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# 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, show that the proposed controller can perform accurate power sharing and is more accurate than conventional droop control with considerably low active power oscillations. The comparative results with the conventional virtual complex impedance illustrate the effectiveness of the proposed approach in terms of controller overshoot, controller settling time, and circulating current reduction percentage as well as the effect on the voltage of the point of the common coupling (PCC) of MG.

**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.

Accurate power sharing in islanded MG could be affected by the changing behaviour of the renewable energy resources, changing topology of the MG, inverter output filter, and feeders' mismatching. Equal load sharing conditions based on the capacity of the sources is the best situation in this work as the renewable energy resources are considered to be at the same weather conditions and with the same type of generation.

The effect of the feeders' mismatching and overcoming this problem are the scope of this study. 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 $\boldsymbol{Q-V}$ 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 $\boldsymbol{\alpha\beta}$ frame was proposed in [9], [11]. The authors in [9] used virtual resistance $\boldsymbol{\alpha}$ component to control active power flow. While, $\boldsymbol{\beta}$ 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.

The advantages of the proposed approach are simple design procedure, reduced transient overshoot as compared to conventional virtual complex impedance. 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

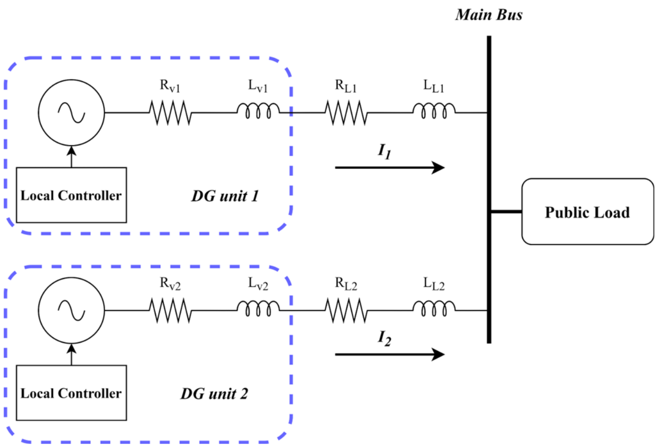


Fig. 1. Islanded AC MG.

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 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].

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

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

Where, $\boldsymbol{\omega^*}$ and $\boldsymbol{V^*}$ inverter frequency, voltage, reference frequency and reference voltage, respectively. $\boldsymbol{m}$ , $\boldsymbol{n}$, $\boldsymbol{P}$ and $\boldsymbol{Q}$ are active power droop coefficient, reactive power droop coefficient, output active power, and reactive power of the inverter, respectively. $\boldsymbol{\Delta\omega_{max}}$ , $\boldsymbol{\Delta V_{max}}$ ,$\boldsymbol{P_{max}}$ and $\boldsymbol{Q_{max}}$ 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.

## 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:

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

Where $\boldsymbol{V_{ref}}$ is the reference voltage that is fed to the inner control loops of the local controller. $\boldsymbol{V_{droop}}$ is the droop control output voltage which is calculated from Eq (2). As shown in Eq (3), the virtual complex impedance reshapes the reference voltage $\boldsymbol{V_{ref}}$ of the DG units to make them work at the same voltage level (both magnitude and angle). By applying this concept, the circulating currents between the DG units would be diminished largely. $\boldsymbol{V_{virtual}}$ is the voltage drop on the virtual impedance which is estimated as follows:

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

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

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

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

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

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

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

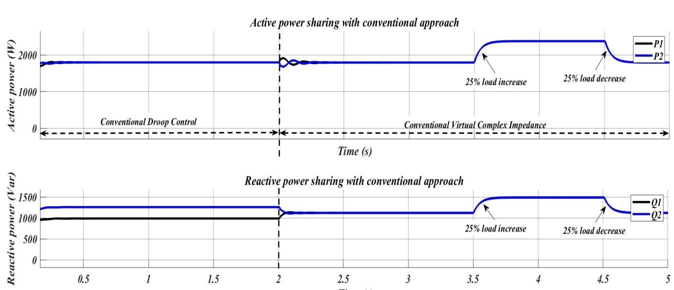


Fig. 2. active power (upper) and reactive power (lower) sharing with conventional virtual complex impedance.

