective voltage and frequency regulation in islanded mode, the microgrid must utilize both a frequency control loop and a voltage feedback control loop, integrated into the current control path of the VSC (PV-based microgrid inverter).

These designed controllers are intended to regulate the injection of active and reactive power into the islanded system, ensuring that both voltage and frequency at the bus connected to the PCC remain stable.

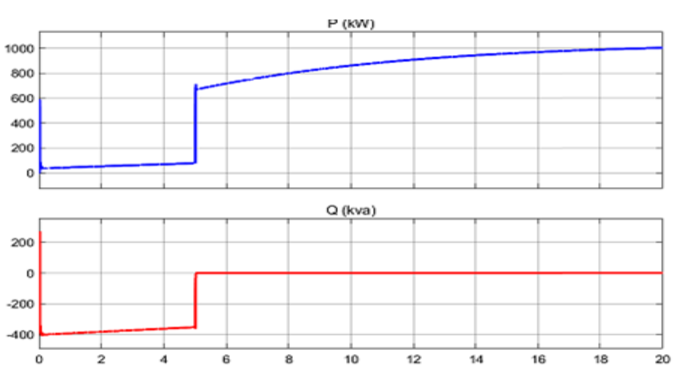


Fig. 11. Active and reactive power in V/f state

Fig. 11 illustrates the variations in active and reactive power, which are regulated to maintain a stable frequency. This scenario corresponds to the islanded mode frequency controller, where the bus connected to the PV unit operates as a V/f bus.

Accordingly, all adjustments in active and reactive power are implemented to keep the frequency constant. Fig. 12 shows the frequency response when the microgrid enters islanded mode, with the bus connected to the PV plant functioning as a V/f bus.

A-1. Increasing Microgrid Load with Voltage Feedback Controller Design

A critical aspect for evaluating the reliability of microgrids and their distributed and renewable energy resources is maintaining the stability of a microgrid that initially operates connected to the upstream network and later transitions into islanded mode. Microgrids operating in islanded mode must be designed so that the addition of new loads does not lead to a complete collapse or blackout of the islanded system.

In this context, the PID controller for a microgrid transitioning into islanded mode must be designed to ensure that both frequency and voltage remain stable, while also appropriately handling load increases on the islanded system. Therefore, in this section, a voltage feedback controller is designed to maintain the voltage amplitude during the microgrid's transition to islanded operation.

As shown in Fig. 13, the islanding event occurs at 5 seconds. Since the primary objective is to control frequency and voltage, the active and reactive power adjust accordingly to maintain these critical parameters stable. At 15 seconds, an inductive load is applied to the islanded microgrid. In this scenario, to continue controlling frequency and voltage, the active and reactive power vary in such a way that both voltage and frequency remain stable within the islanded microgrid. Fig. 14 illustrates the corresponding frequency profile.

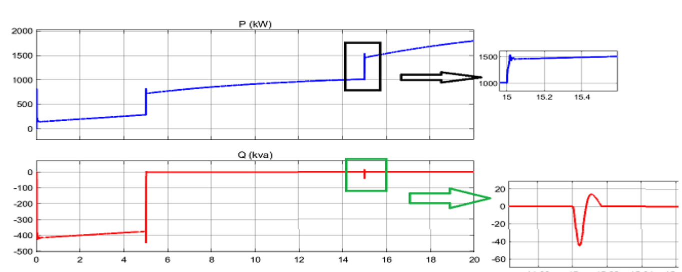


Fig. 13. Active/reactive power of the islanded microgrid under increased load

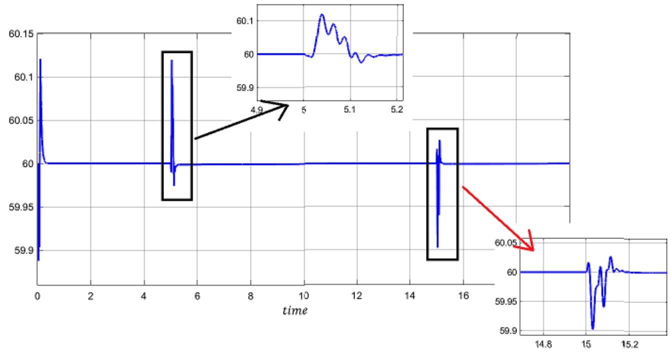


Fig. 14. Frequency of the islanded microgrid under increased load

Fig. 14 shows that the system enters islanded mode at 5 seconds, during which a significant amount of active power is injected into the islanded microgrid to supply the load, thanks to controllers such as PID. At 15 seconds, while the system continues to operate in islanded mode, an additional load is applied. According to the controllers in place, the active and reactive power adjust accordingly to ensure that the frequency remains within a stable range. Fig. 15 illustrates the corresponding voltage and current variations under the added load in the islanded system.

