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Virtual voltage control to redistribute reactive power of generators in a microgrid

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ABSTRACT

The paper examines a strategy for managing voltage control in a microgrid by redistributing reactive power among its distributed generators. Unlike traditional droop control, the new control approach can provide a more accurate reactive power response based on a virtual impedance that helps calculate a virtual voltage. In addition, this virtual impedance is employed for the current controller inverter to improve the results. The adaptive virtual voltage control works well to provide active and reactive power. The proposed control works effectively by balancing the active and reactive power of the grid and maintains the fundamental frequency. The control technique assists the new microgrid (MG) in adapting the operation effectively and redistributing the active and reactive power.

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1. INTRODUCTION

The power industry is fundamentally changing because of environmental and energy cost issues. Some of these changes consider using renewable energy sources (RESs). These new sources are integrated into the power grid as distributed generation (DG), typically connected to the power grid by power electronics [1]. Some advantages of using DGs in the power grid are that they help reduce environmental issues and power losses, increase energy utilization, and improve reliability.

Compared to traditional generators, DG units often have a higher level of controllability and operability [2]–[4]. In addition, microgrids (MGs) play a significant role in ensuring electrical grid stability [5], [6]. Thus, MGs help improve power grid operation, including new specific applications [7]. Frequency and voltage magnitude droop control have traditionally achieved decentralized power share [8], [9]. However, if the feeders are predominantly resistive, the droop control in the MG is susceptible to some stability problems in the power control [10].

One of the most appealing characteristics of an MG is its ability to operate in island mode, which guarantees service reliability in the event of a power outage [11]. DG units must work with an island-mode microgrid to balance generation and load by controlling voltage and frequency. Thus, previous research has employed droop control to share power in decentralized networks without relying on communications [12]–[14]. However, this type of network always faces control, stability, and power-sharing challenges [12], [15], [16]. In island-mode MG, multiple DG units share active and reactive power according to their rating.

The frequency and voltage magnitude droop regulations are commonly used in power systems to represent specific synchronous machines [10], [17]. Thus, the frequency droop technique is adequate to share active power. However, network resistances and loads affect the voltage drop technique [18], [19]. As a significant advance in droop control applications, the virtual impedance approach improves stability and power sharing [20]–[23]. However, other network configurations presents some difficulties in distributing reactive power [24]–[26].

The stability of the MG has been improved with the virtual frequency–voltage frame and virtual active and reactive power [27]. However, these techniques present some difficulties in managing errors in reactive power sharing. Therefore, island-mode MGs have been researched [28], [29]. Other applications focus on uninterruptible power systems to avoid mutual control wires while sharing power [10], [30]. This technique is reliable and flexible, but its application is limited.

An MG enables the DG systems to operate in island mode, which increases the availability and power quality of electricity supplied to consumers [11]. However, island-mode MGs present challenges such as power balance between generation and load and reactive power distribution. Droop control enables decentralized control without having to rely on external communication connections. While frequency droop is an accurate technique to share active power, voltage droop is sometimes inefficient for sharing reactive power due to network impedances, load fluctuations, and DG power differences [18]. As a result, reactive power sharing in MGs has been researched, and several control strategies have been presented [31]–[34].

According to the literature analyzed in this research, recent studies have concentrated on active power control, but reactive power sharing techniques require accurate developments. Therefore, this study focuses on how reactive power can be distributed more effectively between generators in a MG by using a virtual voltage in the inverter voltage controller to increase the output signal. The main contributions of this article are related to employing virtual voltages at each inverter to redistribute reactive power between inverters and optimize the voltage control signal sent to the current controller.

2. MATERIALS AND METHODS

2.1. Control method

Figure 1 presents the diagram of the control technique proposed in this research. The P-ω controller regulates the frequency and distributes active power equitably among the DGs. The virtual voltage is calculated with the active power and the virtual impedance. Then, the voltage is employed as an input for the controller, specifically a proportional resonant. The resulting output signal is then sent to the current controller, which utilizes proportional control to enhance the signal directed to the pulse width modulation (PWM). This ultimately enables the inverter switch to attain the desired current and voltage.

