An Adaptive Virtual Impedance Based Droop Control Scheme for Parallel Inverter Operation in Low Voltage Microgrid

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ABSTRACT

This paper presents an adaptive virtual impedance based droop control scheme for parallel inverter operation in low voltage microgrid. Because it is essential to achieve power sharing between inverters in microgrid, various droop control schemes have been proposed. In practice, the line impedance between inverters and the point of common coupling (PCC) in microgrid are not always equal. This imbalance in line impedance often results in a reactive power mismatch among inverters. This problem has been solved by introducing a virtual impedance loop in the conventional droop control scheme. However, the reactive power sharing performance of this method is still deteriorated when the line impedances change during operation. To overcome such a problem, a new control scheme that is based on a virtual impedance loop and an impedance estimation scheme is proposed. To monitor the changes in line impedances, the impedance estimator is implemented by using the output voltages and currents of inverters as well as the voltages at the PCC. To compensate for the reactive power mismatch due to the line impedance changes, the estimated line impedance is fed to the virtual impedance loop in which it adjusts the virtual impedance value. Comparative simulation results with the conventional ones verify the effectiveness of the proposed adaptive virtual impedance based droop control scheme.

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1. INTRODUCTION

Today, due to the concern for environmental problems, many countries in the world have started their transition from fossil fuel to renewable energy such as the wind and solar energy. Because renewable energy sources are usually distributed in a wide area, the conventional centralized generation and distribution system have become insufficient. In the last decades, microgrid mainly based on distributed generation (DG) system, electrical energy storage system (ESS), and smart control based on the information and communication technologies has allowed the conventional power systems to support renewable energy. Besides, a significant number of populations all around the world still have no access to the electricity due to living in the remote area where the power grid cannot reach. The advent of microgrid is a promising solution to bring electricity to such area without extending the existing power grid [1]. However, intensive researches are required to put this advanced system into practice since microgrid technology is still a new horizon of power system engineering.

Microgrid is a small-scale grid that is formed by DG systems, ESS, and loads interconnected, controlled, and located at local distribution grid. Generally, microgrid can function either in grid-connected mode or in islanded mode [2]. In microgrid, it is vital to distribute the load demand proportionally among converter modules, which guarantees the reliability of the parallel inverter operation. Many power sharing methods have been proposed in [3] with different system complexities and power sharing performances. Generally, most of these methods require the interconnection between DG systems [3]-[4]. However, the additional interconnections increase the system complexity. Furthermore, these interconnections may be causative of reducing the reliability of the entire microgrid since the entire system can be shut down even when the fault occurs only in one DG system.

In order to overcome the aforementioned problem, intensive researches have been conducted to develop a method without requiring any interconnection between parallel-connected inverters. Among these methods, a droop control scheme has been proven as the most simple and effective one [5]. Generally, the droop method is simple to implement and it does not require any communication between modules. Besides, the droop control has the plug-and-play feature, which enables the system expansion to be easy and allows replacing DG unit within the system without making the entire system shutdown. Therefore, this configuration of microgrid is quite suitable for applications in which DG systems spread in a wide area.

The droop control scheme was initially developed for the predominantly inductive transmission line. When the droop control is implemented in an inductive microgrid, its effectiveness in terms of distributing total load demand among all the DG systems within microgrid has been proven in [6]. However, the load sharing performance of the conventional droop control scheme is degraded when the transmission line is predominantly resistive. To solve such a problem, a variation of the droop control scheme has been introduced for the resistive line case in [7] as the purpose of providing a good load sharing performance under all condition. However, these droop control schemes still have one significant drawback, which is the power sharing performance is highly sensitive to line impedance difference between inverters. Especially, the reactive powers are not properly shared between inverters when the line impedance between the inverters and the point of common coupling (PCC) is different.

This problem has been solved in [8] by introducing a robust virtual impedance loop which can change the inverter output impedance as well as mitigate voltage distortion problem caused by harmonic loads. This robust impedance method also improves the power sharing performance during transient and grid fault. This virtual impedance method is proven effective to enhance the power sharing stability and to eliminate circulating currents between inverters. In [9]-[11], virtual impedance has been implemented in order to achieve accurate reactive power sharing when the line impedance between inverters is different. However, none of the aforementioned variations of virtual impedance has considered the case of varying line impedance during operations.

