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Improved Droop Control Method for Reactive Power Sharing in Autonomous Microgrids

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ABSTRACT

Conventional droop control method has been widely adopted for power sharing between Distributed Generators (DGs) in microgrids. However, the mismatched feeder impedance of the Voltage-Sourced Inverters (VSI) may generate reactive power sharing error during islanding operation of a microgrid. In this paper, an improved droop control method is suggested to improve the reactive power sharing accuracy. In the proposed method, the slope correction of the droop characteristics is performed in such a way that the reactive power sharing error is reduced. In this method, the errors of reactive power sharing are detected by applying a clear signal to the microgrids and, then, by adding a new term to the P-ω and correcting the slope of Q-E, the reactive power sharing is done. In this way, the proposed method can successfully improve the reactive power sharing accuracy even at different X/R ratios. Another feature of this method is its high operation speed compared to the other methods of droop feature correction. The simulation results for a prototype microgrid point to the efficiency and flexibility of the proposed method.

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1. INTRODUCTION

With the technological development of the world and the expansion of industries, demand for electric power has been continuously increasing over the last years [1-5]. Therefore, widespread use of renewable energy sources plays an important role in the modern electrical system [6-9].

Microgrid (MG) is an important and necessary part of the development of smart grids [10-12]. MGs are becoming more and more interesting due to their ability to reduce environmental impact of electric supply, reduce investment in plant, equipment, and cost, increase energy efficiency and stability as well as ride-through capability provided by energy storage, and alleviate the consequences of sudden grid outages [13, 14]. From the perspective of customers, a microgrid is a grid system that supplies reliable and high-quality electric power autonomously [15, 16]. The most relevant challenges concerning microgrid protection and control include modeling, bidirectional power flows, uncertainty, stability issues, and low inertia [17, 18].

In summary, the reasons for the popularity of microgrids include (a) the ability to combine a variety of energy generation methods and (b) uninterrupted power supply in areas with unreliable centralized power grids [19, 20]. So far, various studies have been done on the microgrid in terms of classifications, control, optimization, policy, and stability [21, 22].

A microgrid can operate in grid connected or standalone (islanded) modes [23-26]. It enjoys the capability of operating in islanded mode and in an autonomous fashion [27, 28]. Separation of microgrids from the distribution network brings about a significant change in the performance and control objectives of distributed sources within the microgrid [29, 30].

The control in the micro-grid system makes it difficult to coordinate various micro-power types to establish stable frequency and voltage [31-33]. The microgrid control objectives include [34, 35]: (a) reactive and active power can be independently controlled; (b) voltage sag and system imbalances can be corrected; and (c) the microgrid can meet the requirements of the grid's load dynamics. Microgrid control methods and parameters to be controlled are listed in Table 1 for the two MG operating modes.

Proper harmony among various generation sources should be made to prevent any interference. To achieve the control objectives, there are two methods of centralized and local strategies for microgrid in the autonomous mode [36]. Table 2 briefly describes the advantages and disadvantages of these two methods [37, 38].

The sharing of reactive power in an autonomous microgrid is affected by the asymmetry of local loads and the impedance

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mismatch, which is a challenge [39, 40]. Several methods have been proposed for the reactive power sharing in autonomous MGs in various pieces of literature [41, 42].

Droop control in stand-alone microgrids is an important method for sharing demand power between generators [43, 44]. However, the analysis of the method indicates the poor performance of this control method in reactive power sharing [45, 46].

An analytical method for an island microgrid was presented to evaluate the full control method in [47]; in order to evaluate the performance of the controller, three types of load were examined.

Table 1. Control methods for inverter-based MG

Operation mode	The parameters must be controlled		Control method
	Active and reactive power	Voltage and frequency	
Grid-connected mode	×	-	Constant current control PQ control
Islanded mode	×	×	P-f control Q-V control

Table 2. Control methods in mg based on structure

Control structure	Characteristic	Advantage	Disadvantage
Centralized	It has a main controller and determines what other controllers located in each inverter should do.	Performs quite well.	Relying on the proper performance of the main controller. Requiring active communication network.
Decentralized	Several inverters work together to establish the voltage, frequency, and network, which is done only on the basis of local measurements by each inverter.	Reliable MG performance does not depend on any one unit. No need for high-speed communications. Local information only.	Possibility of slowing down the transient response of inverters after a disturbance. Dependence of the ability to divide loads for inverters on feeder impedances and control parameters.