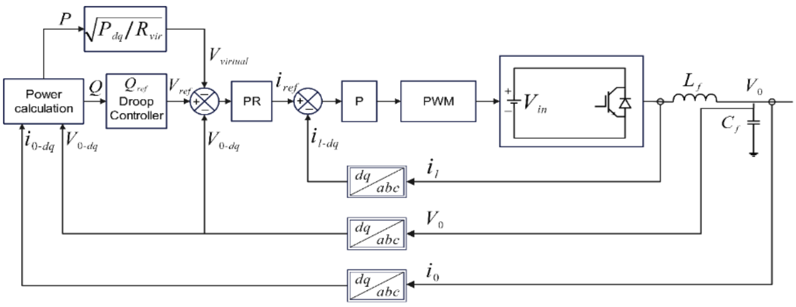


Figure 1. Proposed control technique used for the DGs

2.2. Voltage loop controller

Figure 2 presents a voltage controller diagram established in a synchronous reference frame. The voltage loop controller is built based on a proportional resonant configuration during the steady-state operation. From these diagrams, the state equations are obtained as (1)-(4).

$$\frac{dA_d}{dt} = (V_d^{**} - V_{od}) - w_0^2 B_q + w_0 A_q \quad (1)$$

$$\frac{dA_q}{dt} = \left(V_q^{**} - V_{oq}\right) - w_0^2 B_q - w_0 A_d \quad (2)$$

$$\frac{dB_d}{dt} = A_d + w_0 B_q \quad (3)$$

$$\frac{dB_q}{dt} = A_q - w_0 B_d \tag{4}$$

Then, the algebraic equations are obtained as in (5) and (6).

$$i_{id}{}^* = k_{pv}(V_d{}^{**} - V_{od}) + k_{iv}B_d \tag{5}$$

$$i_{iq}{}^* = k_{pv}\left(V_q{}^{**} - V_{oq}\right) + k_{iv}B_q \tag{6}$$

As in (7)-(10) present the linearized model representing the small-signal state space.

$$\begin{bmatrix} \Delta \dot{A}_{dq} \\ \Delta B_{dq} \end{bmatrix} = A_{vol}\begin{bmatrix} \Delta A_{dq} \\ \Delta B_{dq} \end{bmatrix} + B_{vol1}\left[\Delta V_{odq}{}^{**}\right] + B_{vol2}\begin{bmatrix} \Delta i_{idq} \\ \Delta V_{odq} \end{bmatrix} \tag{7}$$

Where, according to (8) and (9).

$$A_{vol} = \begin{bmatrix} 0 & w_0 & -w_0{}^2 & 0 \\ -w_0 & 0 & 0 & -w_0{}^2 \\ 1 & 0 & 0 & w_0 \\ 0 & 1 & -w_0 & 0 \end{bmatrix} B_{vol1} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} B_{vol2} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ -1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \end{bmatrix} \tag{8}$$

$$\left[\Delta i_{dq}{}^*\right] = C_{vol}\begin{bmatrix} \Delta A_{dq} \\ \Delta B_{dq} \end{bmatrix} + D_{vol1}\left[\Delta V_{od}{}^{**}\right] + D_{vol2}\begin{bmatrix} \Delta i_{idq} \\ \Delta V_{odq} \end{bmatrix} \tag{9}$$

And the parameters C_{vol}, D_{vol1}, and D_{vol2} are defined as (10).

$$C_{vol} = \begin{bmatrix} 0 & 0 & k_{iv} & 0 \\ 0 & 0 & 0 & K_{iv} \end{bmatrix};\ D_{vol1} = \begin{bmatrix} k_{pv} & 0 \\ 0 & k_{pv} \end{bmatrix};\ D_{vol2} = \begin{bmatrix} 0 & 0 & -k_{pv} & 0 \\ 0 & 0 & 0 & -k_{pv} \end{bmatrix} \tag{10}$$