In some European countries, an estimation of grid impedance is a mandatory function for a photovoltaic (PV) system connected to the utility grid for islanding detection [12]. This requirement drew the academic attention toward grid impedance identification. In addition, the information on line impedance is useful for fault detection, grid unbalance detection, and control purposes. In [12], the authors presented a method to estimate line impedance using the variation of active and reactive powers dispatched by inverters. This method requires inducing the variation of both active and reactive powers manually and frequently, which is undesirable in a droop control system. An automated impedance estimation method has been introduced in [13] by using an optimization algorithm. Despite its good performance in line impedance estimation, this method suffers from high computational burden, and thus, it cannot be operated in real time. Another impedance estimation method using modal analysis theory has been proposed to calculate the line impedance in real time [14]. However, this method is too complicated and requires a lot of approximation and simplification during calculation process, which results in large errors in inductance calculation. In [15], a combination of the nonintrusive passive methods and the active methods has been employed to estimate the line impedance in microgrid. Even though the communication between inverters is not desirable, it is necessary to implement a communication system between each inverter and the PCC [16]. This communication system is beneficial for the implementation of multilevel control algorithm. In addition, the information on the PCC voltage can be obtained using this communication channel. This allows the control system to calculate the line impedance in real time with small computational resource and high accuracy.

This paper presents an adaptive virtual impedance based droop control scheme for parallel inverter operation in low voltage microgrid to ensure the power sharing performance even when the line impedance is subject to change. In the proposed method, the line impedance is first estimated in real time and the virtual impedance is adjusted accordingly to reflect the change in line impedance by the estimated value.

This paper is organized as follows. Section 2 discusses the standard structure of microgrid and the conventional virtual impedance based droop control scheme. Section 3 explains the proposed adaptive virtual impedance method as well as the estimation scheme of line impedance. In section 4, the simulation results conducted in Matlab/Simulinks environments is presented. Finally, this paper concludes in Section 5.

2. MICROGRID STRUCTURE AND CONVENTIONAL VIRTUAL IMPEDANCE BASED DROOP CONTROL

A typical structure of a microgrid is shown in Figure 1. Microgrid consists of DG systems and loads capable of operating with, or independently from, the main power grid. Microgrid is connected to the power grid at the PCC. However, when the fault occurs in the utility grid, microgrid is disconnected from the main power grid and is transferred to islanded mode. In this mode, microgrid supplies entire load demand in local area by distributing the total demand into each DG system according to its rated power. In addition, the least important load can be shutdown if microgrid is inadequate to supply the entire load demand in order to maintain the supply for critical ones.

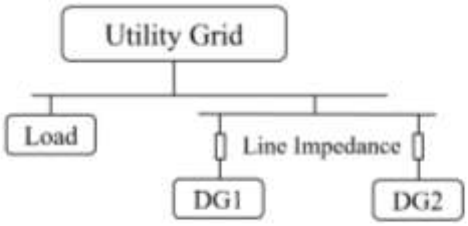


Figure 1. Schematic diagram of a microgrid

Droop control has been a popular method adopted for microgrid since it does not require any high bandwidth communication channel for control purposes. This is a very preferred feature in microgrid because the DG systems are often distributed in wide area. The main idea of the droop control comes from the self-regulation feature of the synchronous generator.

Figure 2 demonstrates a simplified model representing the connection of power converter to utility grid through transimision line with given impedance. In Figure 2(a), the grid-connected inverter is depicted as an ideal voltage source. According to this simplified diagram, the active and reactive powers transferred to the grid by a grid-connected inverter can be written as follows:

$$P_A = \frac{V_A}{R^2+X^2}\left[R\left(V_A - V_B\cos(\varphi_1-\varphi_2)\right) + XV_B\sin(\varphi_1-\varphi_2)\right] \quad (1)$$

$$Q_A = \frac{V_A}{R^2+X^2}\left[-RV_B\sin(\varphi_1-\varphi_2) + X\left(V_A - V_B\cos(\varphi_1-\varphi_2)\right)\right] \quad (2)$$

where P_A and Q_A are the active and reactive powers delivered from the inverter to the grid, respectively, V_A and V_B are the inverter output voltage and the PCC voltage, respectively, $Z_i = R + jX$ is the line impedance, and φ_3 is the current phase angle. The relation between V_A and V_B is depicted in phasor domain as shown in Figure 2(b). From (1) and (2), the phase angle and voltage are related with the active and reactive powers as

