21th International Conference on Renewable Energies and Power Quality (ICREPQ'23)
Madrid (Spain), 24th to 26th May 2023
Renewable Energy and Power Quality Journal (RE&PQJ)
ISSN 2172-038 X, Volume No.20, September 2023

Accurate Power Sharing in Islanded AC Microgrid Using A Virtual Complex Impedance

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Abstract. Distributing the loads equally between the distributed generator (DG) units is an important issue in islanded microgrid (MG). The inaccurate power sharing may lead to cascaded outage of the DG units due to the overload and eventually, the MG system will shut down. Conventional droop control is used widely to perform power sharing. However, it cannot share load accurately between DG units due to feeder mismatching. From this perspective, this work proposes a complex virtual impedance to eliminate feeder mismatching, compensate for the reactive power sharing errors, and achieve accurate power sharing between the DG units. In addition, this work proposes to use an insertion function to insert the virtual complex impedance to reduce the active power oscillations. Simulation results, obtained using MATLAB/SIMULINK, shows that the proposed controller can perform accurate power sharing and is more accurate than conventional droop control with considerably low active power oscillations.

Key words. Droop control, Virtual impedance, Power sharing, Feeder mismatch, Islanded microgrid.

1. Introduction

Power sharing in microgrids (MGs) means distributing the load currents, active and reactive power between the distributed generator (DG) units according to their rated power. In case of renewable energy DG units, the loads are shared according to the available generated power as they are weather dependent units. Inaccurate power sharing between DG units may lead them to be overloaded and can cause the protection devices to isolate the overloaded DG unit. As a result of the protection isolation process, the MG could shut down and the power supply to the loads will be interrupted. Therefore, it is very vital to perform power sharing accurately especially in islanded mode of operation in MG. Several controllers have been introduced in the literature to overcome this problem. One of the most used controllers is conventional droop control [1], [2].

Conventional droop control is preferred because of its simple construction and operation. Another important feature of it is that it does not need communication channels between the DG units to exchange the generation information. Despite these features, conventional droop control has a major drawback in sharing reactive power accurately between DG units under feeder mismatching situations. MG changing topology due load connection and disconnection can affect the accurate reactive power sharing. To overcome this problem, several modifications were presented in the literature. These modifications can roughly be divided into adaptive droop control or virtual impedance loop utilization [1], [3], [4].

Adaptive droop control techniques include tuning the droop control coefficients [5], [6], tuning the no-load voltage level [7], or adding extra adaptive terms to the droop equations [1], [8]. Based on the computation of the transient energy delivered to the load from each inverter unit, the authors in [5] proposed an adaptive $Q-V$ droop coefficient to accommodate the load change, feeder mismatching, and achieve accurate reactive power sharing. This technique updates the coefficient value after every load change in the system. The method proposed in [6] depends on complex calculations to determine the droop coefficients values. The basic steps of this technique can be summarized as, injecting a current signal to the system the MG apparent impedance, system eigen values are then calculated by matrix fitting technique, eventually, droop coefficients will be modified based on the dominant eigen values of the previous step to ensure a stable operating system. Instead of adaptively tuning the droop coefficients, the authors in [7] proposed a no-load voltage tuning method to overcome the conventional droop control drawbacks. This technique proposed coupling the no-load voltage to the frequency which is stable in the entire system. Using the adaptive neuro fuzzy inference system (ANFIS), an adaptive technique was presented to adjust the droop control coefficients to meet the load demand and feeder mismatching in [1]. However, this technique can impose a computational burden on the system controller and without proper tuning of the parameters, the system may be unstable. A generalized droop control equations were used in [8]. To estimate the system impedance angle for the generalized droop control, an impedance-based model reference adaptive system was adopted for online estimation.