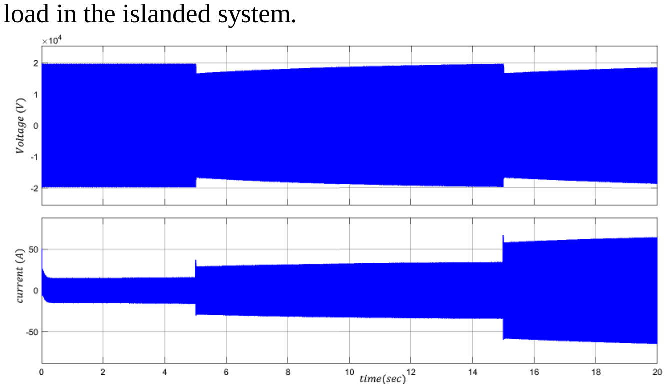


Fig. 15. Voltage and current in the islanded microgrid under increased load

Fig. 15 illustrates the voltage and current variations during islanding. At 5 seconds, when the microgrid enters islanded operation, voltage and current change according to the loss of connection with the upstream grid. At 15 seconds, when an additional load is applied, the voltage and current adjust again to maintain system stability.

A-2. Switching from PQ Control Mode to Voltage Feedback Control in Islanded Microgrids

In this section, the objective is to design a controller that converts the active and reactive power control mode (PQ) into a voltage feedback control mode when the microgrid becomes islanded. This ensures stable voltage and frequency regulation under islanded conditions. The proposed control method combines PQ and V/f controllers.

The operation principle is as follows: before the microgrid disconnects from the upstream network, active and reactive power loops regulate P and Q. Once the main grid connection is lost, the microgrid enters an islanded mode, which can be unstable if not properly managed. At this point, the designed controller switches from PQ mode to voltage feedback mode, maintaining voltage and frequency within safe limits.

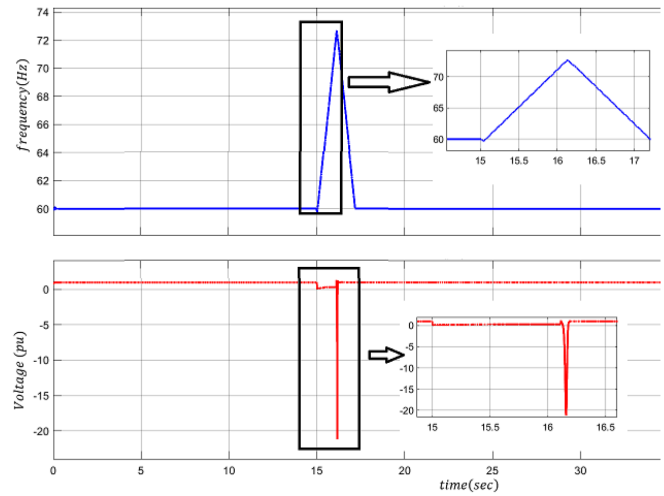


Fig. 16. Switching of voltage and frequency control from PQ mode to voltage feedback control

The proposed strategy switches the control loops based on voltage feedback. Specifically, if the reference frequency exceeds the permissible range around 60 Hz for more than 1 second, the controller automatically transitions from PQ control to voltage feedback control, ensuring the islanded microgrid remains stable.

Fig. (16) illustrates that until the 15th second, the microgrid, while connected to the upstream network, is controlled by active and reactive power control loops (PQ mode). After the 15th second, when the microgrid enters islanded operation, a one-second detection and transition period is considered, after which the controller switches from PQ mode to voltage feedback control (V/f mode) to stabilize voltage and frequency within the allowable range. In this approach, the frequency initially experiences a deviation, and after applying voltage feedback control, the system reaches a stable state.

