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# Design and Performance Evaluation of a Local Voltage Controller for Islanded AC Microgrids

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**Abstract- — During islanded operation, AC microgrids operate without grid support, making voltage regulation a critical challenge due to load variations, intermittent renewable generation, and inverter-dominated dynamics. In such conditions, maintaining stable voltage becomes difficult without effective local control mechanisms. This paper presents a decentralized voltage control approach based on a PI-dominant PID controller applied at the primary control level. The proposed controller regulates the inverter output voltage to handle disturbances arising from load changes and renewable energy fluctuations, including photovoltaic and fuel cell sources. The control strategy is simple, does not require communication infrastructure, and is suitable for practical implementation. Simulation results obtained using MATLAB/Simulink demonstrate that the proposed method improves voltage stability, minimizes oscillations, and maintains acceptable performance under varying operating conditions.**

**Keywords— Islanded AC MG, local VC, PC, PI-dominant PID, IBDG, hybrid MG.,**

## I. INTRODUCTION

Reliable access to electrical energy is a fundamental requirement for socio-economic development, particularly in rural and semi-urban regions where grid infrastructure is often weak or inconsistent. Although significant progress has been made in grid expansion, many areas still experience unreliable supply, voltage fluctuations, and poor power quality. These challenges have accelerated the adoption of decentralized energy solutions, especially hybrid renewable energy-based microgrids, which can provide stable and continuous electricity independent of the main grid. [1], [2]

A microgrid can be defined as a localized electrical network that integrates multiple Distributed Energy Resources (DERs), such as photovoltaic systems, fuel cells, wind turbines, and energy storage units. These resources typically operate through power electronic converters and can function either in grid-connected mode or in islanded mode. The flexibility of switching between these modes makes microgrids highly suitable for modern power systems, especially in remote or critical applications. [5]

Among the different operating modes, islanded operation presents the most demanding control scenario. In the absence of support from the utility grid, the microgrid must independently regulate both voltage and frequency while continuously supplying local loads. This task becomes more complex due to fluctuating load conditions, intermittent renewable energy generation, and the dominance of inverter-based sources. As a result, maintaining stable operation under such conditions requires well-designed and reliable control strategies. [3]

Voltage regulation is one of the most critical control objectives in islanded AC microgrids. Inadequate voltage control can lead to degraded power quality, increased harmonic distortion, and even system instability. The presence of multiple DERs with different dynamic characteristics further complicates coordination and control. Therefore, the development of effective voltage control techniques remains an active area of research in microgrid systems. [8]

Conventional control methods, particularly those based on PID controllers, are widely used due to their simplicity and ease of implementation. However, fixed-gain controllers may not always perform satisfactorily under varying operating conditions, such as sudden load changes or parameter uncertainties. This highlights the need for careful system modeling and performance evaluation of control strategies specifically designed for islanded microgrid applications.[5]

In this work, an islanded AC hybrid microgrid is modeled, and a local voltage control strategy based on a PI-dominant PID controller is developed. The system integrates renewable energy sources through inverter-based interfaces, and the proposed control scheme is implemented using

MATLAB/Simulink. The performance of the controller is evaluated under different operating conditions to assess its effectiveness in maintaining voltage stability and improving overall system performance.

## II. PROPOSED SYSTEM WITH TRANSFER FUNCTION

Figure 1 illustrates the proposed system, which is an islanded AC hybrid microgrid developed to supply local three-phase loads using inverter-based Distributed Energy Resources (DERs). The system integrates a photovoltaic (PV) source and a fuel cell to form a hybrid generation unit capable of operating independently after disconnection from the utility grid at the Point of Common Coupling (PCC). During islanded operation, the microgrid is required to maintain voltage stability and acceptable power quality despite variations in load demand and fluctuations in renewable energy generation.[8], [9], [11]

Since no external grid is available to provide voltage or frequency reference, the responsibility of regulation shifts entirely to the local control system. In this work, a grid-forming Voltage Source Inverter (VSI) is employed to establish the voltage reference and ensure stable operation of the microgrid. A PI-dominant PID controller is implemented at the primary control level to regulate the inverter output voltage. The controller generates appropriate control signals, which are converted into PWM pulses for inverter switching, enabling precise voltage control under dynamic conditions.[10]