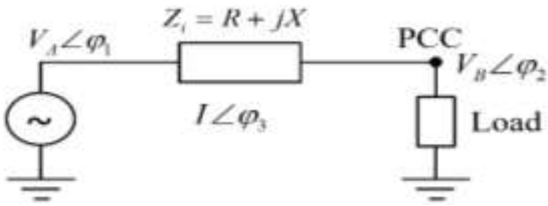
$$\sin(\varphi_1-\varphi_2) = \frac{XP_A - RQ_A}{V_A V_B} \quad (3)$$

$$V_A - V_B\cos(\varphi_1-\varphi_2) = \frac{RP_A + XQ_A}{V_A} \quad (4)$$

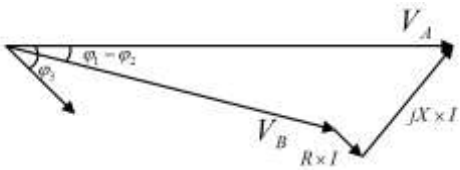
In practice, the most common case is that the line impedance of microgrid is purely inductive. In this case, it is reasonable to assume that the resistive part of the line impedance can be neglected. Furthermore, because the angle difference between the inverter output voltage and PCC voltage $(\varphi_1-\varphi_2)$ is very small, we can also assume $\sin(\varphi_1-\varphi_2)\approx\varphi_1-\varphi_2$ and $\cos(\varphi_1-\varphi_2)\approx 1$. From these assumptions, (3) and (4) are rewritten as

$$\varphi_1 - \varphi_2 = \frac{XP_A}{V_A V_B} \tag{5}$$

$$V_A - V_B = \frac{XQ_A}{V_A} \tag{6}$$



(a) Equivalent circuit



(b) Phasor diagram

Figure 2. Simplified model representing the connection of power converter to utility grid

As can be seen in (5) and (6), the active and reactive powers are dependent on the voltage difference and power angle $(\varphi_1 - \varphi_2)$. The active power can be controlled by adjusting the power angle. The reactive power can be also controlled by the inverter output voltage. From these relations, it is possible to regulate the active and reactive powers injected to the grid by controlling the magnitude and frequency of the inverter output voltage. This scheme permits the coordination between parallel-connected inverters in microgrid since it is possible to control the active and reactive powers of each individual inverter autonomously. The droop control laws for inductive line impedance can be expressed as follows:

$$f^* = f_n - k_P (P_{ref} - P_A) \tag{7}$$

$$v_{ref}^* = V_n - k_Q (Q_{ref} - Q_A) \tag{8}$$

where f^* is the reference frequency, f_n is the rated frequency of microgrid, k_P is the frequency droop coefficient, P_{ref} is the reference active power of inverters, v_{ref}^* is the reference voltage, V_n is the rated voltage of microgrid, k_Q is the voltage droop coefficient, and Q_{ref} is the reference reactive power of inverters.

Figure 3 demonstrates a general block diagram of the conventional droop control scheme to control an inverter as a grid-forming converter. In this figure, the power sharing controller consists of two steps. In the first step, the active and reactive powers dispatched by the inverter are calculated using the measured output voltages and currents. The information on the active and reactive powers is fed to the droop controller to produce the voltage and frequency references. The voltage and frequency references from the droop control scheme are used in the voltage regulator whose output is the current reference for the current regulator.

In the ideal condition, the conventional droop control in Figure 3 provides good power sharing performance between parallel inverters. However, in practice, the line impedances between inverters and the PCC are different. This mismatch results in the unbalanced reactive power sharing. In order to solve this problem, it is intuitive to introduce physical impedance in each inverter to balance the mismatch. However, this solution is not viable since it increases the size and cost of the whole systems. A more efficient solution is to implement virtual impedance instead of physical impedance.

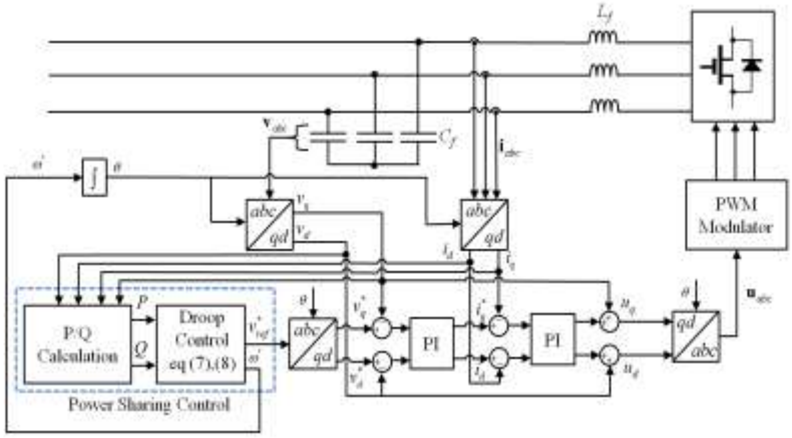


Figure 3. Block diagram of the conventional droop control

Virtual impedance method is based on the idea of including the effect of physical impedance virtually into the control structure. In the virtual impedance method, new reference value for the voltage regulator is obtained using that of the conventional droop control scheme as follows:

