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Analysis and Simulation of Inverter-Based Microgrid Droop Control Method in Island Operation Mode

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Abstract
The microgrid consists of several distributed generation units and operates in two modes, connected to the network and autonomous. A good microstructure, especially in autonomous mode, requires a power management strategy. In an island microgrid, there are two methods of centralized and decentralized control. In an island microgrid, the slope changes characteristic of the frequency droop of the source frequency have the greatest effect on the dynamics of the system's response to disturbances in the microgrid. In this paper, the inverter-based microgrid droop control method in island operation mode is analyzed and simulated. The studied system has three scattered sources and six local times. The simulation results are shown using MATLAB software for different modes.

Keywords: Island Microgrid, Droop Control, Inverter Based Microgrid.

1. INTRODUCTION

Over the years, energy resources have been one of the most important factors in the economic, industrial, and scientific life of countries, and national security and the stability of government systems depends to a large extent on access to energy resources [1-7]. And fossil energy sources do not meet this need for future evolution [8, 9]. Therefore, the use of non-renewable energy sources is increasing [10-15].

Scattered energy sources are the main component of microgrids [16-19]. A set of scattered sources and sensitive loads are capable of being disconnected from the grid and forming a self-operating microgrid. The microgrid consists of a number of distributed

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generation units (renewable and non-renewable), energy savers and loads that can be controlled and provide electrical power and heat if needed [20, 21]. Figure (1) shows an example of a microgrid connecting different sources. Microgrid modeling varies based on the components used. Scattered storage resources are used to balance production and consumption in the microgrid.

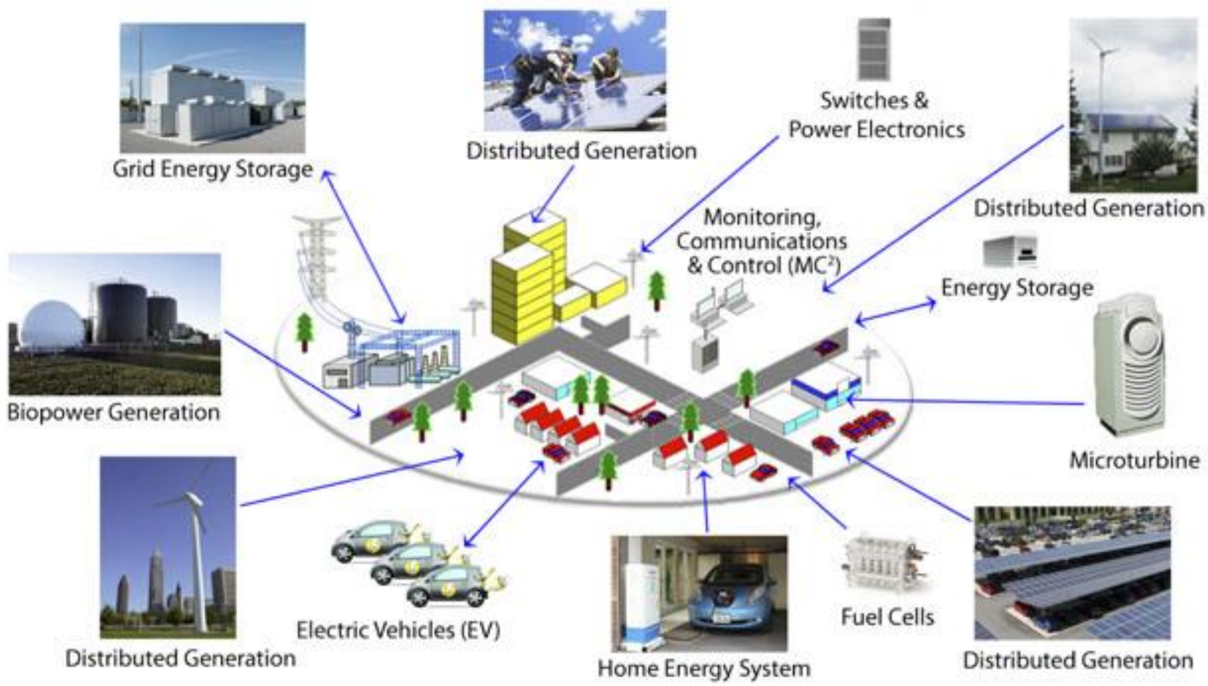


Fig. 1. A sample microgrid.