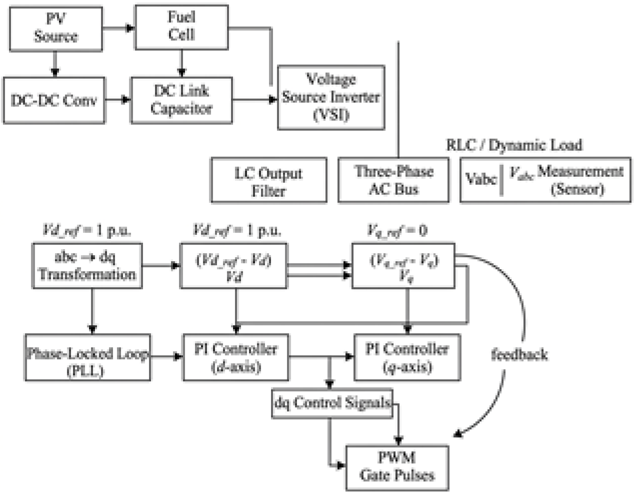

Fig.1 Block diagram of proposed System

The proposed system also includes essential components such as a DC-link capacitor for voltage stabilization, LC filters for harmonic reduction, and measurement blocks for feedback control. The control strategy is designed to respond quickly to disturbances such as sudden load changes or renewable power variations. Additionally, the decentralized nature of the controller eliminates the need for communication links, improving system reliability and ease of implementation. The overall configuration ensures effective voltage regulation, enhanced stability, and improved performance of the microgrid during islanded operation.[8], [11]

Distributed Energy Sources: The microgrid combines a photovoltaic system and a fuel cell stack. Both sources deliver DC power and are connected to a common DC bus through dedicated DC–DC converters. [7]

DC Link: A DC-link capacitor smooths voltage ripples, provides short-term energy buffering, and stabilizes the inverter input during dynamic operating conditions.

Voltage Source Inverter (VSI): The VSI converts DC power to AC and operates in grid-forming mode. It regulates the AC voltage magnitude, supplies local loads, and ensures stable islanded operation. An LC filter is used at the output to reduce switching harmonics.

Voltage Measurement and Reference Frame: Three-phase output voltages are measured and transformed into the dq reference frame using a PLL and abc–dq transformation, enabling decoupled voltage control.

PID-Based Voltage Control: The controller tracks fixed voltage references (d-axis: 1 p.u., q-axis: 0) using PI-dominant PID controllers to generate control signals for voltage regulation. [4]

The controller output in dq frame can be expressed as:

PWM and Switching Control: Control signals are converted into PWM gate pulses for the inverter switches, allowing precise adjustment of the output voltage. [14]

Load Conditions: The system feeds a three-phase RLC load and is tested under varying load and voltage reference conditions to evaluate voltage regulation performance.

## III. MODELLING OF PROPOSED SYSTEM

Building on the benefits of effective microgrid control, this section outlines the control strategy adopted in this study and explains how it is applied to achieve stable and reliable microgrid operation.

### 1. Basic Parameters

Maintaining stable voltage and power levels in a microgrid is more complex compared to conventional power systems. This is primarily due to the presence of multiple distributed energy resources (DERs), each with different characteristics and dynamic behavior. The decentralized and interconnected structure of a microgrid further increases the difficulty of achieving coordinated control. Therefore, effective operation of the system depends on careful consideration and proper tuning of several important parameters, which are discussed in the following sections.

### Voltage Stability

Voltage stability in a microgrid depends on several interacting factors, including voltage regulation capability, waveform quality, and overall system performance. It can be understood as the ability of the system to keep the voltage magnitude within acceptable limits under both steady-state conditions and disturbances such as load changes or generation variability. In practice, this is achieved by equipping each Distributed Energy Resource (DER) with a local control mechanism that actively supports voltage regulation. If adequate control is not maintained, the system may experience voltage variations, oscillatory behavior in reactive power, and deterioration in power quality, ultimately affecting the reliability and safe operation of the microgrid. [9], [10], [11]

### Frequency

During islanded operation, all Distributed Energy Resources (DERs) must collectively maintain the system frequency, as there is. [12]

### Load-sharing Active and Reactive Power, LS P & Q

Effective sharing of active and reactive power among Distributed Energy Resources (DERs) is essential for efficient microgrid operation. It ensures that the total load demand is distributed among available sources in a coordinated manner, thereby minimizing system losses and improving overall performance. Proper load allocation allows each DER to operate within its rated capacity, avoiding excessive stress or overloading of individual units. This balanced distribution of power also contributes to stable operation and enhances the reliability of the microgrid under steady-state conditions.