$$v_{ref} = v_{ref}^{*} - Z_{vi}.i_o \tag{9}$$

where v_{ref} is new reference value fed to the voltage regulator, i_o is the inverter output current, and Z_{vi} is the virtual impedance. The block diagram of the virtual impedance based droop control is shown in Figure 4. When the effect of virtual impedance is included in the control structure, the equivalent line impedance of inverters can be obtained as follows:

$$Z_{eq} = Z_{vi} + Z_i \tag{10}$$

where Z_i is the physical line impedance and Z_{eq} is the equivalent line impedance.

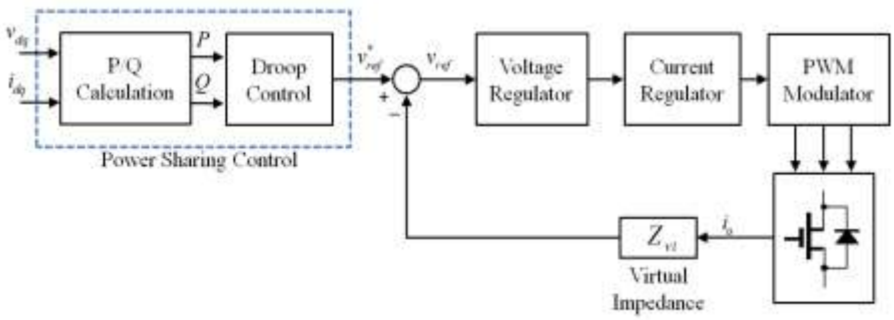


Figure 4. Block diagram of the virtual impedance scheme

3. ADAPTIVE VIRTUAL IMPEDANCE METHOD USING LINE IMPEDANCE ESTIMATION

In order to implement an adaptive virtual impedance method, an estimation scheme for the line impedance is required by using the information on the PCC voltage. As pointed out in [16], the communication channel between inverters and PCC allows the controller of the parallel-connected inverters to obtain the crucial information for calculation of line impedance.

One-phase phase-locked loop (PLL) is implemented at the PCC to determine the magnitude and frequency of the PCC voltage. The obtained outputs of the PLL are transmitted to the controller of the individual inverter. The cost of implementing one-phase PLL is not high since it requires only one voltage sensor at the PCC. In addition, it can be realized with small computational effort and reasonable accuracy [17].

Figure 5 illustrates the detection scheme of the PCC voltage and phase angle using one-phase PLL by measuring one-phase voltage. The outputs of the PLL algorithm are the phase angle φ_2 and the magnitude of voltage V_q at the PCC which are used in the estimation scheme for the line impedance. Using the obtained information on the PCC, the line impedance between the inverter and the PCC can be calculated as follows:

$$Z\angle\theta = \frac{V_A\angle\varphi_1 - V_B\angle\varphi_2}{I\angle\varphi_3} \quad (11)$$

where $V_A\angle\varphi_1$ is phasor expression for the inverter output voltage, $V_B\angle\varphi_2$ is phasor expression for the PCC voltage with $V_B = V_q$, $I\angle\varphi_3$ is phasor expression for the current in transmission line, and $Z\angle\theta$ is the line impedance. Since all the variables are available at individual inverter controller, the impedance estimation scheme can be easily executed in real-time with low computational efforts.