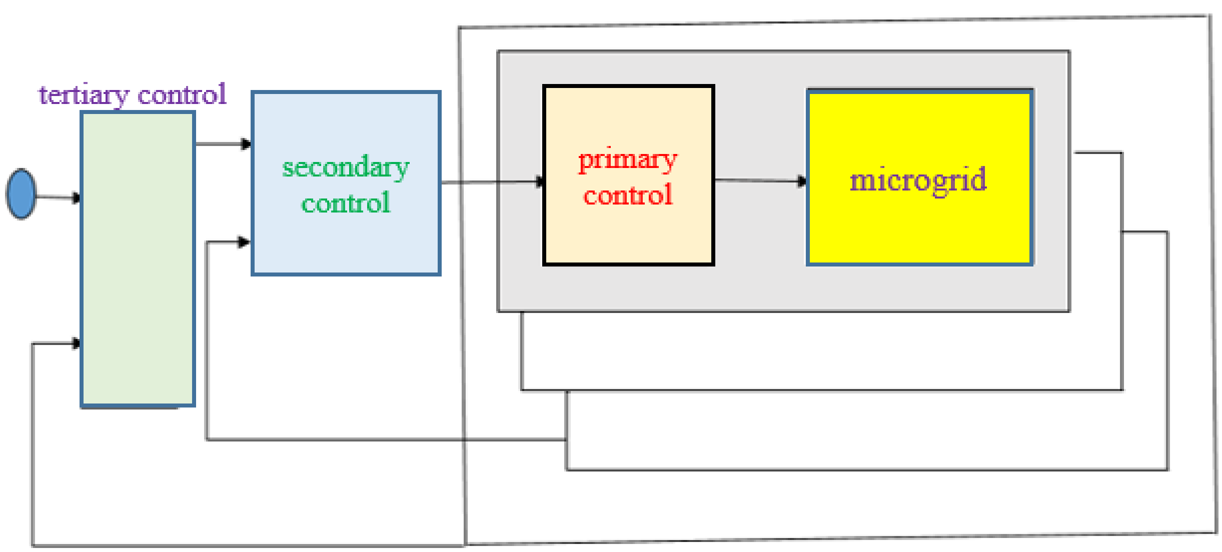


Fig. 2. Hierarchical control system.

In the case of island work, the existence of energy storage resources is very important [22, 23]. One of the important cases in island microgrids is to follow the load changes, which due to the fact that most of the resources in the microgrid are without the inertia or with little inertia, there is a need for an energy storage source in order to balance in transient periods [24, 25]. The use of batteries parallel to the dc link capacitor at the inverter input and the use of energy storage sources independently in different microgrid locations are practical solutions to this problem [26, 27].

In the case of permanent operation of an island microgrid, energy storage resources are used to compensate for the effect of power changes on uncontrollable resources. In the case of a transient network connection, it is not very important because the possible lack of microgrid power during the transient period is compensated by receiving energy from the network. But in the case of permanent operation, economic issues can show the importance of having scattered storage resources in the microgrid. Therefore, the microgrid is designed to purchase and store cheap energy from the grid during off-peak hours and to use the stored energy during peak hours [28, 29].

The grid-connected control system must control the sources so that each source produces a certain amount of active and reactive power. In island mode, there are two methods of centralized and decentralized control to achieve control goals such as frequency control, voltage control, and proportional load distribution between sources. In the centralized control method, a central controller, by receiving various information from the network, generates the necessary control signals and sends them to the sources [30]. In this method, although achieving control goals is easier, but due to the need for a broadband telecommunication channel, control of resources and their stability will be directly dependent on the establishment and accuracy of the operation of this telecommunication channel. Therefore, the cost of the system increases and its reliability decreases to some extent. The main tasks of the microgrid control system are [31, 32]:

A. Adjusting the voltage and frequency in both operating modes connected to the main and island network
B. Appropriate load sharing between distributed energy sources
C. Maintaining microgrid stability
D. Controlling the power distribution between the microgrid and the main network based on economic policies
E. Synchronous transition between network and island operating modes

To achieve the control objectives, a hierarchical control structure according to Figure (2) is required, which has three levels of control: first, second and third. Maintaining frequency and voltage stability in the island state is the responsibility of the first level [33, 34].

In order to prevent the adverse effects of creating circulating flows between sources due to the presence of local and common loads, independent and proportional control of active and reactive power in the island microgrid at the first level of control is performed. The second level compensates for the deviation in the frequency and voltage values resulting from the application of the first level control strategies. The third level controls the power distribution between the microgrid and the main network and ensures optimal performance in accordance with economic policies.

In the decentralized control method, each source has an independent primary controller that generates the required control signals based solely on local measurements. In this method, broadband telecommunication signals are not used and the telecommunication channel is used to optimize the controllers or applications such as energy management system and in fact in the higher layers of the controller that do not require wide bandwidth and are interrupted. It does not interfere with the normal process of resource control and microgrid stability [35, 36].

The use of common drop characteristics due to the possibility of local implementation can improve the performance of the microgrid and the load distribution between units, regardless of the number and distance of micron sources. These methods reduce the generated active power by increasing the frequency of the network and reducing the amount of reactive power injected if the network voltage level is increased by using control characteristics. Typical drop characteristics are lines with a negative slope on the frequency-active power (ω-P) voltage-reactive power (E-Q) plane. The input of these characteristics is real and reactive power and their output is the reference values for the frequency and amplitude of the source terminal voltage.