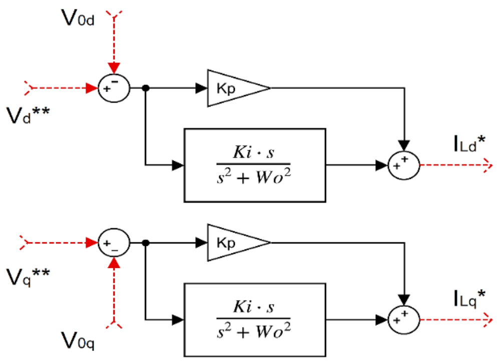


Figure 2. Voltage controller

2.3. Current loop controller

The new loop algebraic equations of the controller are as (11) and (12).

$$V_{pwmd}{}^* = k_{pi}(i_{id}{}^* - i_{id}) \tag{11}$$

$$V_{pwmd}{}^* = k_{pi}\left(i_{iq}{}^* - i_{iq}\right) \tag{12}$$

The model of the current loop controller can be defined as in (13).

$$\left[\Delta V_{pwmdq}{}^*\right] = D_{cor1}\left[\Delta i_{idq}{}^*\right] + D_{cor2}\begin{bmatrix} \Delta i_{idq} \\ \Delta V_{odq} \end{bmatrix} \tag{13}$$

Where:

$$D_{cor1} = \begin{bmatrix} k_{pi} & 0 \\ 0 & k_{pi} \end{bmatrix} \tag{14}$$

$$D_{cor2} = \begin{bmatrix} -k_{pi} & 0 & 0 & 0 \\ 0 & -k_{pi} & 0 & 0 \end{bmatrix} \quad (15)$$

According to (9) and (15), the expression $\Delta V_{pwmdq}{}^{*}$ is obtained as (16).

$$[\Delta V_{pwmdq}{}^{*}] = D_{cor1} C_{vol} \begin{bmatrix} \Delta A_{dq} \\ \Delta B_{dq} \end{bmatrix} + D_{cor1} D_{vol1} [\Delta V_{odq}{}^{**}] + (D_{cor1} D_{vol2} + D_{cor2}) \begin{bmatrix} \Delta i_{idq} \\ \Delta V_{odq} \end{bmatrix} \quad (16)$$

2.4. Three-phase half-bridge circuit

The state equations are expressed as (17)-(20).

$$\frac{di_{id}}{dt} = \frac{-r}{L} i_{id} + w_0 i_{lq} + \frac{k_{pwm}}{L} V_{pwmd}{}^{*} - \frac{1}{L} V_{od} \quad (17)$$

$$\frac{di_{iq}}{dt} = \frac{-r}{L} i_{iq} + w_0 i_{ld} + \frac{k_{pwm}}{L} V_{pwmq}{}^{*} - \frac{1}{L} V_{oq} \quad (18)$$

$$\frac{dV_{od}}{dt} = w_0 V_{oq} + \frac{1}{c} i_{Ld} - \frac{1}{c} i_{od} \quad (19)$$

$$\frac{dV_{oq}}{dt} = -w_0 V_{od} + \frac{1}{c} i_{Lq} - \frac{1}{c} i_{oq} \quad (20)$$

Thus, the linearized small-signal state-space models can be represented as (21) and (22).

$$\begin{bmatrix} \Delta \dot{i}_{idq} \\ \Delta V_{odq} \end{bmatrix} = A_{LC} \begin{bmatrix} \Delta i_{idq} \\ \Delta V_{odq} \end{bmatrix} + B_{LC1} [\Delta V_{pwmdq}{}^{*}] + B_{LC2} [\Delta i_{odq}] \quad (21)$$

$$A_{LC} = \begin{bmatrix} \frac{-r}{L} & w_0 & \frac{-1}{L} & 0 \\ -w_0 & \frac{-r}{L} & 0 & \frac{-1}{L} \\ \frac{1}{c} & 0 & 0 & w_0 \\ 0 & \frac{1}{c} & -w_0 & 0 \end{bmatrix}; B_{LC1} = \begin{bmatrix} \frac{k_{pwm}}{L} & 0 \\ 0 & \frac{k_{pwm}}{L} \\ 0 & 0 \\ 0 & 0 \end{bmatrix}; B_{LC2} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ \frac{-1}{c} & 0 \\ 0 & \frac{-1}{c} \end{bmatrix} \quad (22)$$