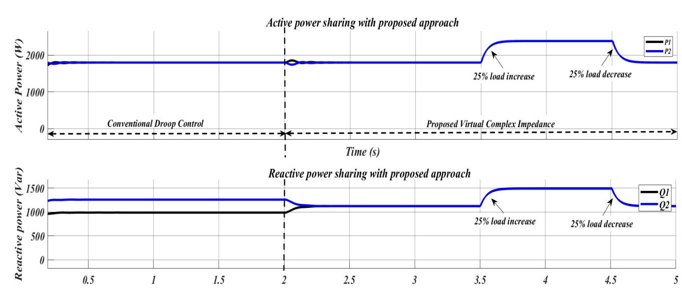


Fig. 3. active power (upper) and reactive power (lower) sharing with proposed virtual complex impedance.

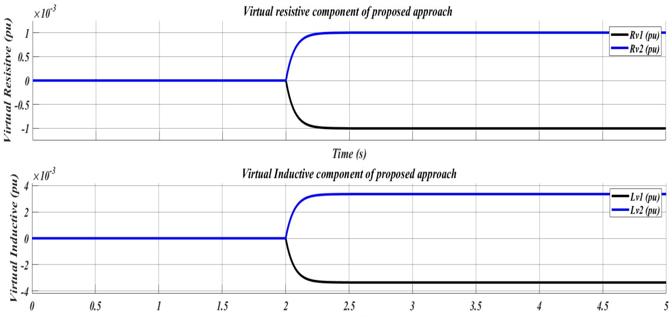


Fig. 4. Virtual resistive (upper) and inductive (lower) parts of the proposed approach with implemented insertion function applied to both of the DG units.

In case of more than two DG units in the system, compensating all of them to the highest (positive virtual impedance) or lowest (negative virtual impedance) feeder impedance would share the loads accurately. However, this approach would cause sever voltage distortion at the PCC. So, it would be a common practice to compensate the DG units to an intermediate impedance or optimal impedance to eliminate voltage distortion at the PCC. This means that the feeders with higher impedances than optimal impedance, would have negative virtual impedance. While, the feeders with lower impedance than optimal impedance will have positive virtual impedance.

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:

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

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 $\boldsymbol{x}$ represents the time. The function reaches an amplitude of 1 at 0.25 s and inserted at t=2 s. Two exponential functions are implemented to facilitate the insertion of the virtual impedance into the control loop instead of using a step function which could increase the transient power oscillations.

Table I.- system parameters

| Parameter | Symbol | Value |
|---|---|---|
| DC link voltage | $V_{dc}$ | 500 V |
| LCL filter | $L_1/C/L_2$ | 500uH/50uF/200uH |
| Feeder line 1 | $Z_{l1}$ | 0.1488+j0.4969 Ω |
| Feeder line 2 | $Z_{l2}$ | 0.093+j0.31 Ω |
| Droop reference voltage | V* | 230 V |
| Droop reference frequency | ω* | 314.16 rad/sec |
| P/ω coefficient | $m_p$ | 2.5937e-4 rad/sec/W |
| Q/V coefficient | $n_q$ | 0.0015 V/Var |
| Insertion function terms | a | 0.9775 |
| | b | 0.008884 |
| | c | -1.713e13 |
| | d | -15.24 |

## 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. Table I. shows the system parameters of MG system.

Case 1:

The active and reactive power sharing are tested with conventional virtual complex impedance and proposed virtual complex impedance in Fig. (1) and Fig. (2) respectively.

At $\boldsymbol{t = 0{:}2\ sec}$; conventional droop control is applied to both of the system with 75% of the load. As shown in Fig. (1) and Fig. (2), conventional droop control can share the active power correctly as the frequency is constant across the system and unaffected by the feeders' mismatching. On the contrary, inaccurate reactive power sharing is shown because of the unequal feeders with unequal voltage drops.

At $\boldsymbol{t = 2\ sec}$; both conventional virtual complex impedance and proposed virtual complex impedance are inserted in Fig. (1) and Fig. (2) respectively. As shown, both of the two methods can share the reactive power effectively under unequal feeders at steady state. However, the transient performance of conventional virtual complex impedance is undesirable as compared to proposed virtual impedance. Furthermore, the transient oscillations with conventional approach are higher than with proposed approach. In addition, the settling time of conventional approach is larger than the proposed one as shown in table II.