So far, various studies have been conducted on the application of the drop characteristic for microgrid control.

In reference [37], by writing all the dynamic equations governing the system and linearizing the equations, the model of each component of the system is obtained and by combining the model of different components, the model of the complete state space of the system is obtained. Then, by analyzing the sensitivity analysis on the eigenvalues of the system, it is shown that the dominant poles of the microgrid have the greatest dependence on the actual output power of the scattered sources in it. In fact, the presence of these special values causes the power to fluctuate to the dynamic response of the system and in more critical conditions can lead to microgrid instability. In this reference, it is also shown that by reducing the slope of the characteristic ω-P, the damping of power fluctuations can be increased. It is clear that the use of such a solution will reduce the speed of response of scattered sources in the case of pursuing load changes and increase the sensitivity of power sharing to the operating point of the system.

In [38], by examining the different drop coefficients and their effect on the performance of the photovoltaic system and the output power, the allowable range of changing the drop coefficients in the island performance mode is determined. Selecting drop coefficients outside the allowable range causes system instability.

In reference [39], in order to ideally distribute reactive power and improve stability in island microgrids, a method based on mixed virtual impedance is proposed. The proposed virtual impedance consists of two parts which are resistance and inductance.

The virtual impedance resistive term is obtained to adjust the voltage drop at the output of the E-Q characteristic by adjusting the slope of the proposed ΔRv-P characteristic. An integral control loop is used to adjust the slope of the ΔRv-P characteristic. The virtual impedance inductive part adjusts the output current angle of the sources with the aim of increasing the inductive property of the system and reducing the combination of active and reactive power control.

In this method, a low-bandwidth telecommunication link is used to send the reference bus information to the local controller of each micro-source to adjust the virtual impedance.

Extraction and determination of the allowable range of slope changes of drop characteristics and its optimal adjustment with the aim of ensuring voltage regulation and optimal stability margin and increasing the accuracy of power distribution are of particular importance. In this paper, common methods of microgrid control in an island state are reviewed and the usual dropout strategy for local control of an island microgrid is analyzed by simulating the studied system. The structure of the article is as follows. The second section describes the typical frequency and voltage drop characteristics for dominant resistance or dominant inductor networks. The third section describes how to slump strategies work. In the fourth part, the specifications of the studied system are given along with the specifications of the control system. In the fifth part, the simulation results for the two modes of the effect of switching common and local loads, and the effect of slope changes of drop characteristics on the accuracy of power distribution and transient response of the system are shown. Finally, the conclusion of the article is stated in the sixth section.

2. VOLTAGE AND FREQUENCY DROP CONVENTIONAL CHARACTERISTICS

In high voltage and medium voltage microgrids, the mains have a predominant inductance. Therefore, assuming the network is a inductive, the resistance property of the lines can be ignored. In this case, the active (P_i) and reactive (Q_i) power relations for inductive microgrids are:

$$P_i = \frac{V_{pcc} E_i}{X_i} Sin\delta_i \tag{1}$$

$$Q_i = \frac{E_i V_{pcc} Cos\delta_i - V_{pcc}^2}{X_i} \tag{2}$$

where δ_i is the load torque angle. The power angle of each source is directly related to the active output power and also the difference in voltage drop is directly related to the reactive output power of the source. Therefore, the magnitude of the voltage and frequency of the microgrid can be controlled using active and reactive power. In microgrids with predominant inductive properties, the usual voltage and frequency drop characteristics can be used as follows [40].

$$\omega - \omega_n = -m_p \left(P - P_n \right) \tag{3}$$

$$E - E_n = -n_q \left(Q - Q_n \right) \tag{4}$$

In these relationships, ω-ωn and E-En represent the deviation of the system frequency and voltage from the nominal values, and p-Pn and Q-Qn are the mean values of the active and reactive power of the sources. In microgrids with predominant inductance, by setting the mp and nq parameters as the slope of the frequency and voltage drop characteristics, the active and reactive power of the sources can be used as the input of the drop characteristics and control the system voltage and frequency.

In low voltage microgrids, the lines have the dominant resistance property. In this type of microgrids, the inductive term of the line impedance can be omitted. Therefore, the relationships between the active power and the reactive output of the source are expressed as follows:

$$P_i = \frac{E_i}{R_i}\left(E_i - V_{pcc} Cos\,\delta_i\right) \tag{5}$$

$$Q_i = \frac{-E_i V_{pcc}}{R_i} Sin\,\delta_i \tag{6}$$

Unlike inductive microgrids, the voltage amplitude is controlled by the active power and the system frequency is directly related to the reactive power output of the sources. Reverse drop characteristics for controlling the voltage and frequency of resistive microgrids are expressed as follows:

$$E - E_n = -m_p\left(P - P_n\right) \tag{7}$$

$$\omega - \omega_n = n_q\left(Q - Q_n\right) \tag{8}$$

where m_p is frequency droop characteristic and n_q is voltage droop characteristic.