Virtual impedance techniques include virtual resistance [9]–[11], virtual reactance [12], [13], and virtual complex impedance methods [3], [14]. These methods rely on adjusting the voltage reference of the droop control by simulating the behavior of a physical impedance without inserting it. Virtual resistance in $\alpha\beta$ frame was proposed in [9], [11]. The authors in [9] used virtual resistance α component to control active power flow. While, β component was used to control the reactive power flow to the system. On the other hand, sliding mode control (SMC) was utilized with active power error to determine the value of the virtual resistance to be inserted in the control loop. The magnitude of the virtual resistance was designed to be higher than the magnitude of the combined resistive and inductive parts of the feeder impedance in [10]. By this designing approach, the virtual resistance plays a dominant role in the control as the feeder impedance effect is neglected. Virtual impedance techniques are proposed for resistive-based MGs or for neglected inductive parts of the system feeders. Virtual impedance can provide a system damping performance. Although, the improper value design may lead to system instability issues and main bus voltage distortion. The virtual reactance techniques can decouple the active and reactive powers to control them individually. The virtual reactance method was built in [13], is a communication-based approach to exchange the reactive power generation data between DG units. Based on the reactive power error between the DG units, the value of the virtual reactance is calculated and inserted to compensate for the power sharing errors. Based on the same concept of the reactive power sharing error, the authors designed a decentralized adaptive reactance in [12]. Although, the good performance of the virtual reactance technique, it still neglects the resistive part of the feeder impedance. The presented approaches in [3], [14], take into account both the resistive and inductive parts of the system's feeders. The authors in [14], proposed a virtual negative inductance to counteract the line inductance combined with a virtual resistance to enhance the impedance matching. On the other hand, a negative virtual resistance with a virtual inductance was presented in [3] to elevate system stability and power sharing performance.

So, the objective of this work is to eliminate feeders' mismatching, achieve accurate reactive power sharing, and enhance system stability. Therefore, the contribution of this work can be summarized as follows:

1) Designing a complex virtual impedance to overcome the feeders' mismatching with accurate power sharing between DG units.
2) An insertion function: instead of inserting the complete value of the virtual complex impedance directly into the system, an exponential insertion function is used to insert the complete value of the virtual impedance from 0 to 100% in 0.25 s to reduce the active power oscillations that may occur in the system as well as facilitating the smooth transition to accurate power sharing.

This paper is organized as follows, section 2 illustrates the MG system structure and operation, section 3 contains the adaptive virtual impedance technique and the exponential insertion function, section 4 has the simulation results and discussion, and the conclusion is presented in section 5.

2. Microgrid structure and operation.

This section illustrates the MG system under study with its main components. It also contains the basic operation and equations of conventional droop control utilized in this work.

A. Microgrid structure.

The MG system used in this study is shown in Fig. 1. The configuration of the MG system is a parallel connection. Where multiple DG units could share the system load as shown. It consists of a DG unit, feeder impedance, main bus, and a public connected load. Furthermore, the DG unit consists of a renewable energy source and could be simulated as a DC link for illustration simplicity. Then, the DG unit is coupled with a power electronic inverter. It also has an LCL filter connected to its output to reduce harmonic and ripples of the generated AC power. Each DG unit is equipped with a

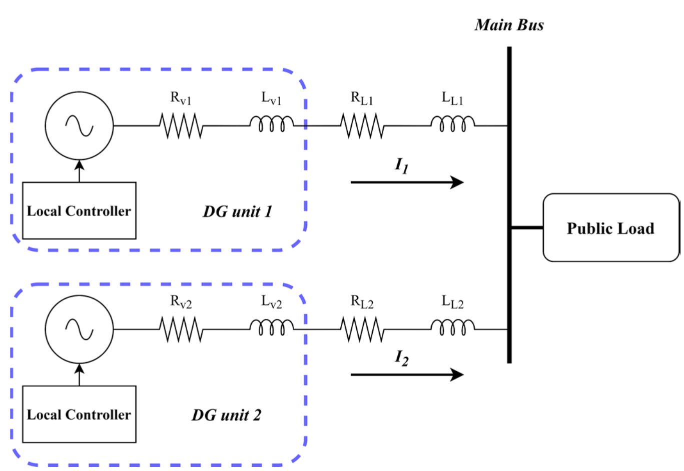


Fig. 1. Islanded AC MG.

local controller to control the flow of the output current according to the load demand as well as a virtual complex impedance that will be illustrated more in detail later.

B. Conventional droop (P/ω- Q/V) control.

Based on the synchronous machines, as the active and reactive power of the system changes, the system frequency and voltage will be changed accordingly. Inspired by this concept, the conventional droop control uses the inverter frequency to control the injected active power to the system. While the inverter magnitude voltage is used to control the injected reactive power. Eq (1) and Eq (2) describe the performance of the conventional droop control [12].

$$\omega = \omega^* - mP,\ \ m = \frac{\Delta\omega}{P_{max}} \tag{1}$$

$$V = V^* - nQ,\ \ n = \frac{\Delta V}{Q_{max}} \tag{2}$$

Where ω , , ω^* and V^* inverter frequency, voltage, reference frequency and reference voltage, respectively. m , n , P and Q are active power droop coefficient, reactive power droop coefficient, output active power, and reactive power of the inverter, respectively. $\Delta\omega$, ΔV ,P_{max} and Q_{max} are maximum allowed frequency deviation, maximum allowed voltage deviation in the system, maximum active power of the inverter, and maximum reactive power of the inverter, respectively.