According to (23), $\Delta V_{pwmdq}{}^{*}$ can be substituted by (21).

$$\begin{bmatrix} \Delta \dot{i}_{idq} \\ \Delta V_{odq} \end{bmatrix} = A_{LC} \begin{bmatrix} \Delta i_{idq} \\ \Delta V_{odq} \end{bmatrix} + B_{LC1} D_{cor1} C_{vol} \begin{bmatrix} \Delta A_{dq} \\ \Delta B_{dq} \end{bmatrix}$$
$$+ B_{LC1} D_{cor1} D_{vol1} [\Delta V_{odq}{}^{**}] + B_{LC1} (D_{cor1} D_{vol2} + D_{cor2}) \begin{bmatrix} \Delta i_{idq} \\ \Delta V_{odq} \end{bmatrix} + B_{LC2} [\Delta i_{odq}] \quad (23)$$

2.5. Line impedance

The state equations are represented by (24) and (25). These equations represent the line impedance model of the microgrid.

$$\frac{d_{iod}}{dt} = \frac{-r_L}{L_i} i_{od} + w_0 i_{oq} + \frac{1}{L_i} V_{od} - \frac{1}{L_i} V_{bus\,d} \quad (24)$$

$$\frac{d_{ioq}}{dt} = \frac{-r_L}{L_i} i_{oq} + w_0 i_{od} + \frac{1}{L_i} V_{oq} - \frac{1}{L_i} V_{bus\,q} \quad (25)$$

Finally, the (26) presents the linearized small-signal state-space models.

$$[\Delta \dot{i}_{odq}] = A_L [\Delta i_{odq}] + B_{L1} \begin{bmatrix} \Delta i_{idq} \\ \Delta V_{odq} \end{bmatrix} + B_{L2} [\Delta V_{bus\,dq}] \quad (26)$$

Where,

$$A_L = \begin{bmatrix} \frac{-r_L}{L_i} & w_0 \\ -w_0 & \frac{-r_L}{L_i} \end{bmatrix}; B_{L1} = \begin{bmatrix} \frac{1}{L_i} & 0 \\ 0 & \frac{1}{L_i} \end{bmatrix}; B_{L2} = \begin{bmatrix} -\frac{1}{L_i} & 0 \\ 0 & -\frac{1}{L_i} \end{bmatrix} \quad (27)$$

2.6. Complete model of the inverter

A complete inverter model is obtained when integrating different state-space models and the modified current controller. This is the mathematical model of the inverter that is used in the microgrid:

$$[\dot{\Delta X}] = A[\Delta X] + B_1[\Delta V_{odq}^{\ *}] + B_2[\Delta V_{bus\ dq}] \tag{28}$$

$$\Delta X = [\Delta A_{dq}\ \Delta B_{dq}\ \Delta i_{idq}\ \Delta V_{odq}\ \Delta i_{odq}\ \Delta P_{odq}] \tag{29}$$

where A, B_1, and B_2 are defined as (30).

$$A = \begin{bmatrix} 0 & 0 & 0 & A_p \\ A_{vol} & B_{vol2} & 0 & -B_{vol1}D \\ B_{LC1}D_{cor1}C_{vol} & A_{LC} + B_{LC1}(D_{cor1}D_{vol2} + D_{cor2}) & B_{LC2} & -B_{LC1}(D_{cor1}D_{vol3}\ C) \\ 0 & B_{l1} & A_l & 0 \end{bmatrix}$$
$$B = \begin{bmatrix} B_p \\ B_{vol1}\ C \\ B_{LC1}D_{cor1}D_{vol1}C \\ 0 \end{bmatrix} B_2 = \begin{bmatrix} 0 \\ 0 \\ 0 \\ B_{L2} \end{bmatrix} \tag{30}$$

3. RESULTS AND ANALYSIS

This research uses a network with two DGs and one load, as shown in Figure 3. This load considers different consumptions that change over time. DGs must supply power to the load considering the impedance of the network, and control must consider all load variations. Furthermore, voltage is improved by applying a strategy based on virtual voltage that is calculated according to the network impedance and the variable loads.