Fig. (17) shows the active and reactive power values in PQ mode and the transition process to voltage feedback control.

Thus, the active and reactive power outputs are shown when the microgrid switches from PQ mode to voltage

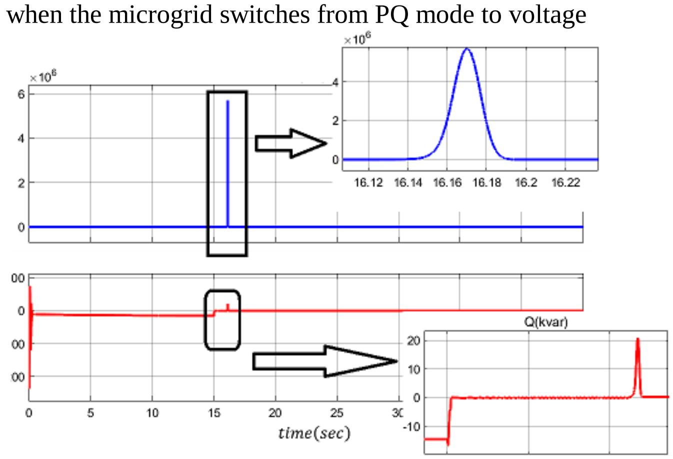


Fig. 17. Transition of active and reactive power from PQ mode to voltage feedback control

feedback control in islanded operation. The proposed hybrid control (a combination of voltage feedback and PQ control) ensures that if the microgrid remains disconnected from the upstream network for 1 second, it transitions from PQ mode to voltage control mode.

B. Photovoltaic Microgrid Based on Fuzzy Controller

A fuzzy logic controller is designed using the voltage output of the photovoltaic unit within the microgrid as a tool to significantly improve the dynamic performance of the DC-DC boost converter. The main objective of this section is to present a fuzzy control scheme for photovoltaic microgrids operating in islanded mode. The DC-DC boost converter exhibits a nonlinear function of the duty cycle due to the small-signal model, and the proposed control method is applied to boost converters [33].

B-1. Block Diagram of the Fuzzy Logic Controller (FLC)

Fig. 18. Block Diagram of the Fuzzy Logic Controller

In this fig.:

- Fuzzification converts numerical input values into fuzzy membership degrees
- Inference Engine Applies the set of IF-THEN fuzzy rules to generate fuzzy conclusions
- Defuzzification Transform the aggregated fuzzy output into a crisp numerical control value [36].

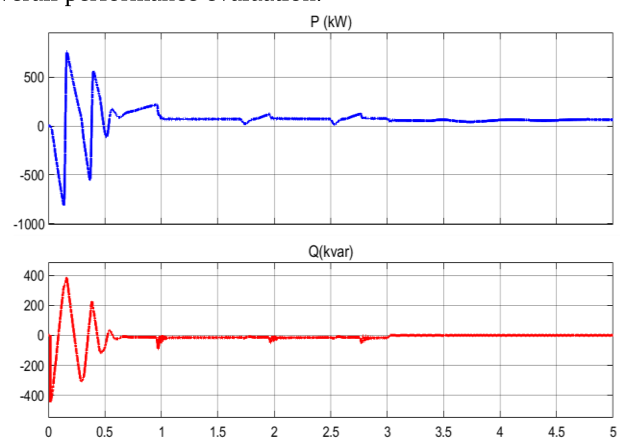
Fuzzy controllers do not require an exact mathematical model; instead, they are designed based on general system knowledge [33]. The designed fuzzy controller regulates the output of the DC-DC boost converter using a Mamdani-style fuzzy logic system. In this system, two input variables are used: the error (e) and the change in error (de). The output variable (u) represents the PWM duty cycle. When islanding occurs, the error signal (e) enters the PV control system as one input, and the change in error (de) serves as the other input to the PV pulse control system, which adjusts the DC-DC boost converter of the solar system to deliver higher output power to the islanded microgrid.

The fuzzy control rules are derived from analyzing the system behavior. In formulating these rules, it must be considered that using different control rules depending on operating conditions can significantly improve the converter's dynamic response and robustness. Initially, when the output voltage deviates from the set point, i.e., the error (e) may be PB (Positive Big) or NB (Negative Big), the corrective action performed by the controller must be strong. In other words, the duty cycle should be close to zero or one to ensure the fastest possible dynamic response. Table 2 presents the fuzzy logic rules designed.