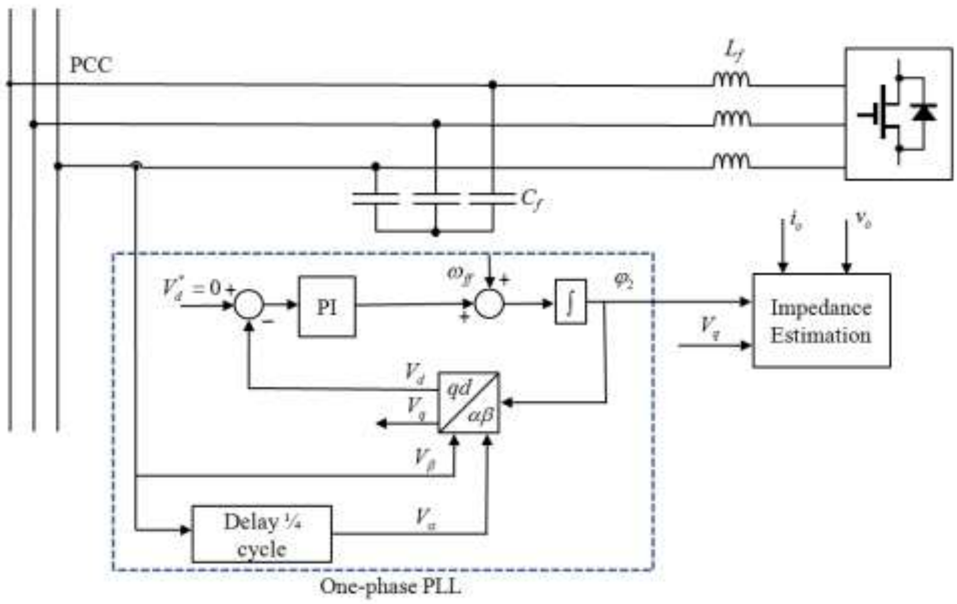


Figure 5. Detection of PCC voltage and phase angle using one-phase PLL method

Main disadvantage of the conventional virtual impedance based droop control is that it cannot share the reactive power properly when the line impedances are changed during operation. This gives rise to the need of a control scheme that can achieve accurate reactive power sharing even when the line impedance changes. In order to accomplish such a goal, the equivalent line impedance between inverters and PCC are kept constant. In the proposed adaptive virtual impedance scheme, the virtual impedance parameters of each inverter are adjusted according to the physical line impedance as follows:

$$v_{ref} = v_{ref}^* - Z_{vi}.i_o \quad (12)$$

$$Z_{vi} = Z_{eq} - Z_i \quad (13)$$

Even when the line impedance is changed during operation, the proposed scheme ensures a proper reactive power sharing by adjusting the virtual impedance value according to the variation in line impedance.

Since the estimation scheme of the line impedance is fast and simple, the impedances change can be estimated and compensated in real time. Figure 6 shows the complete block diagram of the proposed adaptive virtual impedance based droop control scheme.

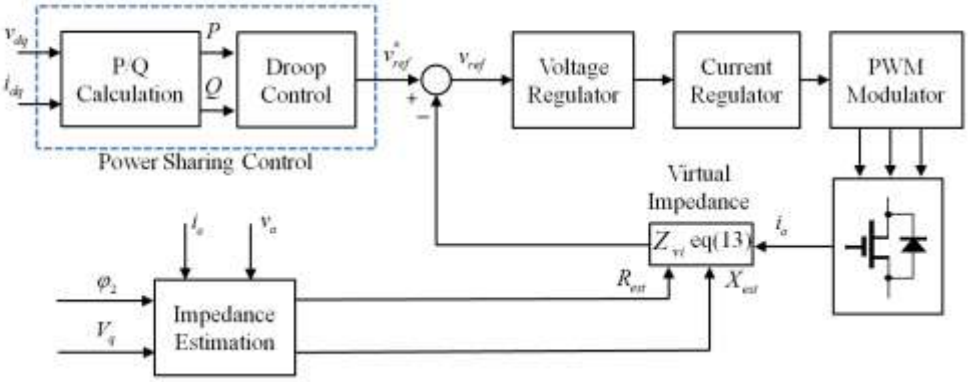


Figure 6. Block diagram of the proposed adaptive virtual impedance based droop control scheme

4. SIMULATION RESULTS

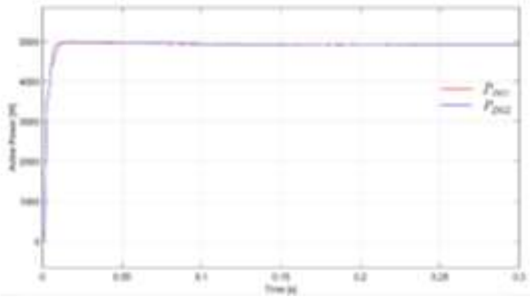
In order to evaluate the performance of the proposed adaptive virtual impedance based droop control strategy, the simulations have been carried out on the Matlab/Simulink environment for a system consisting of two parallel-connected inverters. The system parameters for simulation are given in Table 1.