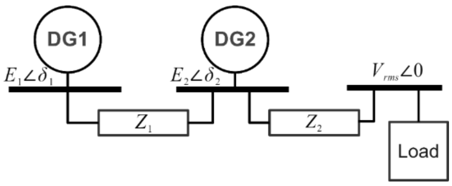


Figure 3. Diagram of the network for the test

3.1. Active power

Figure 4 presents the active power delivered by the generators, where Figure 4(a) displays the response of DG1 and Figure 4(b) the response of DG2. The response of the generators depends on the droop control and virtual voltage control. The results show that the control strategies respond to various changes in the power of the load. This result shows how the power is increased according to the consumption of the load.

Figure 5 presents the behavior of the active power of DG1 and DG2. Figure 5(a) displays the response of the virtual voltage control, and Figure 5(b) shows the response of the droop control. The inverters share active power with two independent controllers. During various load shifts, these techniques correctly distribute active power. Figure 6 presents the reactive power generation with both controllers. The suggested virtual voltage regulation strategy is seen in Figure 6(a). Moreover, Figure 6(b) shows the droop control strategy.

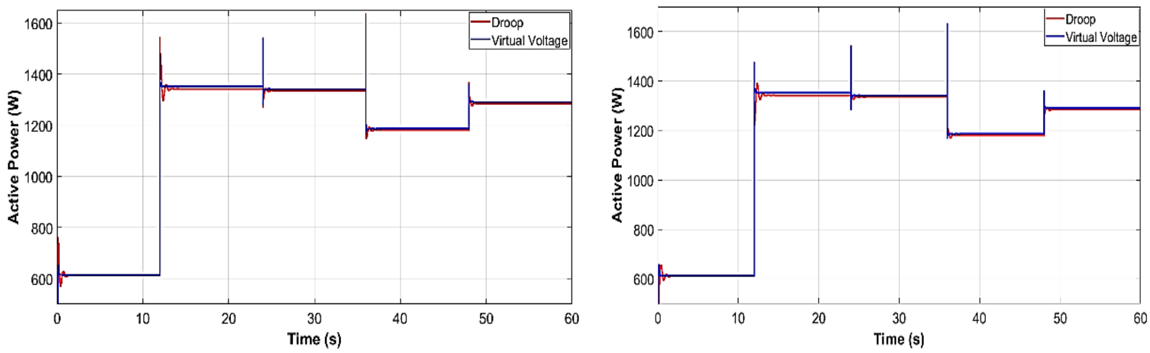
The virtual voltage control technique efficiently shares the reactive power for different load changes. This is not accomplished with the droop control within the first seconds. After adding more load, the control strategy reacts well to the changes. Generators supply the same power with the proposed approach, while with the droop control the power for both generators are different.

Figure 7 presents the reactive power behavior in both generators applying virtual voltage and the droop controllers. Figure 7(a) displays the results of DG1, and Figure 7(b) DG2. In the simulation, the virtual voltage controller works better and more quickly than the droop controller.

Figure 8 shows the frequency for both control approaches (virtual voltage and droop) when incorporating various electrical loads. The virtual voltage controller adapts to load changes more quickly and effectively than the droop control approach. These graphs were created considering various load variations. For the events created, the frequency stabilizes a few seconds after the load changes. The frequency value adjusts quickly as the load varies, and the controller preserves the nominal frequency.