The magnitude of the source voltage, unlike the frequency, is a local quantity, so the voltage drop characteristic cannot cause the ideal division of reactive power in inductive microgrids and active power in resistive microgrids. The impedance inequality of the lines connected to the sources, the existence of a pair between the active and reactive powers of each source, and also the limitation of the changes in the size of the source voltage are the effective factors in reducing the accuracy of power distribution based on drop characteristics.

3. IMPLEMENTATION OF DROOP STRATEGIES AND PERFORMANCE

As the load on the system increases, the scattered resources in the microgrid do not necessarily compensate for the new overload in the same amount or in proportion to their rated power. After a new load enters the circuit, some of the resources in the microgrid take on less production and some more production. Based on the inherent property of the ω-P characteristic, less productive resources will have higher frequencies and more productive resources will have lower frequencies. Therefore, the voltage of higher frequency sources will be pre-phased compared to lower frequency sources, and this pre-phase will increase over time.

In an inductive network, the production of active power is proportional to the difference of the phase of the resources. For this reason, the pre-phase output voltage in less productive sources leads to an increase in their production capacity. Given that in the steady state the frequency of all sources reaches the same value, the ω-P characteristics eventually move the point of the resource to the equilibrium point where the output of each resource is proportional to its nominal power.

As new loads enter the circuit, some of the resources in the microgrid are less reactive and some more. According to the E-Q characteristic, sources with lower output will have higher terminal voltage and sources with higher reactive output will have lower voltage. In a network with inductive lines, reactive power flows from the buses with a larger voltage range to the buses with a smaller voltage range. Therefore, the reactive output power of resources with lower output that has a larger voltage range will gradually increase, and the reactive output power of resources with higher output that has a smaller voltage range will gradually decrease. In a symmetric network in which the output impedance of the sources is equal, the mentioned process continues until the voltage drop on the output impedance of all sources is equal and as a result the output terminal voltage of all sources will be equal. Therefore, considering the E-Q characteristic, the reactive production of resources reaches a common value. In this case, the reactive power generation has reached the ideal distribution, or in other words, the reactive power sharing error is zero. But in a real microgrid, the grid is usually not symmetric and the output impedance of the sources is different. For this reason, the voltage droop across the network impedances and consequently the different bus voltages will not be equal. Therefore, different sources will have different working points in their E-Q characteristic and the ideal sharing will not be achieved.

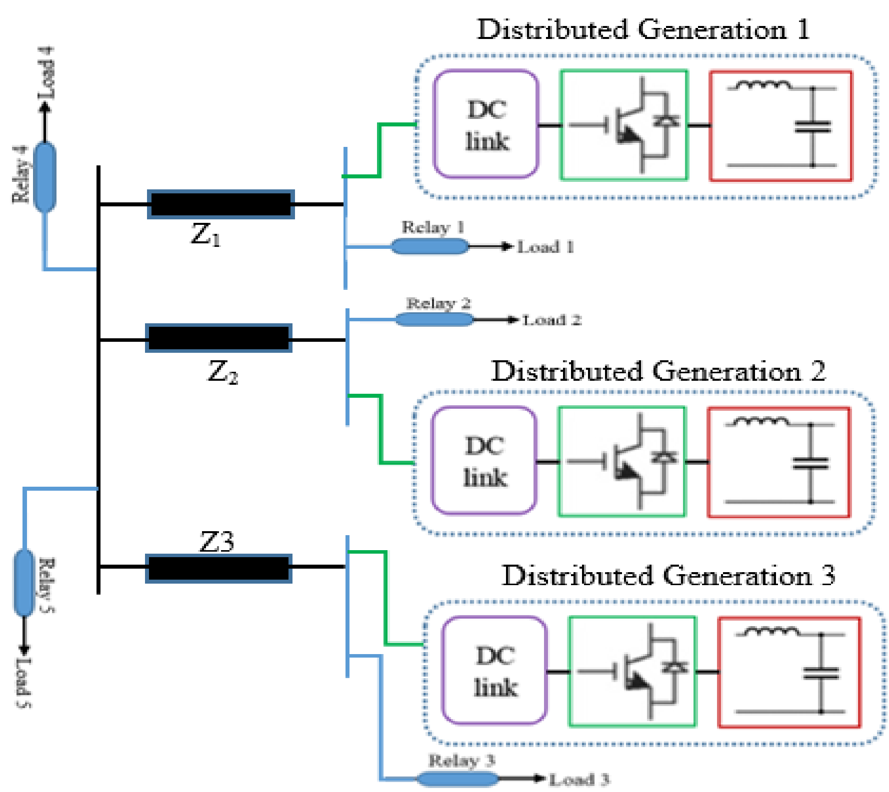


Fig. 3. The studied system with three distributed generation sources.