Table 1. Simulation parameters for DG system consisting of parallel inverters

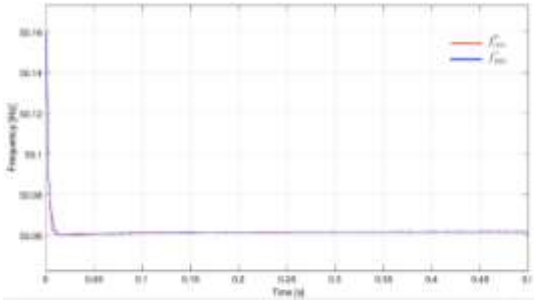
Nominal active power P_n	8 kW
Nominal reactive power Q_n	200 Var
Frequency droop coefficient k_P	-2×10^{-5}rad/W
Voltage droop coefficient k_Q	-5×10^{-4}V/Var
DC link voltage	800 V
PCC voltage	380 V (line-to-line)
Line impedance	0.642Ω, 0.46mH
Equivalent line impedance	0.7+*j*0.25 Ω
Switching frequency	10kHz

Figure 7 shows the simulation results of the conventional droop control scheme under the case that there is no difference in line impedance between inverters. As is shown in Figure 7(a) and Figure 7(c), both the active and reactive powers of two DG systems injected to the grid are equally shared. Figure 7(b) and Figure 7(d) denote the frequency reference and voltage reference in both inverters, respectively. These reference values are produced by the droop control scheme and the active and reactive powers delivered to the grid can be effectively regulated by changing these reference values. Beside good power sharing performance, the control structure also shows good results in view of the output voltages and output currents as illustrated in Figure 7(e). When the power is properly shared among inverters, the circulating currents between inverters are small and negligible as indicated in Figure 7(f).

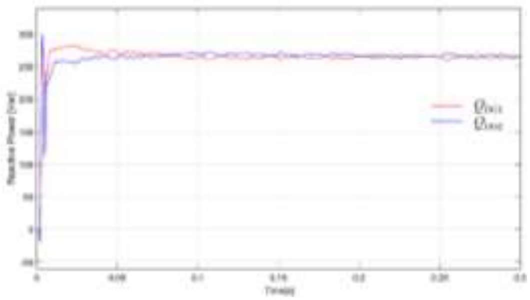
Figure 8 shows the performance of the conventional droop control scheme based on the virtual impedance method when the line impedances of each inverter are different. Figure 8(a) clearly demonstrates that the reactive powers dispatched by each inverter converge to the same values after small transient period. In addition, as is shown in Figure 8(b), the active power injected to the grid is almost unaffected by the difference in line impedance. To examine the performance of the virtual impedance based droop control method under line impedance change during operations, the line impedance is changed at t=0.4s. At the beginning, the line impedance values of both the two inverters are 0.642+*j*0.11Ω. However, the line impedance in DG1 inverter is changed to 0.642+*j*0.22Ω at 0.4s while that of DG2 inverter is kept to the same value.



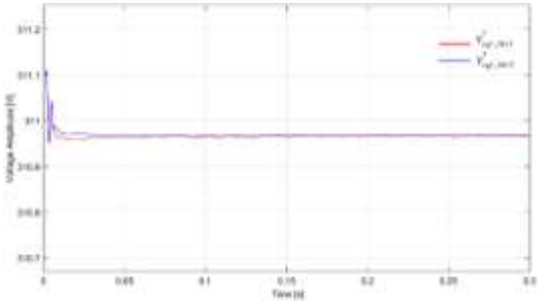
(a) Active power sharing characteristics



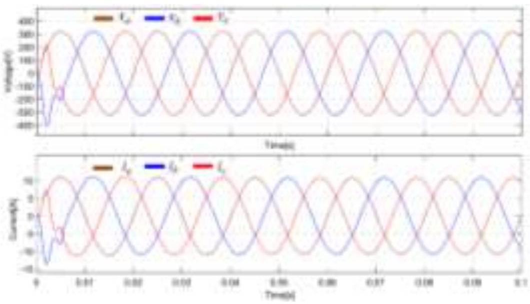
(b) Frequency reference produced by droop control



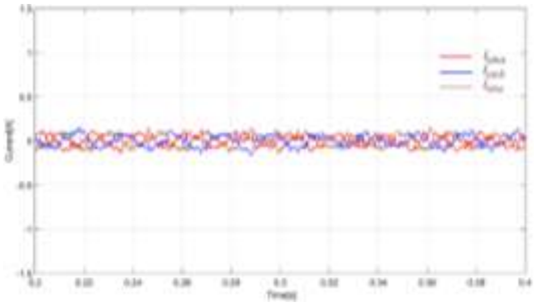
(c) Reactive power sharing characteristics