### 2. Modelling Equation of Proposed System

In the proposed system, several electrical parameter equations play a crucial role in analyzing and controlling system performance. These equations form the basis for understanding the behavior of key variables such as voltage, current, and power within the microgrid.

#### 1. Instantaneous Power Equations

$$\mathrm{p(t)} = \mathrm{v(t)} \times \mathrm{i(t)} = \mathrm{V_m I_m} \cos(\omega \mathrm{t} + \theta) \ldots\ldots (1)$$

#### 2. Active Power

$$P = |V| \times |I| \cos\theta \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

#### 3. Reactive Power

$$Q = |V| \times |I| \sin\theta \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

#### 4. Apparent Power

$$S = P + jQ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

#### 5. Capacitor

$$X_C = \frac{1}{wC} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

#### 6. Inductor

$$XL = wL \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

#### 7. Per unit value

$$Per\ Unit\ (P.U) = \frac{Actual\ Value}{Base\ (reference)\ Value} \ldots\ldots\ldots (7)$$

### 3. Key Components

This section describes the main components used in the simulation to develop the local controller. The proposed control scheme is implemented at the primary control level of the microgrid control hierarchy, and the key elements involved are outlined below.

### Energy Sources

Energy sources in a microgrid are the components responsible for converting various forms of energy into electrical power. In modern microgrid systems, renewable sources are commonly utilized due to their eco-friendly nature and long-term sustainability. Typical examples include photovoltaic (solar) systems, fuel cells, wind turbines, and other renewable technologies. In this work, a photovoltaic source and a fuel cell are considered and modeled within the simulation framework to represent the renewable energy generation of the proposed microgrid.

### Capacitor (C)

The capacitor is generally connected between the energy source and the inverter to support stable system operation. Its main function is to smooth out fluctuations in the DC voltage and minimize ripple effects. It also serves as a temporary energy storage element, supplying or absorbing power during sudden changes or transient conditions. Additionally, the capacitor helps balance the power flow between the source and the inverter by charging and discharging as required. This action ensures more stable operation and contributes to maintaining better power quality within the microgrid

**Inductor (L)**

An inductor, often called a reactor or coil, is a passive electrical element that stores energy in the form of a magnetic field when current passes through it. The voltage across the inductor is generated due to variations in this magnetic field, as described by electromagnetic induction principles. In power electronic systems, inductors are commonly used to limit rapid changes in current and to ensure smoother energy transfer, thereby contributing to stable and reliable circuit operation.

**Local Controller (LC)**

Local controllers play a vital role in managing the operation of individual Distributed Energy Resources (DERs) and, in certain cases, the connected loads within [4]

**PID Controller Tuning Method**

The PI-dominant PID controller parameters were tuned using an iterative simulation-based approach in MATLAB/Simulink. The tuning procedure was performed in a structured manner to achieve a suitable balance between transient response and steady-state accuracy.

At the initial stage, the proportional gain (Kp) was gradually increased to improve the speed of system response while ensuring that excessive oscillations or instability did not occur. After obtaining a satisfactory transient response, the focus was shifted to the integral gain (Ki). This parameter was adjusted to reduce steady-state error and improve the accuracy of voltage tracking. Care was taken to select an appropriate value of Ki, as excessively high values can lead to increased oscillations and longer settling times.

Subsequently, the derivative gain (Kd) was fine-tuned to enhance the damping characteristics of the system. The inclusion of the derivative term helps in reducing overshoot and improves system stability, particularly during sudden load variations or disturbances.

The primary objectives of the tuning process were as follows:

- To achieve a shorter settling time
- To minimize steady-state error
- To reduce overshoot
- To ensure stable and accurate voltage regulation under varying load conditions

| Parameter | Typical Starting Range |
|---|---|
| Kp | 0.5 – 4.79 |
| Ki | 48 – 458 |
| Kd | 0 – 0.01 |

**Voltage Source Inverter (VSI)**

Voltage Source Inverters (VSIs) are essential components in microgrid systems, as they are responsible for controlling the output voltage, frequency, and power supplied to the loads. During islanded operation, the VSI operates in a grid-forming mode, where it establishes the reference voltage required for stable system functioning. This makes the inverter a critical element for maintaining reliable operation in the absence of the main grid. Figures 2 and 3 present the MATLAB/Simulink model developed in this work to simulate and evaluate the performance of the hybrid AC microgrid and its control strategy. [13], [15]