Table 1. ***System specifications studied.***

Parameter	Symbol	Value
Nominal power of resources	$S_{n1}=S_{n2}=S_{n3}$	1 kVA
Nominal frequency	f_n	50 Hz
Dc link voltage	V_{dc}	208 V
Line impedance 1	Z_1	1.6 + j2.45 Ω
Line impedance 2	Z_2	1.1 + j1.508 Ω
Line impedance 3	Z_3	0.8 + j1.130 Ω

Table 2. ***Control system specifications.***

Slope	Symbol	Value
Frequency droop characteristic	m_p	0.00105 rad/(s.W)
Voltage droop characteristic	n_q	0.00250 V/VAr

Table 3. ***Inverter specification.s***

Slope	Symbol	Value
LC filter	L_F L_C	3 mH, 75 µF
Switching frequency	fs	10 kHz

In fact, unlike the ω-P characteristic, which provides the ideal distribution for active power due to the same frequency in the network, in the case of the EQ characteristic, due to the localization of the voltage amplitude parameter, the ideal reactive power distribution is achieved only when this parameter Local (voltage) has the same value at the output terminal of all sources, although this problem is not usually achieved in a microgrid with a general structure [41].

4. THE SYSTEM UNDER STUDY

The microgrid configuration of the under study sample/system is shown in Fig. 3. This microgrid consists of 3 DG units with similar capacities that are connected in parallel to the common bus and feed the local and common loads. Loads L1 to L4 are local loads connected to distributed generation sources and loads L5 and L6 are common loads connected to a common bus. The three DG units have the same rated power of 1 kVA and each includes a DC voltage source and an inverter to convert DC voltage to AC voltage. The inverter is connected to the microgrid via an LC filter.

The specifications of the studied system are given in Table 1. The local loads are the same, equal to 1215 watts and 1030 watts. The specifications of the control system and inverter are given in Tables 2 and 3.

5. SIMULATION RESULTS

In this part, the studied system is simulated for two modes. First, the switching effect of common and local loads on the changes of active and reactive powers of the output and output of the voltage and frequency drop characteristics are shown and then the effect of changes in the slope of the drop characteristics on the power distribution accuracy and transient response of the system is investigated.

5.1. Switching the Common and Local Loads

By changing the load on the island microgrid, the inverter controller is expected to respond quickly to the load change and distribute it appropriately between sources.

In this case, first the microgrid is launched without the presence of load 4. Then, in 0.5 seconds, the local load enters the system, and then in 1 second, the related keys are disconnected and the local and common loads, i.e. load 4 and load 5, are separated from the network.

In the following, the simulation results of active power output, reactive power, voltage drop characteristic and frequency droop characteristic of sources due to load changes are shown. Given that the sources in the studied microgrid have the same capacity and the frequency drop coefficients are the same for all sources, it is expected that the active power required by the load will be evenly distributed among the sources.

As shown in Fig. 4, the ideal distribution of active power is obtained between the sources, and all three sources have the same share in the supply of load active power. Resource point changes due to switching common and local loads which do not cause defects in the frequency control function and active power, because frequency is a global parameter and its changes spread like a virtual telecommunication link in the network and equalize active power. It is produced by resources. It produces resources.

As shown in Fig. 5, it can be seen that reactive power, unlike active power, is not evenly distributed among sources.

Accordingly, in Fig. 6, it can be seen that the output of the frequency drop characteristic of all sources is equal throughout the simulation interval. Equalizing the output characteristic of the resource frequency drop means dividing the ideal active power. Also, the output of the resource drop characteristic according to Fig. 7 is not equal due to the difference in the parameters of the network lines.

As can be seen, the active power is carefully divided between the sources using the usual frequency drop characteristic. However, using the usual voltage drop strategy has caused a significant reactive power distribution error. Based on the above results, it can also be stated that sudden load changes do not affect the accuracy of active power distribution, while the reactive power distribution error depends on the load changes.

Please kindly note that the objective of reactive power sharing is to properly share reactive power among DGs according to their reactive power ratings. In fact, reactive power sharing is of paramount value in the control of islanded microgrids. Unbalanced reactive power sharing can result in voltage deviations, deteriorated quality of power delivered to the customers, unplanned load shedding, outage of DGs, and even instability of microgrid. Given these facts, corrective schemes are highly required to ensure the optimality of reactive power sharing.

5.2. The Effect of Slope Changes of Falling Characteristics

The response of typical frequency/voltage drop characteristics for power distribution between inverter voltage sources is relatively slow and is usually accompanied by oscillating currents. The slowness of the dynamic response of typical fall control is due to the use of medium resource power in drop characteristics, which uses low-pass, low-bandwidth filters to calculate the average true and reactive power resource. Therefore, the system dynamics are strongly influenced by the characteristics of these filters as well as the slope values of the drop characteristics. On the other hand, because the slope of the voltage and frequency drop characteristics is determined and limited according to the maximum acceptable deviation for the frequency and amplitude of the output voltage, so there is always a trade-off between power distribution accuracy, transient response correction and voltage adjustment accuracy. Intrinsic is established.