(d) Voltage reference produced by droop control



(e) Three-phase output voltages and currents

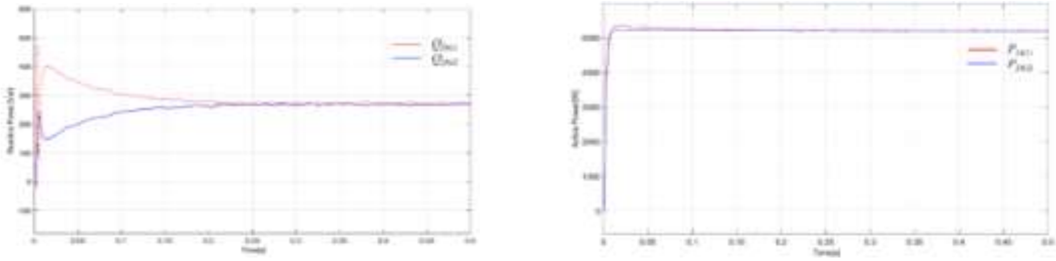


(f) Circulating currents

Figure 7. Performance of the conventional droop control scheme

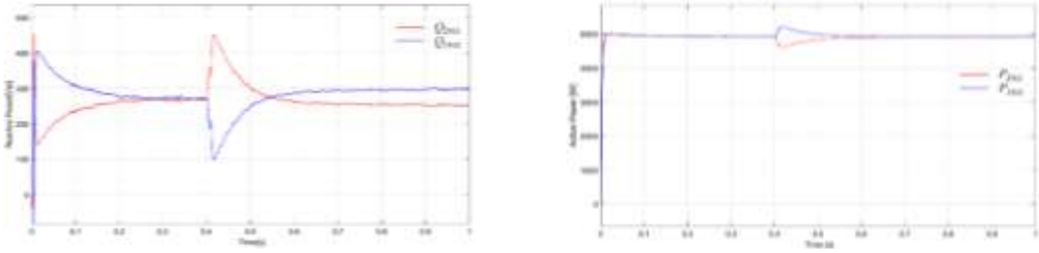
Figure 9 shows the simulation results for this case. Except for the line impedance change, the other simulation conditions are the same as Figure 8. It is clear from Figure 9(a) that the reactive powers in both inverters quickly converge to the same value before the change in line impedance is introduced, which is well consistent with the results in Figure 8. However, as soon as the line impedance is changed at 0.4s, both inverters do not share the reactive powers well as shown in Figure 9(a), which clearly shows the weakness of the virtual impedance based droop control method. Unlike the reactive power characteristics, the active power sharing is unaffected by the change in line impedance. Even if a small discrepancy in the active power sharing is observed only during transient periods due to the change in line impedance, two active powers are quickly maintained to the same value.

The power sharing performance of the proposed droop control scheme under line impedance change is shown in Figure 10. Similar to the previous cases, the change in line impedance does not affect the performance of the active power sharing as can be seen in Figure 10(b). Though a small perturbation is observed in the active power characteristics, it quickly recovers to the desired performance. The effectiveness of the proposed method is confirmed in Figure 10(a). Before the line impedance change, the reactive powers of two DG inverters are equally shared. Even when the change in line impedance is introduced, the proposed scheme shows a good behavior in the reactive power sharing of the system after temporary fluctuation during transient periods. These simulation results prove the superiority of the proposed method over the conventional virtual impedance scheme.



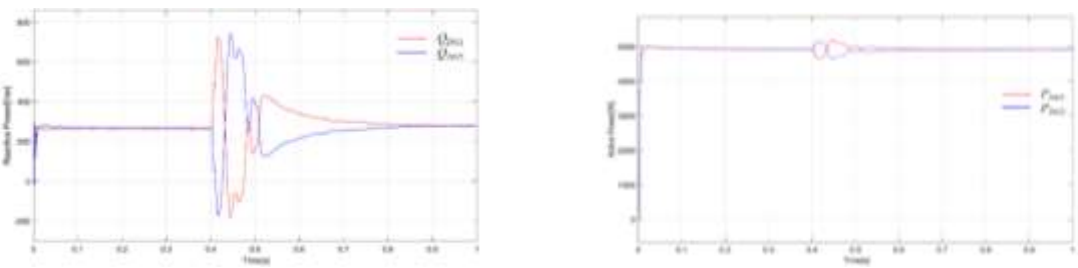
(a) Reactive power sharing characteristics (b) Active power sharing characteristics

Figure 8. Performance of the conventional virtual impedance based droop control scheme