**Block and MATLAB Simulation Diagram**

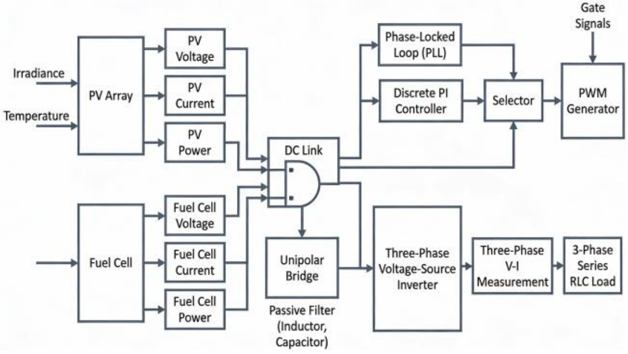

Fig 2 block diagram

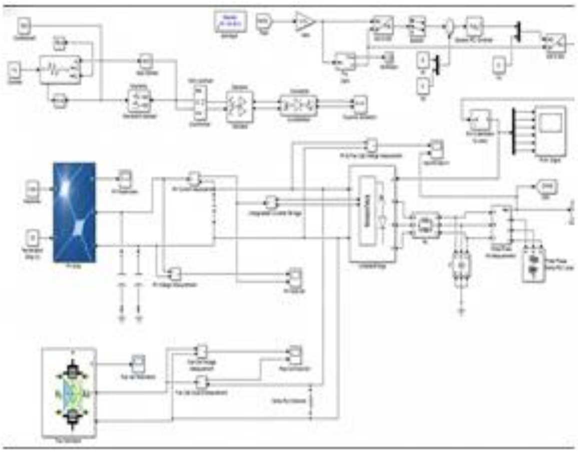

Fig.3 MATLAB Simulation Proposed System

## IV. RESULT AND DISCUSSION

The analysis examines the performance of the voltage control strategy under varying load conditions and changes in power contribution from distributed sources. Key components, including controller parameters, inverter model, passive elements, and a three-phase RLC load, are configured within practical limits. Simulation results from MATLAB/Simulink show that the proposed control approach maintains stable voltage and accurately follows the reference signal under different operating conditions.

Scenario 2: In this scenario, the photovoltaic and fuel cell parameters are kept constant, while the system reference voltage is fixed at 415 V. The three-phase RLC load is varied to evaluate the effectiveness of the voltage controller. The corresponding operating conditions are summarized in Table 1. At a load of 10 kW, the controller effectively regulates the output voltage, increasing it from 316.269 V to 417.846 V, which is close to the reference value. When the load is increased to 50 kW, the output voltage reaches 383.268 V from an input of 356.192 V, indicating acceptable performance. However, at higher loads, the controller's capability begins to decline. At 100 kW, the output voltage drops to 323.269 V, and at 150 kW, it further decreases to 276.812 V.

These observations indicate that the controller performs well under low and moderate load conditions but struggles to maintain voltage regulation at higher loads, where its operating limits are exceeded. The corresponding waveforms are presented in Figures 4–7.

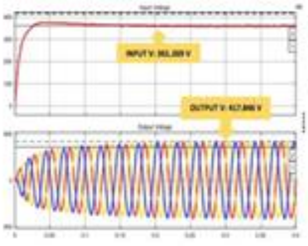

Figure 4. Input and output voltage with 10kW load

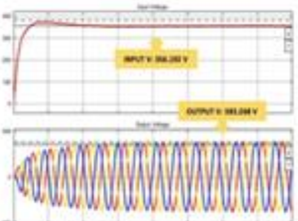

Figure 5. Input and output voltage with 50kW load

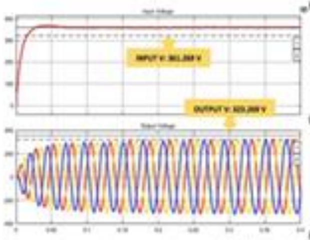

Figure 6. Input and output voltage with 100kW load

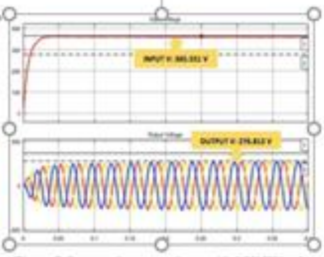

Figure 7. Input and output voltage with 150kW load

**Performance Analysis Table**

| Load (kW) | Settling Time (s) | Overshoot (%) | THD (%) |
|---|---|---|---|
| 10 | 0.08 | 4.5 | 2.1 |
| 50 | 0.12 | 7.8 | 2.8 |
| 100 | 0.18 | 12.5 | 4.6 |
| 150 | 0.30 | 18.9 | 7.5 |

Scenario 2: In this scenario, the photovoltaic and fuel cell settings, along with the load, are kept constant, while the per-unit (p.u.) voltage reference is varied. The system base voltage remains fixed at 415 V. The different operating conditions are summarized in Table 2.