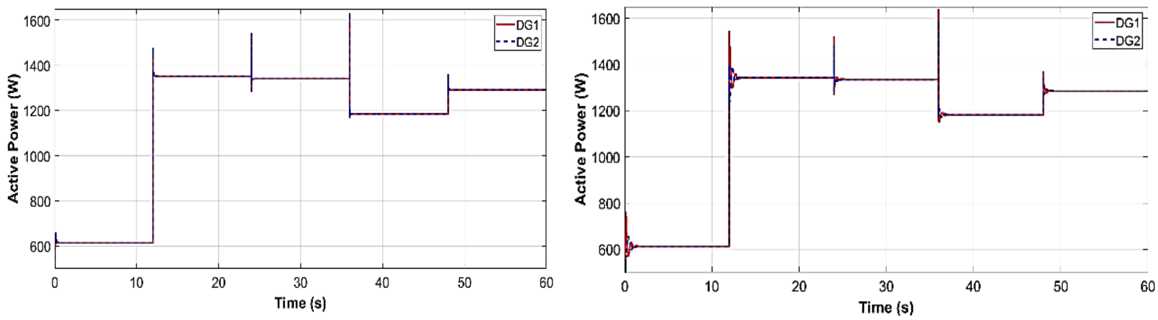
Figure 9 displays the root mean square (RMS) load voltage in the MG. The virtual voltage approach outcomes are given in blue, while droop control is represented in red. Voltage in the node drops suddenly when another load is connected. However, the control procedure quickly restores the voltage to a close-to-original level. As a result, using a simulated voltage, the suggested control strategy preserves a steady voltage value during load changes. The voltage presents lower values with the droop control than those obtained with the virtual voltage. As a result, the virtual voltage approach responds more quickly and accurately than the droop control approach.

Figures 10(a)–10(d) illustrate the power behavior when several loads vary in the network. Active and reactive power capacities of the system are also shown. The power supply increases as the load in the node escalates. A control mechanism monitors and maintains a constant voltage at the node where the loads are connected and disconnected. As a result, the loads consume the same amount of active and reactive power.



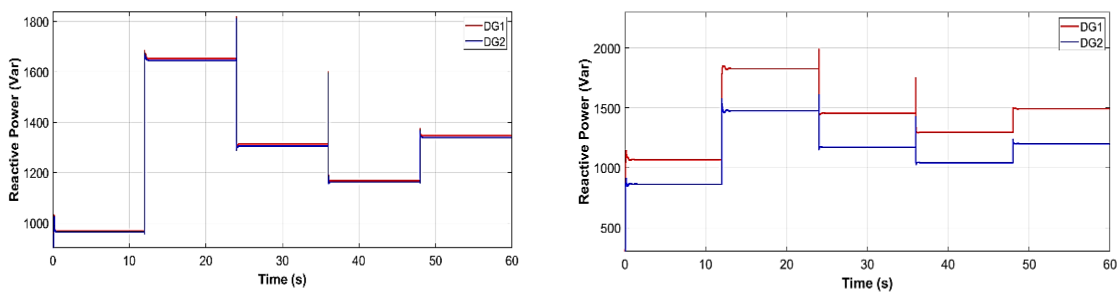
(a) (b)

Figure 4. Active power regulation with the virtual voltage and droop controllers for (a) DG1 and (b) DG2



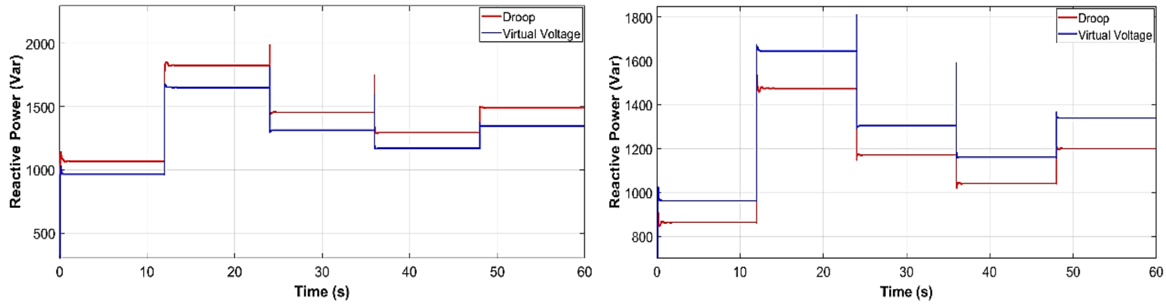
(a) (b)

Figure 5. Active power delivered by generators with (a) virtual voltage and (b) droop control



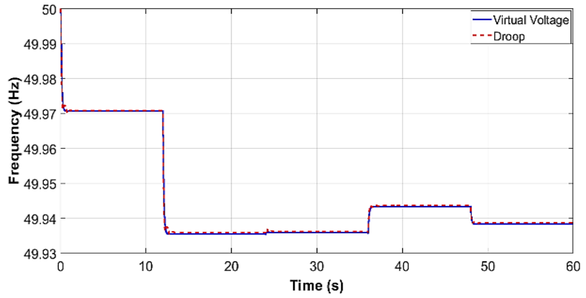
(a) (b)