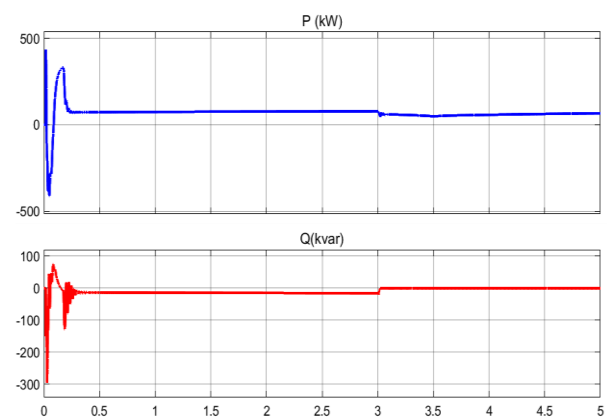
TABLE II
FUZZY LOGIC RULES FOR ERROR (E) AND CHANGE OF ERROR (DE) IN CONTROLLER DESIGN

(de) \ (e)	NB	NS	ZO	PS	PB
NB	NB	NB	NB	NS	ZO
NS	NB	NB	NS	ZO	PS
ZO	NB	NS	ZO	PS	PB
PS	NS	ZO	PS	PB	PB
PB	ZO	PS	PB	PB	PB

When the output voltage error approaches zero, i.e., when the error (e) is NS, ZE, or PS, the current error must be properly considered similar to current-mode control to ensure stability around the operating point. Ultimately, when the current approaches its limit, appropriate rules must be introduced to enforce the current limit while preventing excessive overshoot. Next, the fuzzy control method is compared with the two previously considered methods: the PQ loop control and voltage feedback control, providing an overall performance evaluation.