The results show that the inverter output closely follows the selected reference value. At 1 p.u., the output voltage reaches 417.846 V from an input of 316.019 V. When the reference is reduced to 0.5 p.u., the output decreases to 205.757 V for an input of 528.016 V. Further reduction to 0.25 p.u. results in an output voltage of 107.228 V from an input of 555.062 V.

These observations confirm that the controller accurately tracks the reference voltage and adjusts the output accordingly. The corresponding waveforms are shown in Figures 8–10.

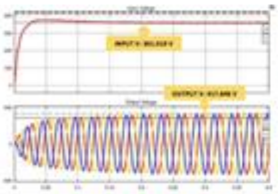

Figure 8. Input and output voltage with 1 p.u. reference voltage value

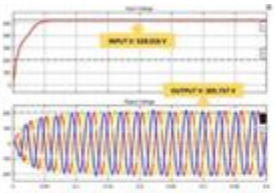

Figure 9. Input and output voltage with 0.5 p.u. reference voltage value

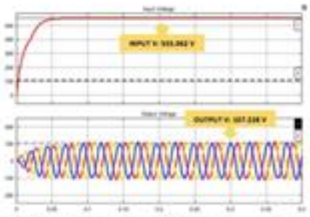

Figure 10. Input and output voltage with 0.25 p.u. reference voltage value

Table 3. Summary of simulated cases for Scenario 1

| No. | Load Variation (W) | Input Voltage (V) | Output Voltage (V) | Per Unit (p.u.) | Output Voltage Reduction (%) |
|---|---|---|---|---|---|
| 1 | 10k | 361.269 | 417.846 | 1.00 | 0.00 |
| 2 | 50k | 356.192 | 383.268 | 0.92 | 7.65 |

| No. | Load Variation (W) | Input Voltage (V) | Output Voltage (V) | Per Unit (p.u.) | Output Voltage Reduction (%) |
|---|---|---|---|---|---|
| 3 | 100k | 361.269 | 323.269 | 0.77 | 22.10 |
| 4 | 150k | 365.551 | 276.812 | 0.66 | 33.30 |

As the load increases, the controller's ability to maintain the reference voltage gradually weakens. Voltage regulation is effective at low and medium loads, but significant output voltage reduction appears at higher load levels, indicating the controller's operating limit.

Table 4. Summary of simulated cases for Scenario 2

| No. | Per-Unit Reference Voltage (p.u.) | Input Voltage (V) | Output Voltage (V) | Output Voltage Reduction (%) |
|---|---|---|---|---|
| 1 | 1.00 | 361.019 | 417.846 | 100.00 |
| 2 | 0.50 | 528.016 | 205.757 | 49.58 |
| 3 | 0.25 | 555.062 | 107.228 | 25.00 |

With fixed generation and load, the inverter output voltage follows the per-unit reference setting closely. Reducing the reference value leads to a proportional decrease in output voltage, confirming effective reference tracking by the voltage controller.

The measured THD values stay below 5% under nominal loading conditions, which complies with the limits specified in the IEEE 519 harmonic standard. This indicates that the proposed controller is effective not only in maintaining the desired voltage level but also in preserving overall power quality within acceptable standards.

## V. CONCLUSION

The controller maintains total harmonic distortion (THD) within 5% up to a load of 100 kW; however, a decline in performance is observed at 150 kW due to limitations in the inverter and control bandwidth. In this work, an islanded AC hybrid microgrid has been modeled to demonstrate the advantages of integrating Distributed Energy Resources (DERs). Although DER integration improves flexibility and sustainability, it also introduces control complexities that must be properly managed.

To address these challenges, a PID-based control strategy is implemented for regulating key system parameters. The controller effectively adjusts the output voltage in response to varying load conditions. Performance evaluation under different scenarios shows that the proposed method ensures stable and reliable voltage regulation within its operating range, making it suitable for microgrid applications.

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