(a) Reactive power sharing characteristics (b) Active power sharing characteristics

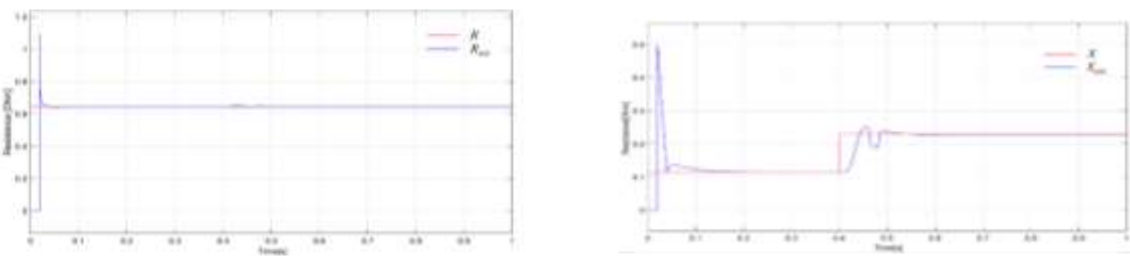
Figure 9. Performance of the conventional virtual impedance based droop control method under line impedance change at 0.4s



(a) Reactive power sharing characteristics (b) Active power sharing characteristics

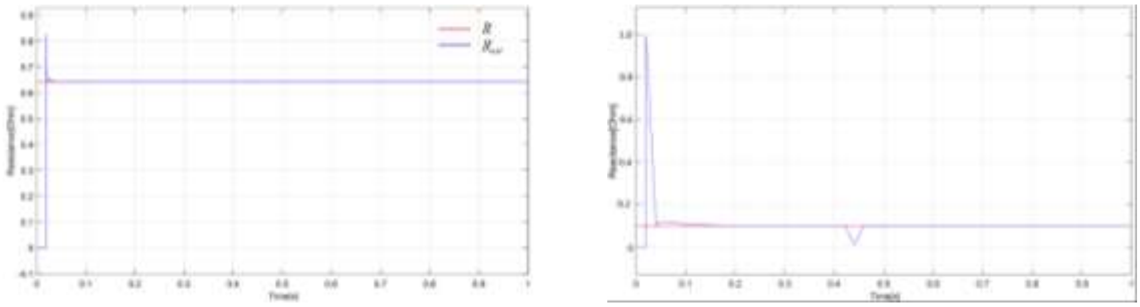
Figure 10. Performance of the proposed method under line impedance change at 0.4s

Figure 11 and Figure 12 show the estimating performance of line impedance in each DG inverter, respectively, when the reactance component of the impedance in DG1 inverter is changed at 0.4s. As can be seen in Figure 11(b), the estimation process is accomplished within 0.55s, reaching the steady-state value precisely. While this transient estimation period causes temporary fluctuation in reactive power sharing characteristics, a proper sharing in reactive power between DG inverters can be achieved by the proposed adaptive virtual impedance based droop control scheme at steady-state.



(a) Resistance estimation (b) Reactance estimation

Figure 11. Estimating performance of line impedance in DG1 inverter



(a) Resistance estimation (b) Reactance estimation

Figure 12. Estimating performance of line impedance in DG2 inverter

5. CONCLUSIONS

To guarantee a proper power sharing performance between DG inverters in low voltage microgrid, this paper has proposed an adaptive virtual impedance based droop control scheme for parallel inverter operation. Even though a proper power sharing is an essential function in DG inverters operated in microgrid, the conventional droop control schemes do not fulfill this requirement successfully in the presence of the change in line impedance between inverters and PCC. Especially, the reactive power mismatch is severe under the variation of line impedance during operation. To overcome this limitation, the proposed scheme estimates the line impedance, which is employed in the virtual impedance method to adaptively adjust the line impedance value. The proposed scheme allows the parallel-connected inverter system to detect and compensate the change in line impedance in real-time. Even when the line impedance is varied during operation in microgrid, a good reactive power sharing performance can be obtained since the estimation scheme can immediately detect the change in line impedance. To validate the effectiveness of the proposed adaptive droop control strategy, the simulations have been accomplished on the Matlab/Simulink environment for two parallel-connected inverters. It has been proved from the comparative simulation results that the proposed method is superior in comparison to the conventional droop control as well as the virtual impedance based droop control. The proposed method can completely eliminate the imbalance in reactive power sharing caused by the difference in line impedance. In addition, it adapts to the change of line impedance in real-time, which yields a preferred feature of DG systems because it does not need human intervention.

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