Also, the simulation results demonstrated that the error intensity and the duration of how the microgrid reaches the fast frequency convergence and the fast performance of the protection system could improve the stability of the system.

An auxiliary controller was proposed in [48] to reduce the fluctuations due to increase in overlap by analyzing the microgrid eigenvalue which does not require network impedance monitoring to adjust the controller. It was also shown that increasing the reactive power drop causes the generated reactive power to be less affected by active charge changes.

In the islanded operation mode, the conventional method for proper load sharing between sources and regulation of the voltage and frequency in the local strategy is to employ the Q-E and P-ω droop characteristics [49, 50]. In this approach, the active power is controlled using the frequency which results in proper real power sharing among DGs, while utilization of conventional droop voltage characteristic does not result in ideal reactive power sharing among DGs because the voltage is a local quantity [51]. Considering the intrinsic relation between the DG terminal voltage and its reactive power generation, it can be easily concluded that changing the Q-E curve specifications, which is the slope or y-intercept, can have a direct impact on the reactive power generation of the DGs and, consequently, power sharing among them [52]. The approach of virtual impedance control is capable of concurrently reviewing the power control instability and power sharing. Given that adding or removing any DG in each point of the microgrid, namely plug-and-play, changes the configuration of the microgrids, without knowing this microgrid configuration in real time, virtual impedance control may not operate well or properly.

In [53], a strategy was provided to correct the Q-E characteristic to improve the ideal reactive power in a microgrid with three micro-sources with local controls. In this approach, the micro-sources work with the conventional curves of Q-E and P-ω in normal conditions and at fixed time intervals, the reactive power sharing error decreases by adjusting the y-intercept of the Q-E characteristic.

Various strategies have been proposed in the literature to address the inaccurate reactive power sharing problem in islanded microgrids. Virtual impedance-based methods were proposed in [54, 55] to enhance the reactive power sharing. This methods focus on reducing the feeder impedance difference of DGs. The virtual impedance is usually considered inductive to increase the X/R ratio of the feeder impedance and, consequently, to reduce the coupling between active and reactive power controls. In [56, 57], a virtual impedance technique was proposed to solve the sharing error caused by mismatched feeder impedances; the main idea was to reduce the difference in the output impedance of DG units. Despite the good performance of these methods, the controller requires a communication structure to obtain instantaneous information about the MG to adopt the desired virtual impedance. In [58, 59], control strategies based on adaptive virtual impedance control were proposed. In [59], an adaptive virtual impedance control scheme was proposed for overcoming the unbalanced and harmonic power sharing in islanded microgrids. In [58], an adaptive complex virtual impedance method was proposed for ideal reactive power sharing in the islanded microgrids. In [54], an improved droop control method was applied for power decoupling and accurate reactive power sharing. The method functions based on virtual power source and composite virtual negative impedance for low-voltage microgrids. In [60], an adaptive voltage droop control method was proposed to improve the reactive power sharing. This method uses two terms to be added to the conventional reactive power droop curve: the first is added to correct the voltage drop across the transmission lines; the second is used to make the system stable under heavy loading conditions. However, this method needs detailed information of the network in advancing the operation.

In this paper, a method for modifying the Q-V characteristic was proposed to achieve the ideal reactive power sharing in microgrids with local control-based micro-sources. In this method, all micro sources operate with theconventional Q-E and P-ω characteristics. At certain times, the Q-E droop curves are adjusted by modifying the characteristic slope so that the reactive power sharing error can be reduced. The proposed method first determines the reactive power sharing errors by injecting small active-reactive power deviations. Then, accurate reactive power sharing is achieved by adding a new term in the P-ωcharacteristic and modifying the slope of the Q-E droopcurve. By using the proposed scheme, the reactive power sharing error is significantly reduced. After correction, the proposed droop controller is automatically switched to the conventional droop controller.

The remainder of the paper is organized as follows:

In the second section, the conventional control method for the microgrid is mentioned. In the third part, the process of correcting the characteristic is stated. In the fourth part, the simulation results for a microgrid with three scattered production units and two linear loads are given. Finally, the conclusion of the article is given in the fifth part.

2. CONVENTIONAL DROOP CONTROL METHOD ANALYSIS

A common method in the case of universal microgrid applications is droop control [61]. For low-voltage microgrids, typical drop control is unusual, as the line impedance between the distributed generation units is usually strong enough to connect the active and reactive DG power [62, 63]. The performance of conventional drop control needs to be improved because the assumption of a drop curve in a part of the operating area of capacitive connection inverters is not valid [64].