Both of the two approaches are tested under 25% load increase and decrease at $\boldsymbol{t = 3.5\ sec}$ and $\boldsymbol{t = 4.5\ sec}$ , respectively. It is

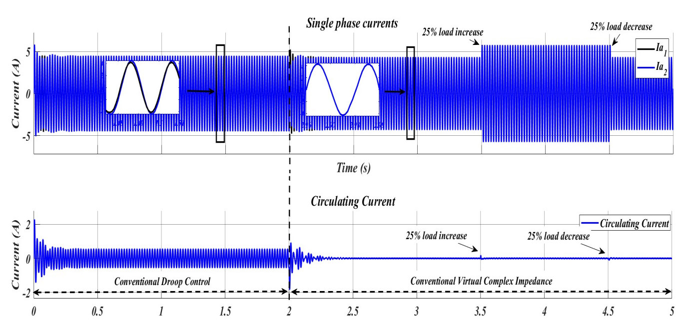


Fig. 5. DG units' phase currents (upper) and circulating current (lower) in case of conventional virtual complex impedance.

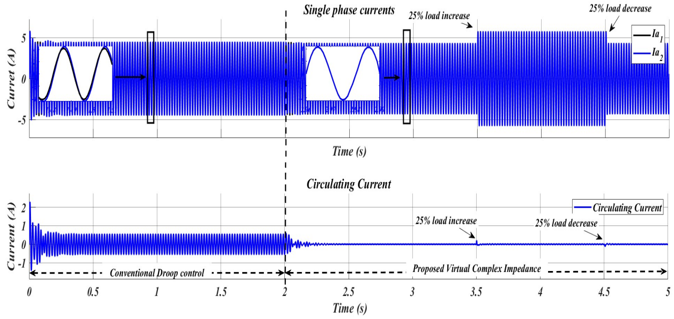


Fig. 6. DG units' phase currents (upper) and circulating current (lower) in case of proposed virtual complex impedance.

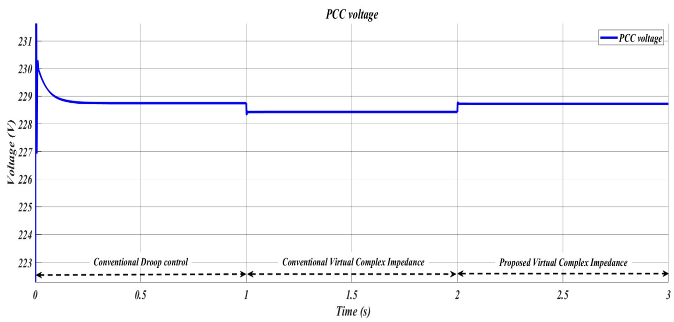


Fig. 7. PCC voltage with conventional approach and proposed approach.

verified that the proposed approach can perform correctly under varying the load as well as the conventional approach. Virtual complex impedance components with implemented insertion function are shown in Fig. (4).

Case 2:

Both of the approaches are simulated under the same time steps as in case 1 to verify the proposed approach under circulating current situation in comparison with conventional approach. Fig. (5) and Fig. (6) show the DG units phase current with circulating current value with conventional approach as well as proposed approach, respectively. As illustrated, both approaches can suppress the circulating current between DG units. In addition, the phased currents get synchronized. However, the proposed approach has more circulating current reduction percentage as the conventional one as shown in table II.

Case 3:

In this case, the PCC voltage distortion is studied under both of the approaches to demonstrate the effectiveness of the proposed approach. The system is simulated as follows; at $\boldsymbol{t = 0{:}1\ s}$, the system is operated with conventional droop control, at $\boldsymbol{t = 1{:}2\ s}$, the system is simulated with conventional virtual complex impedance, and at $\boldsymbol{t = 2{:}3\ s}$, the system is simulated with proposed virtual complex impedance. The total load of the system is connected to the PCC during the various stages of simulation in the case.

Table II.- performance comparison between conventional approach and proposed approach.

| Parameters | Conventional approach | Proposed approach |
|---|---|---|
| Controller overshoot (%) | 106.78 | 103.22 |
| Controller settling time (s) | 0.5 | 0.25 |
| Circulating current reduction (%) | 97.19 | 98.8 |
| PCC voltage (V) | 228.4 | 228.7 |

Conventional virtual complex impedance has severe effect on distorting the PCC voltage as compared to the proposed virtual complex impedance as shown in Fig. (7). The voltage values in both cases are included in table II.

## 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 leads 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 3% and take place in 0.25 s as compared to the conventional virtual complex impedance approach. Thus, the proposed approach outperforms the conventional approach.

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