A major drawback of the conventional droop control is the inaccurate reactive power sharing. This is mainly due to the connected feeders mismatching. This problem could be overcome by using a virtual impedance technique that will be illustrated in the next section.

3. Virtual complex impedance.

In order to share the reactive power accurately between DG units, the voltage drop on the feeders has to be the same. To accomplish this task, a physical impedance will be inserted to one of the feeders to have the same impedance as the other feeder. However, this solution is not practical to solve the problem. Instead, a virtual impedance is inserted in the control loop. In this case, the virtual impedance emulates the voltage drop on an actual impedance as shown in Fig. 1. Then, the virtual impedance voltage drop is used to regulate the voltage reference of the droop control as follows:

$$V_{ref} = V_{droop} - V_{virtual} \tag{3}$$

Where V_{ref} is the reference voltage that is fed to the inner control loops of the local controller. V_{droop} is the droop control output voltage which is calculated from Eq (2). $V_{virtual}$ is the voltage drop on the virtual impedance which is estimated as follows:

$$V_{virtual} = I_o * Z_{virtual} \tag{4}$$

Where I_o is the output inverter current and $Z_{virtual}$ is the virtual complex impedance inserted in the control loop to eliminate feeders' mismatching.
From Fig (1), the total feeder impedance is calculated as:

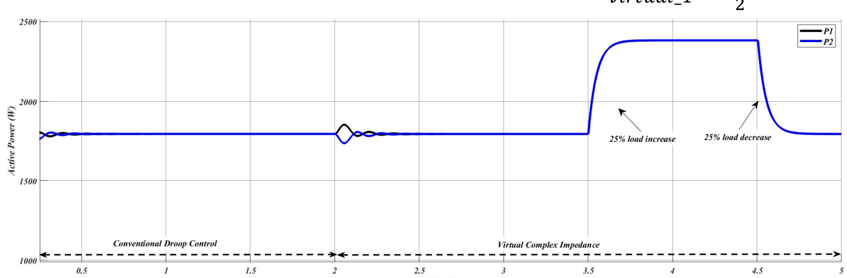
$$Z_t = Z_{line} + Z_{virtual} \tag{5}$$

In case of the added virtual impedance, both the feeders will be equal so,

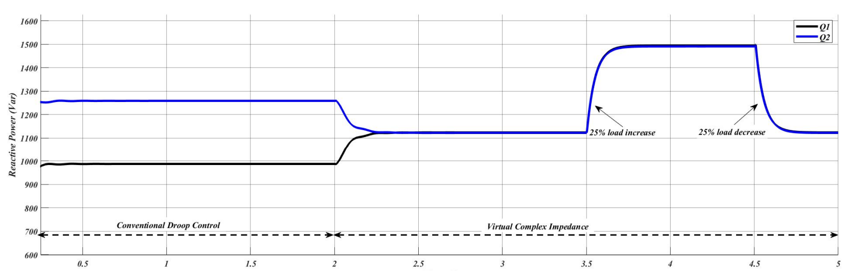
$$Z_{line\_1} + Z_{virtual\_1} = Z_{line\_2} + Z_{virtual\_2} \tag{6}$$

Assuming that $Z_{virtual\_2} = -Z_{virtual\_1}$ and $\Delta Z = Z_{line\_1} - Z_{line\_2}$ and by arranging Eq (6), the virtual complex impedance value can be estimated as follows:

$$Z_{virtual\_1} = \frac{-1}{2} * \Delta Z\ ,\ Z_{virtual_2} = \frac{1}{2} * \Delta Z \tag{7}$$