Figure 1 shows the general diagram of an island microgrid in which a power line (indicated by solid line) is required to trade electrical power, while trade control and status information are shown with a communication line (indicated by dashed line) [65, 66]. Figure 2 shows the equivalent circuit of one DG unit which is connected with an interface filter to the common bus of an AC microgrid. V_T and V_P are the voltage of the ends of the filter capacitor and the common bus voltage, respectively. Line resistance is ignored. Reactance between the inverter and the common bus is denoted by X_i.

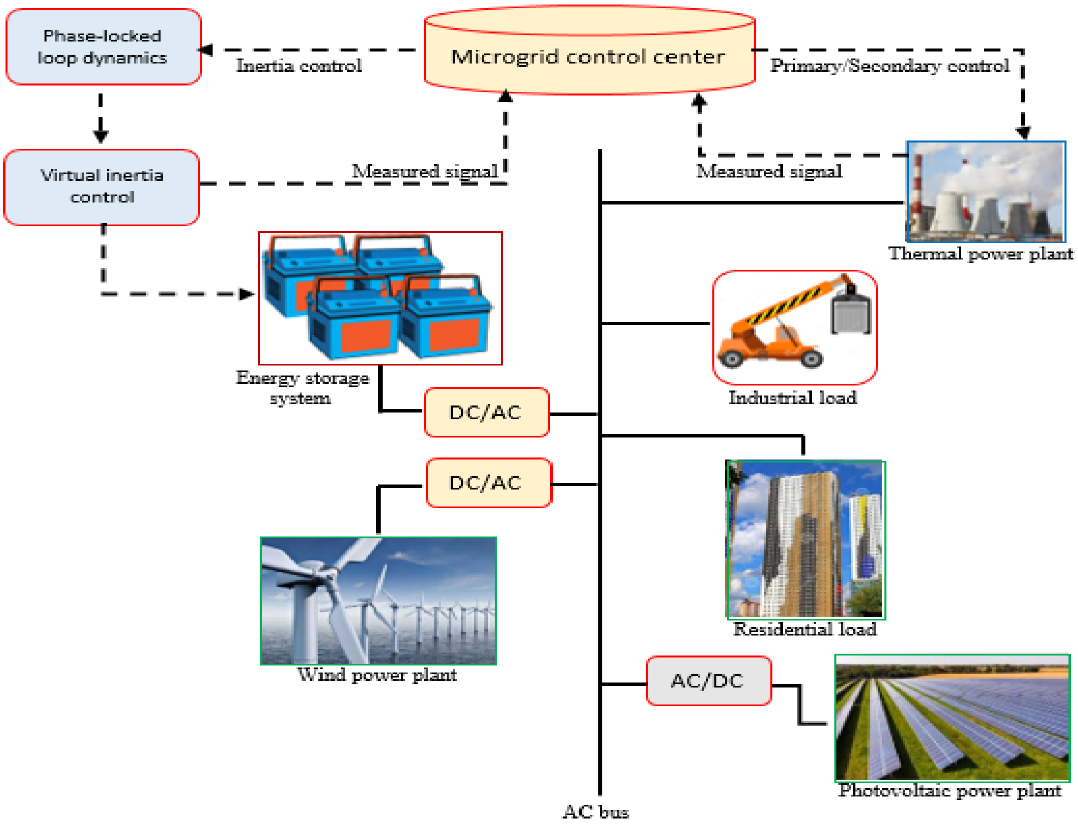


Figure 1. Illustration of the AC microgrid configuration [66]

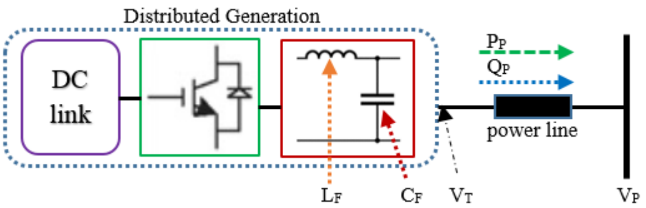


Figure 2. The equivalent circuit of a DG unit connected to a common bus

Based on the equivalent circuit of a DG unit connected to a common bus, the active and reactive output powers of each DG unit are extracted as follows:

$$P_i = \frac{V_T V_P}{X_i} \sin \delta_i \tag{1}$$

$$Q_i = \frac{V_T V_P \cos \delta_i - V_P}{X_i} \tag{2}$$

Neglecting the line resistance and assuming $\cos\delta_i \approx 1$, the active power is proportional to δ_i (or its derivative ω) and, consequently, changing the voltage phase angle of DGs impacts their output active power. According to (2), the output reactive power of a DG unit can be controlled by voltage magnitude of V_T [67]. Therefore, the frequency and voltage droop characteristics are extracted as follows:

$$\omega = \omega_0 - n_p.P \tag{3}$$

$$E = E_0 - n_q.Q \tag{4}$$

where ω_0 and E_0 are no load frequency and voltage, respectively, and n_p and n_q are frequency and voltage droop coefficients, respectively.

It is assumed that DG i^{th} and DG j^{th} are operating in a parallel way with the same nominal capacity and droop characteristic slope. It should be considered that the phase angle changes of δ_i are very small. Increasing the inductance of the network and the slope of the voltage droop characteristic are the two main approaches to improving the reactive power sharing error. Increase in the impedance is usually done by virtual impedance control, which requires the control with a higher bandwidth for the inverter [68]. It should be noted that increasing the droop slope may increase the reactive power sharing error; however, this slope increase generates other issues like V_P reduction or the required reactive power changes (due to voltage changes). Therefore, it can be said that increasing the slope is not a good option to improve the reactive power sharing error.

3. CHARACTERISTIC CORRECTION PROCESS

Reactive power sharing error is caused by various factors in the microgrid. Most reactive power sharing error correction strategies are based on complex circuit models and settings. Therefore, in this section, a correction method is proposed to eliminate the temporary reactive power sharing error without the need for microgrid configuration. Given the frequency is a global parameter throughout the network, any quantity placed on a characteristic with frequency leads to the ideal sharing of that quantity. Therefore, the strategy used to modify the Q-E characteristic is based on the same property. Before starting the process, the production of all micro sources is considered to be approximately the same as the active power P_0. Also, the production of reactive power by each micro-source in ideal sharing conditions is equal to Q_0.

As the feature correction process starts in all the micro-sources, the active power in the droop characteristic of P-ω is replaced with a linear combination of P and Q as in the following to have a new power-frequency characteristic:

$$\omega = \omega_0 - n_p(a.P + b.Q) \tag{5}$$

In these conditions, the Q-E curve remains with the same conditions as that before the compensation.

$$E = E_0 - n_q.Q \tag{6}$$

In this process, the slope of n_q in the above relation is corrected to reach the reactive power sharing.

By keeping the values of a and b fixed in all the micro-sources, aP + bQ will have the same values, as the value of aP + bQ is associated with a feature with one frequency. The goal is to return the value of P to P_0 at the end of the process and the value of Q to Q_0 in all micro-sources. Assuming that the network impedance is mainly inductive, the reactive power is mainly dependent on the voltage and it is determined by the Q-E characteristic.Therefore, the main goal of the characteristic modification process is to modify the slope of Relation (6) so that the reactive power generation of the micropower reaches Q_0. However, Q_0 is a function of the reactive power of the load and the grid, which is an unknown value. If the slope correction of the Q-E characteristic in all micro sources takes place in such a way that the active power returns to P_0 and since aP + bQ are the same in all micro-sources, it can be concluded that Q has the same value in all micro sources and it points to the ideal sharing of reactive power. At the end of the character correction process, aP + bQ is replaced again with the normal character P-ω. The overall process is shown in Figure 3.

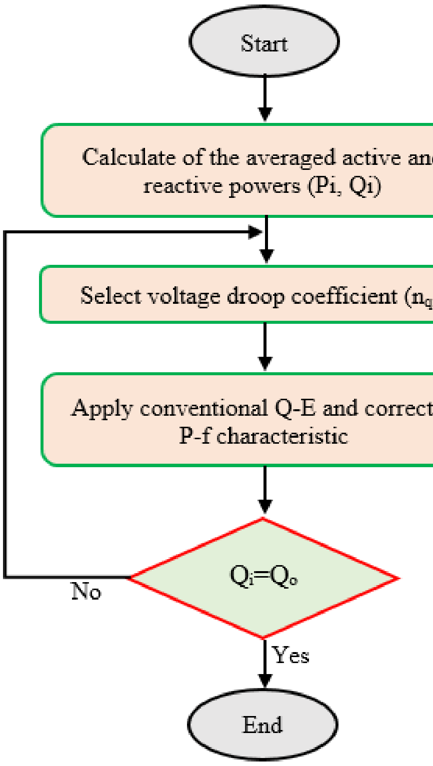


Figure 3. Flowchart of the proposed method

Figure 4 shows the process of the given character correction to synchronize reactive power. As shown in this figure, the character correction process is determined by starting signal activation. The timer block measures the process duration. At the beginning of the process, the sampling and holding block samples and stores the initial amount of active power equal to P_0 to be used during the process.