In this section, to investigate the effect of regulating the slope of the drop characteristics on the accuracy of power distribution, the response of the transient and permanent state of the system and the accuracy of voltage regulation, changes with different drop coefficients have been implemented.

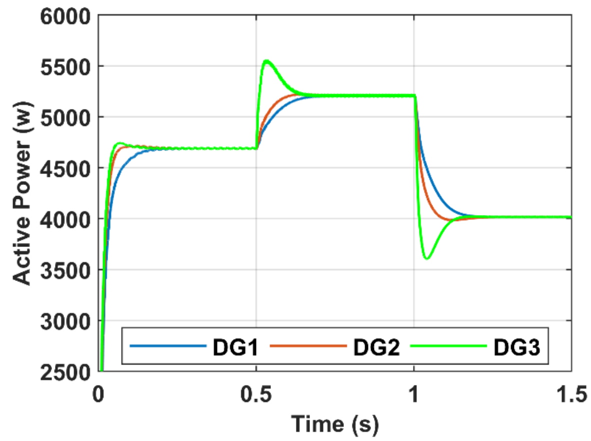


Fig. 4. Active resource power using the usual downtime strategy.

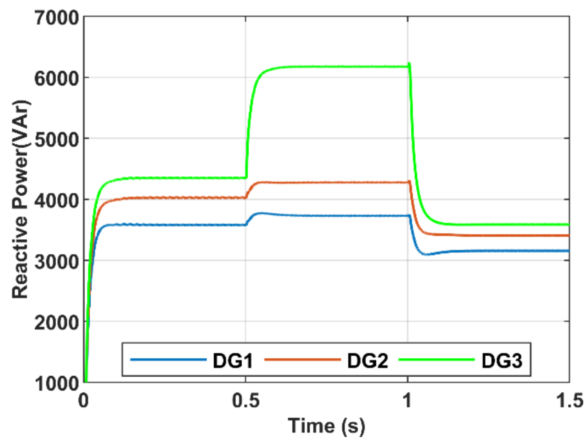


Fig. 5. Reactive power of resources using the usual drop strategy.

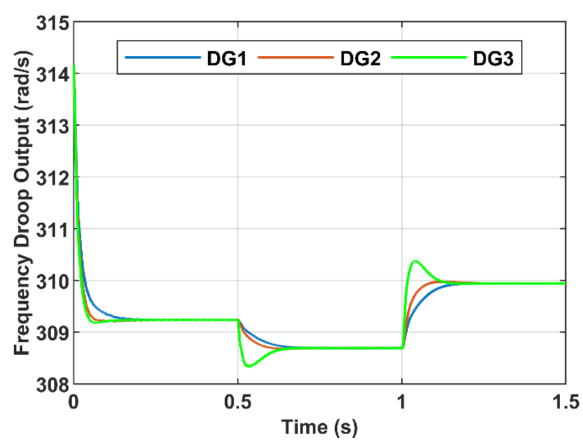


Fig. 6. Output of the frequency drop characteristic of the resource using the usual drop strategy.

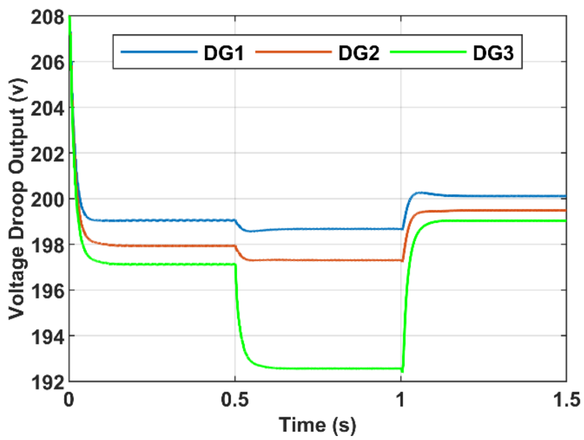
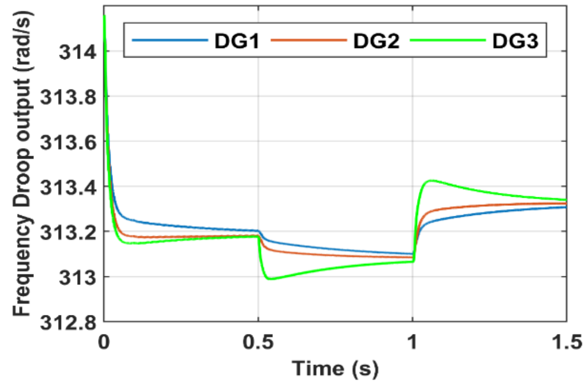