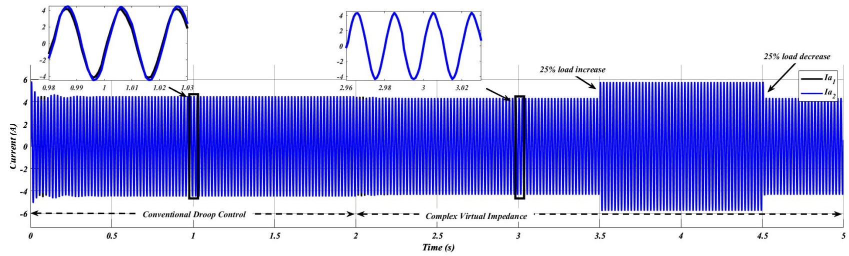


(a)

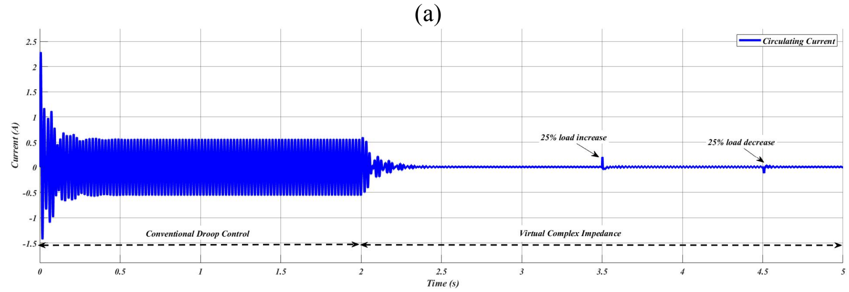


(b)

Fig. 2. Sharing of (a) active power and (b) reactive power.



(a)



(b)

Fig. 3 (a) Single phase DG units' currents. (b) Circulating current

Instead of directly inserting the virtual impedance value into the local controller of the DG unit, this work proposes an insertion approach based on the exponential function. This insertion approach is proposed to reduce the active power oscillation that may occur during the power sharing stage. The exponential function is as follows:

$$Z_{virtual-} = Z_{virtual} * (a \exp(bx) + c\exp(dx)) \quad (8)$$

Where the values of a, b, c, and d are estimated based on the amplitude, insertion time, and required time to reach 100% of the function amplitude. The symbol x represents the time. The function reaches an amplitude of 1 at 0.25 s and inserted at t=2 s. The function parameters could be changed as desired.

4. Simulation and discussion.

The MG system in Fig. 1 is simulated using MATLAB/SIMULINK to verify the effectiveness of the proposed virtual complex impedance with the insertion function.

The case study can be illustrated as follows:

1) At t = 0: 2 sec, 75% of the public load is connected to the main bus with conventional droop control.
2) At t = 2 sec, the proposed virtual complex impedance with the proposed insertion function is activated to share the reactive power accurately.
3) At t = 3.5 sec, the load is increased to reach 100% of its value.
4) At t = 4.5 sec, the load is decreased back to 75% of its value to observe the behavior of the proposed controller under load change.

During conventional droop control, the active power is shared accurately as the frequency is constant across the system as shown in Fig. 2(a). However, at the same period, the reactive power is not shared accurately because of the feeder mismatching as in Fig. 2(b). After inserting the virtual complex impedance in the control loop with the aid of the insertion function, the active power curve experiences a low oscillation with only 4% increase in amplitude. At the same time, the reactive power is shared accurately between the DG units as the feeders mismatching is eliminated as well as the feeders' voltage drop difference. During the period of increasing and decreasing the load with 25%, the DG units can preserve the accurate power sharing between them.

Fig. 3(a) and (b) show the phase currents of the DG units and the circulating current between them, respectively. In Fig 3(a), during the conventional droop control period, it is obvious that the DG units current are not matching each other causing circulating current to flow between them in the same period in Fig. 3(b). With virtual complex impedance, the phase currents between the DG units get matched leading to the decrease of circulating current with more than 98% reduction.

5. Conclusion

This work proposed a virtual complex impedance with an insertion function. The virtual complex impedance is used to decouple the powers and facilitate the control course of the conventional droop and eliminating the feeders' mismatching. This led the controller to share reactive power accurately between the DG units and suppress the circulating current. The proposed technique leads to more than 98% reduction in the circulating current between DG units. Furthermore, the proposed insertion function facilitates the incorporation of the virtual complex impedance into the system without causing big active power oscillations. The active power oscillations have been reduced to 4% and take place in 0.25 s.

Acknowledgment:

We would like to submit our acknowledgment to Prof. Tanemasa Asano, Graduate School of Information Science and Electrical Engineering, Kyushu University, Japan. We are thankful for his guidance, text proof-reading and collaboration throughout the work.

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