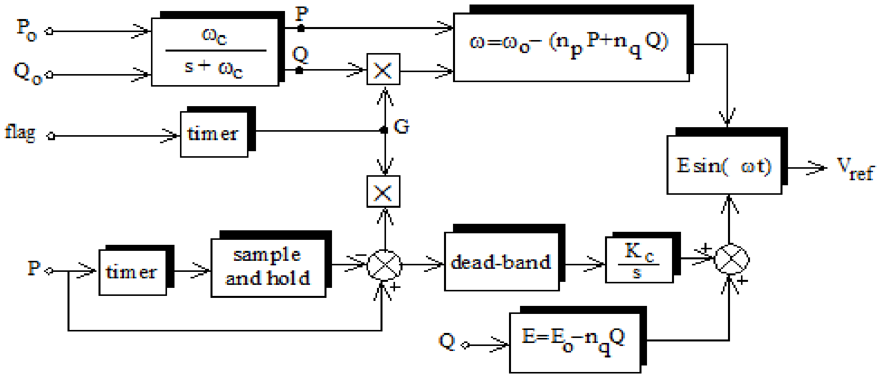


Figure 4. Reactive power synchronizing correction plan

4. SIMULATION RESULTS AND DISCUSSION

In order to evaluate the operational accuracy of the algorithm for correcting the Q-E feature and power ideal sharing between the microgrid sources, the sample microgrid composed of some DGs and loads in Figure 5 is used. Each DG system includes a power supply and an inverter interfaced with the network. In the operation connected to the network, the active and reactive reference power is normally supplied through the main network and the approach of normal droop control can be applied to follow the power. Therefore dividing the power in the network connected mode does not make any problems for the network [69, 70]. When the microgrid is operating autonomously, all the required load of the microgrid should be properly shared through DG units.

The rated rms voltage (L-L) for microgrid 208 V (60 Hz). The active and reactive loads are 3525 W and 1425 Var, respectively.

The filter parameters in the interface inverter include $R_F = 0.2\ \Omega$, $L_F = 5$ mH, and $C_F = 40\ \mu$F. Sampling-switching frequency is 9 KHz ~ 4.5 KHz. Droop coefficients are $n_p = 0.00125$ and $n_q = 0.00143$. Integration dead-band, Integral gain Kc, and LPF time constant are 6 W, 0.0286, and 0.0158 sec, respectively.

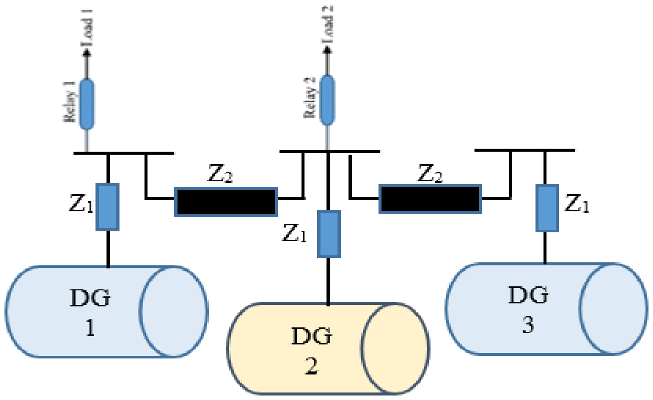
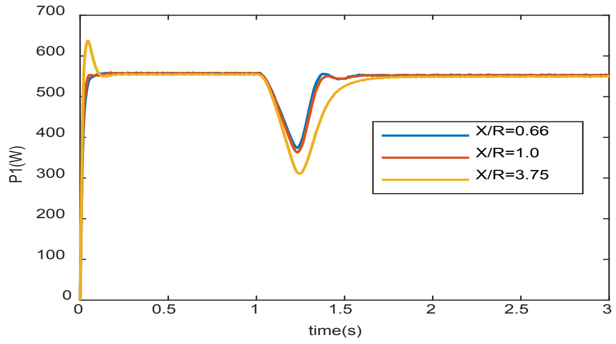