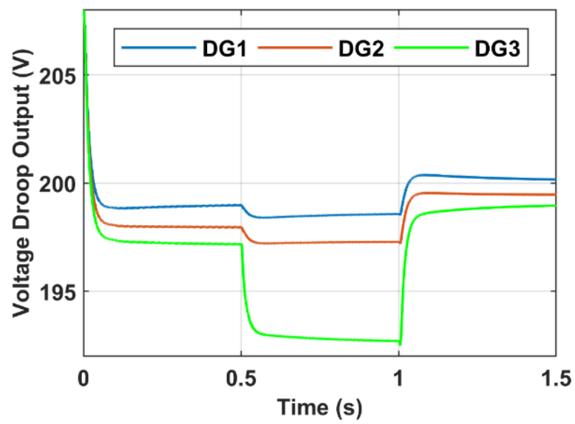
Fig. 7. Output of the voltage drop characteristic of the sources using the usual drop strategy.

Figure (8) shows the output of the frequency and voltage drop characteristics in the case where the slope of the frequency drop characteristic is 1.5 times. However, the characteristic slope of the voltage drop of the sources has not changed. As can be seen, the response of resources to changes due to load switching is associated with sluggish dynamics, and this has led to a lack of convergence of the point of work of resources. In this case, the accuracy of the active power distribution is definitely reduced because the output of the characteristic drop of the sources is not converged.

In Figure (9) it can be seen that by multiplying the frequency drop coefficient by 5 times and keeping the voltage drop characteristic slope constant despite the convergence of the frequency drop output, the system response to resource operating point changes is associated with highly oscillating dynamics. Also, despite the fact that the slope of the voltage drop characteristic does not change, due to the pairing between active and reactive power control, oscillating dynamics can be observed in the output of the voltage drop characteristic. Due to the increase in the MP angular frequency, the output of the sources is out of the allowed range (5% of the nominal frequency). However, the output voltage of the sources is still within its allowable range (10% of the rated voltage).



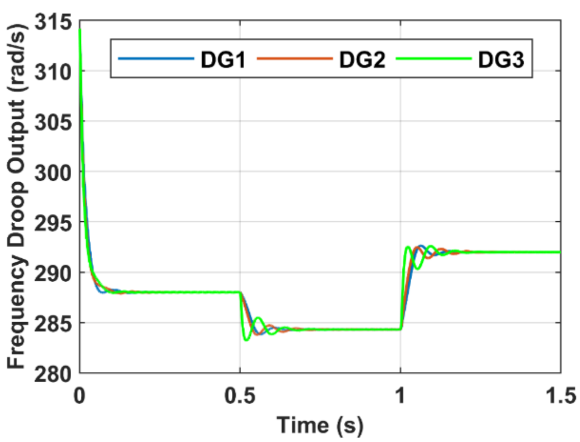
(a)



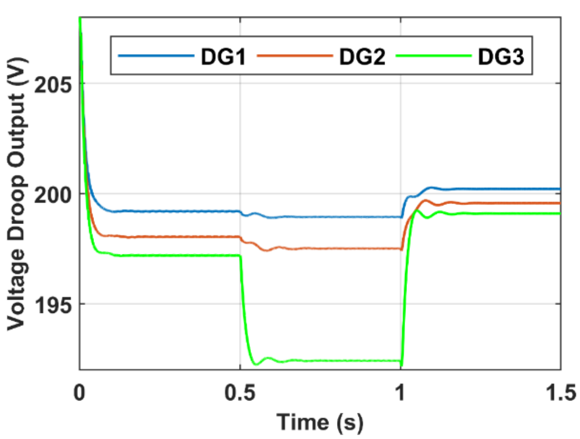
(b)

Fig. 8. Output of temporal drop characteristics for m_p=0.00105 × 1.5, (a) The output of the frequency drop characteristic, (b) Output characteristic of voltage drop.

The curves in Figure (10) and Figure (11) are related to decreasing and increasing the slope of the voltage drop characteristic, respectively. Based on the simulation results, it can be concluded that by reducing the slope of the voltage drop characteristic, the deviation of the output voltage of the sources from the nominal voltage of the network is reduced and the voltage regulation condition is improved. It can also be seen that the reduction of the slope of the characteristic voltage drop of the source voltage did not have a significant effect on the response of the transient and permanent state of the system in the face of changes in the working point of the sources. On the other hand, increasing nq has increased the accuracy of reactive power distribution due to reduction of the output difference characteristic of the voltage drop of the source voltage.