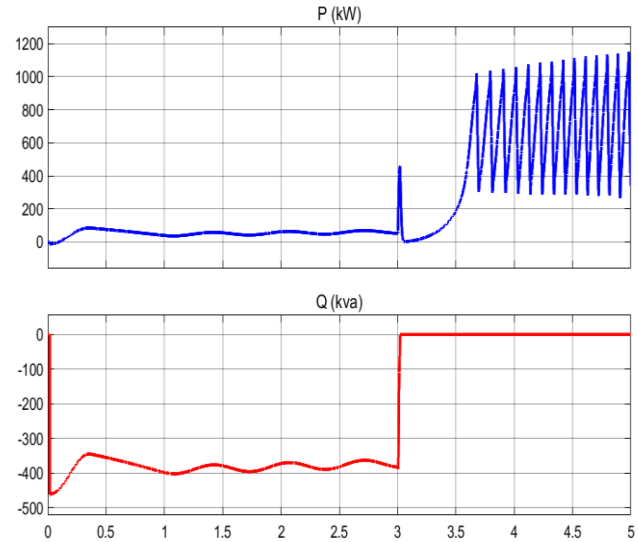


A: Using PQ control loops with fuzzy logic method

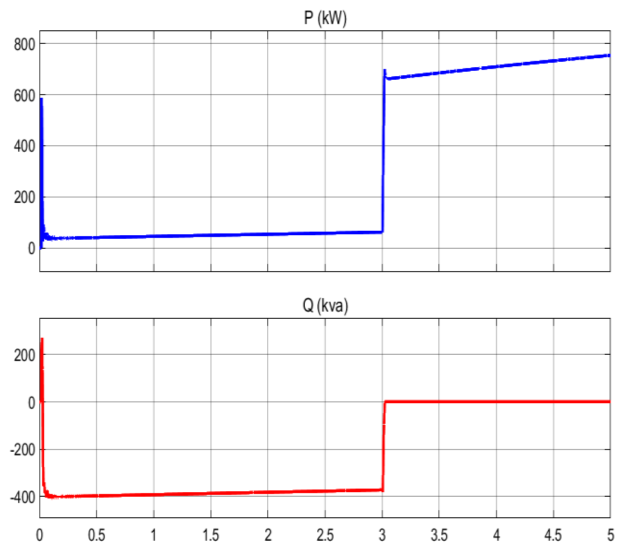


B: Using only PQ control loops

Fig. 19. Comparison of active and reactive output powers



A: Using V/f control loops with the fuzzy logic method

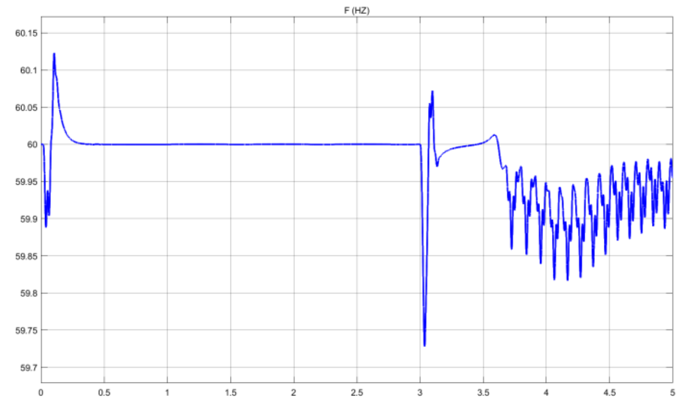


B: Using only V/f control loops

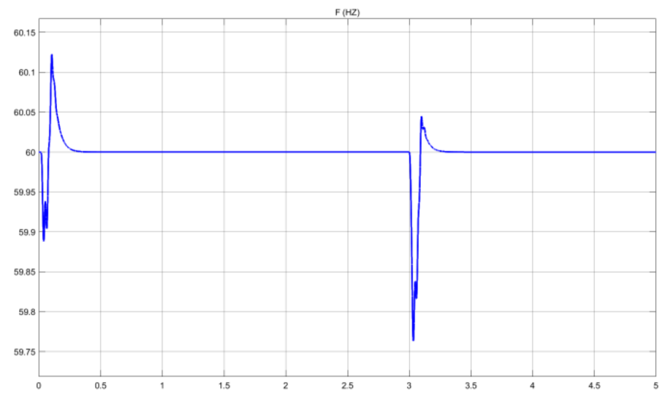
Fig. 20. Comparison of active and reactive power output using the fuzzy logic controller

Fig. 19(a) shows that at the beginning of the simulation and before islanding, more active and reactive power is delivered to the network. However, using only the PQ method results in smaller fluctuations in both active and reactive power. In the voltage control approach, if a comparison is made using fuzzy logic, Fig. 20 and 21 can be used to compare power and frequency performance between the two methods.

As shown in fig. 21, when the fuzzy logic method is used, the active power values experience significant oscillations after islanding, whereas with voltage control, these oscillations are eliminated. Similarly, the frequency under fuzzy logic exhibits fluctuations when V/f control loops are used after the microgrid enters the islanded mode. Therefore, it can be concluded that fuzzy logic is more suitable for controlling active and reactive power loops rather than frequency and voltage control loops.



A: Using the fuzzy logic method



B: Using only V/f control loops

Fig. 21. Frequency comparison

VII. Conclusion

A microgrid, as a part of the distribution network, contains multiple distributed and renewable energy resources capable of supplying local loads. Utilizing distributed and renewable resources within a microgrid can present significant challenges, with islanding being the most critical. The first fundamental step in addressing islanding is its rapid and accurate detection.

When a microgrid is connected to the upstream grid, due to the inertia and dynamics of the upstream network, frequency and voltage control are effectively managed by the upstream grid, which supplies active and reactive power to the microgrid. This is because the upstream grid acts like an infinite bus.

In the islanded mode, many voltage and frequency controllers must be installed within the microgrid, as power balance becomes challenging without connection to the upstream network. Islanding occurs when the microgrid continues to inject power into the system without being aware that it has been disconnected from the main grid. This lack of awareness can adversely affect key network parameters such as voltage, frequency, and power.

This study investigated islanding detection in microgrids using a voltage feedback method. The main objective was to analyze microgrid behavior in the islanded mode and detect disconnection from the main grid using the voltage feedback islanding detection approach. The proposed method was compared with other approaches, including active and reactive power feedback-based methods. Finally, the implementation of a fuzzy logic controller in two combinations was evaluated, and the results indicated that fuzzy logic is more suitable for controlling active and reactive power loops rather than frequency and voltage control loops.

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