Figure 5. The microgrid consists of three DG units and two linear loadfor simulation

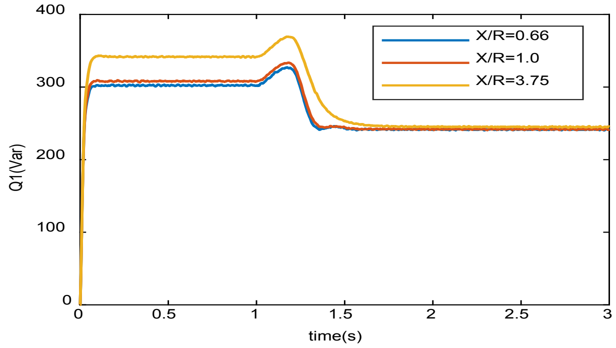
The simulation is done in 3 seconds and the feature correction process is applied on the network in 1-2 seconds to share the reactive power. The simulation results are compared with those in [71] to demonstrate the effect of the proposed method on the power sharing improvement.

To evaluate the robustness of the proposed method to network changes, the microgrid shown in Figure 5 is simulated with three different X/R ratios of low X/R = 0.66, medium X/R = 1, and high X/R = 3.75. Here, power sharing scheme between loads 1 and 2 as well as the microgrid behavior under this condition are analyzed. Figures 6, 7, and 8 show the active and reactive power drawn from the DG1 to DG3, respectively.The results show that the proposed scheme can proportionally share both active and reactive power in the microgrid at different X/R ratios.

According to the conditions mentioned for the microgrid in Figure 5, the output impedance of each DG unit is the most important factor in determining the reactive power drawn from that DG. Therefore, since DG1 has the smallest output impedance with respect to other DGs, it has the lowest voltage drop at the output and, consequently, DG1 provides the largest part of the microgrid reactive power, as shown in Figures 6(b), 7(b), and 8(b). As seen, the use of conventional droop characteristics before t = 1 s leads to a large difference between the reactive powers of the DGs. After starting the process of correcting the droop characteristics, the reactive power sharing error decreases rapidly in less than 0.5 seconds. In other words, all three DGs produce reactive power equal to 243 Var.

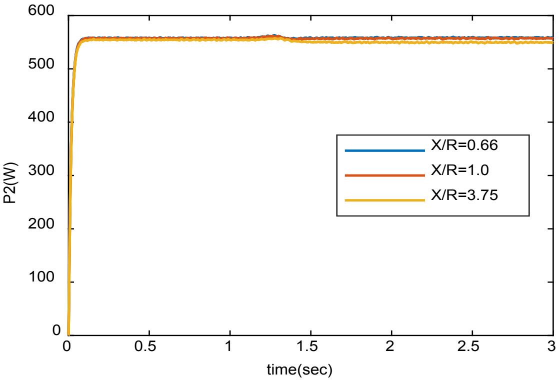


(a) Output active power

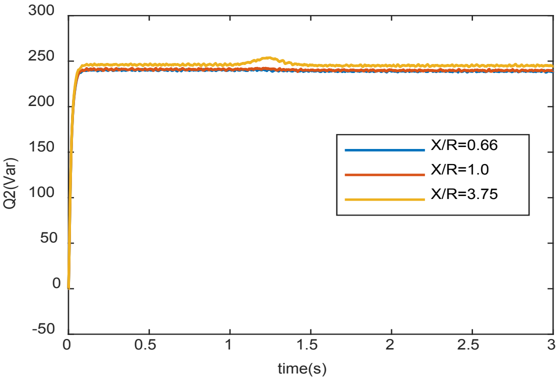


(b) Output reactive power

Figure 6. Output power of the DG1 before, after, and during the reference feature correction process