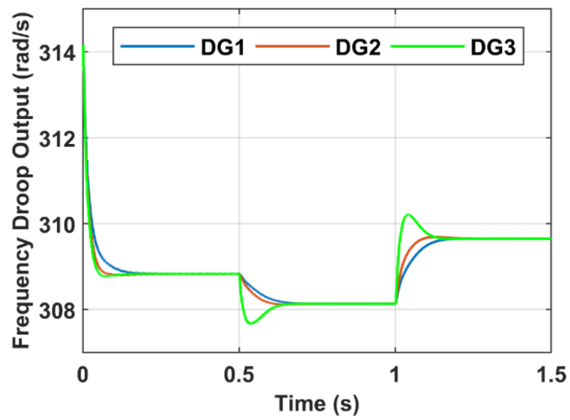


(a)

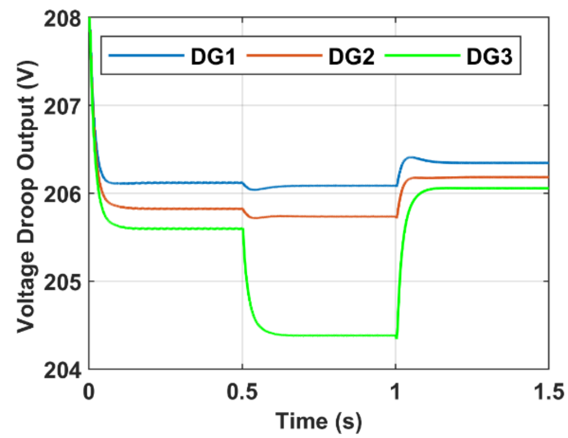


(b)

Fig. 9. Output of drop characteristics for m_p=0.00105 × 5, (a) The output of the frequency drop characteristic, (b) Output characteristic of voltage drop.



(a)

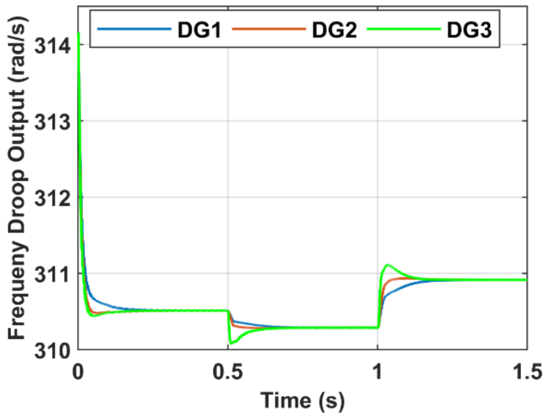


(b)

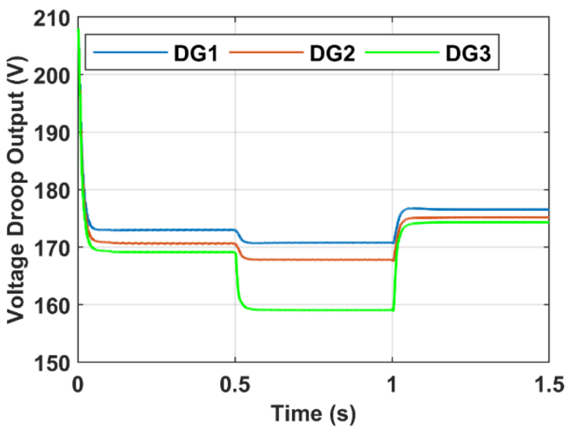
Fig. 10. Output of drop characteristics for n_q=0.0025 × 1/5, (a) The output of the frequency drop characteristic, (b) Output characteristic of voltage drop.

However, increasing the accuracy of power distribution has been associated with a weakening of the output voltage regulation of the sources. So that it can be seen that the output voltage characteristic of the source drop is out of the allowable range.

Therefore, there is an inherent compromise between the accuracy of reactive power distribution and the accuracy of voltage regulation. Also, due to the coupling between active and reactive power control, a 5-fold increase in the slope of the voltage drop characteristic, despite no change in the



(a)



(b)

Fig. 11. The output of the drop characteristics for n_q=0.0025 × 5, (a) The output of the frequency drop characteristic, (b) Output characteristic of voltage drop.

frequency drop coefficient, has caused slight changes in the output of the frequency characteristic. Therefore, by increasing the slope of the frequency and voltage drop characteristics, the effect of active and reactive power control coupling is intensified. This will reduce the margin of stability of the system.

It is necessary to focus on three control levels in microgrids as primary, secondary, and tertiary. These control levels differ in their speed of response and the time frame, in which they operate. The primary control is the first level in the control hierarchy, featuring the fastest response. The proposed power sharing strategy, which is based on the dynamics of inverters, relates to the primary control level. On the other hand, the loads have much slower dynamics than inverters. This means that all loads in the period of primary control level operation can be deemed as constant impedance loads.

6. CONCLUSION

In this paper, common methods of microgrid control in the island state were studied and the usual dropout strategy for local control of island microgrid was investigated and simulated. The usual frequency drop strategy causes the active power to be distributed proportionally between the sources due to the universality of the frequency parameter throughout the network. The typical voltage drop strategy is not accurate enough to divide the reactive power between the sources of a microgrid. Power distribution accuracy and voltage / frequency regulation are inversely related to the inherent nature of drop-down strategies. It was also shown that by increasing the slope of the frequency and voltage drop characteristics, the coupling between active and reactive power control is intensified.

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