Figure 6. Reactive power in DG1 and DG2 with the (a) virtual voltage control and (b) droop control



(a) (b)

Figure 7. Reactive power in both generators with both control strategies (a) DG1 and (b) DG2



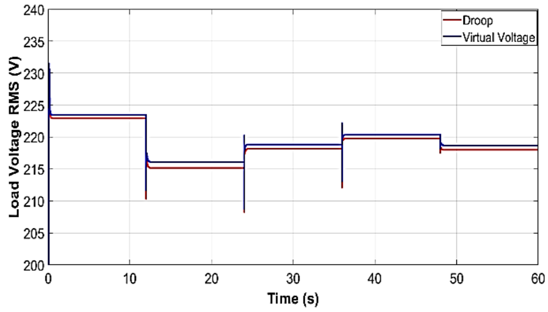
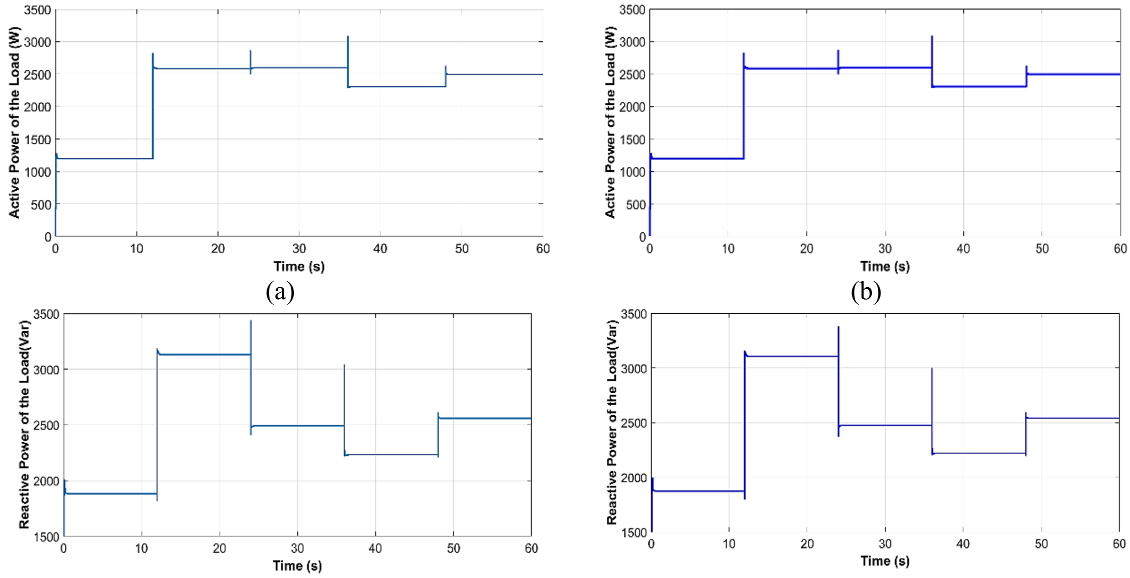


Figure 8. Frequency (virtual voltage vs droop) Figure 9. Load voltage (droop vs virtual voltage)



(a) (b) (c) (d)

Figure 10. Power behavior during disturbances (a) active power with the droop control, (b) active power with the virtual voltage control, (c) reactive power with the droop control, and (d) reactive power with the virtual voltage control

4. CONCLUSION

This article introduced a control approach with virtual voltage to efficiently redistribute reactive power among two generators located in different nodes in an MG. This technique allowed the ability to redistribute the reactive power accurately in the generators despite load variations. The reactive power changes according to the disturbances in the network, and then the voltage is controlled with the proposed control approach. Thus, the proposed control approach applied to the output power of the inverter works well. The frequency remains close to the reference, as the control maintains power balance. The technique assists the new MG in effectively adapting and sharing active and reactive power.

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