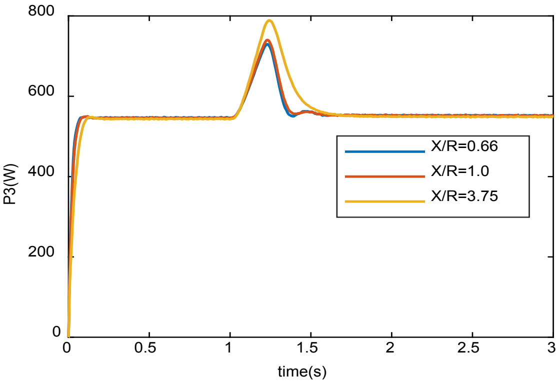


(a) Output active power

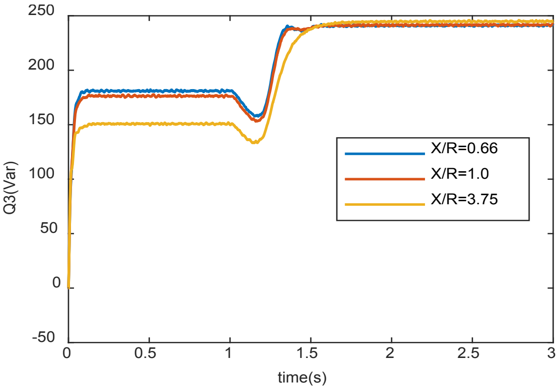


(b) Output reactive power

Figure 7. Output power of the DG2 before, after, and during the reference feature correction process



(a) Output active power



(b) Output reactive power

Figure 8. Output power of the DG3 before, after, and during the reference feature correction process

As illustrated in Figures 6(a), 7(a), and 8(a), the output active powers of DG units are equal prior to the moment t = 1 s. In other words, the active power is ideally shared using the conventional droop characteristics even though the feeder impedances of DGs vary.

The performance of the method presented in [70] can be compared with that of the proposed method using the simulation shown in Figures 9 and 10. As seen, the proposed method is much faster and experiences fewer oscillations to achieve the proper reactive power sharing. Also, according to output power dynamics of the proposed method (see Figures 6, 7, and 8), the overall time to reach the desired conditions is shorter than virtual impedance method.

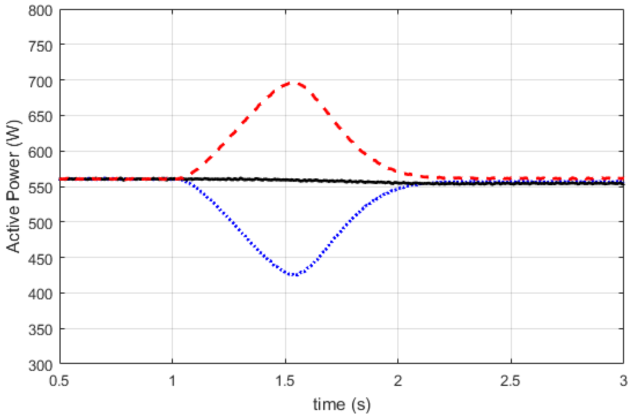


Figure 9. Output active power of the microgrids before, after, and during the reference feature correction process

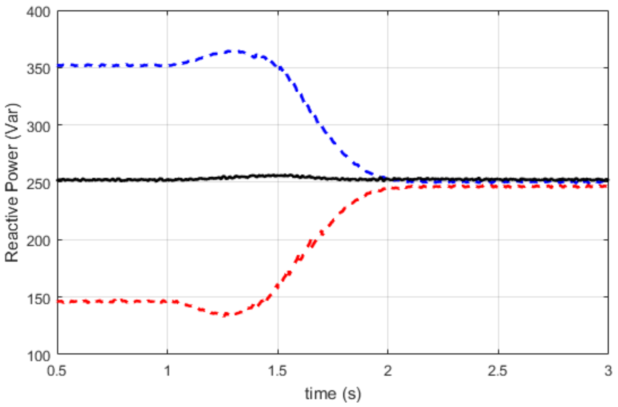


Figure 10. Output reactive power of the microgrids before, after, and during the reference feature correction process

5. CONCLUSIONS

The purpose of this paper was to improve the reactive power sharing error for microgrids with different X/R ratios and any type of topology. In this strategy, first, DGs are controlled using the conventional droop method. Then, at a certain time, the droop characteristics were compensated with a special structure. After the correction of the reactive power sharing error, the proposed droop controller returned to the conventional droop characteristic. To evaluate the method dynamics, simulation results were presented for different system conditions and it was shown that the proposed method was not sensitive to network structure and X/R ratio. The simulation results also showed that this method led to the appropriate reactive power sharing and the reactive power sharing error was minimized. Therefore, the proposed method was resilient with respect to the network changes and X/R ratio changes. The authors' focus for future work is to provide a plan for load sharing in the event of fault.

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