

Voltage Unbalance and Harmonic Compensation through Distributed Generation with Virtual Impedance Control in Islanded Microgrid

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Abstract

Original Research Article

The power sharing and voltage quality are more challenging in islanded microgrids with the unbalance or nonlinear loads. Distributed generations (DGs) can be used to improve the power quality in the microgrids. However, when multiple DGs are participated for the voltage unbalance or harmonic compensation, conventional droop control can cause poor power sharing among the DGs due to mismatched line impedance. This paper proposes a control method of the virtual impedance for proportional sharing of the unbalance or harmonic power. The virtual unbalance or harmonic impedance is adaptively controlled for decreasing of the unbalance or harmonic power sharing error among the DGs. Consensus algorithm is adopted for the adaptive control of the virtual impedance. This method does not require the prior knowledge of the line impedance. Simulation results are presented to validate the proposed method for proportional sharing of unbalance or harmonic power with reducing the unbalance or distortion of voltage at point of common coupling (PCC).

Keywords: Microgrid, Distributed generation, unbalance power sharing, harmonic power sharing, Distributed control, Virtual impedance.

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1. Introduction

Distributed generation (DG) using renewable energy has attracted attention and has been widely applied in many countries around the world [1, 2]. In order to fully exploit the advantages of DG, it is necessary to control a microgrid with the DGs, power storage devices and loads [3, 4].

Nowadays, the use of large amounts of the power electronic devices and unbalance loads in a grid severely degrades the power quality, whereas the load side users have a higher demand for the power quality [22, 23]. Therefore, it is necessary to improve the power quality using passive and active filters. On the other side, the DG system in the microgrid has a similar structure to the static synchronous compensator (STATCOM), so power quality control

can be achieved by rational control of the DG inverter without additional investment [5, 6].

A droop control technique has been proposed to facilitate power sharing without communication between the DGs in the islanded microgrid [7]. The droop control method can result in instability of the control due to coupling between active and reactive power control in the microgrid. Moreover, the active power sharing can be solved exactly, but the reactive power cannot be shared due to the mismatched line impedance [8, 9]. To solve this, the concept of virtual impedance has been developed. By creating a static virtual impedance to the inverter controller, the equivalent line impedance become inductive, which eliminates the coupling between active and reactive power and provides an accurate proportional sharing



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of reactive power as well as active power.

In addition, various types of power sharing using virtual impedance and virtual admittance have been proposed to improve power quality. However, the aforementioned methods have good performance when the value of line impedance is accurately detected [7, 13].

In practice, it is difficult to measure the value of the line impedance exactly, it is necessary to apply the virtual impedance to accurately share the load power without knowing the value of the line impedance. A centralized control method using low-bandwidth communication has been proposed to accurately share power proportionally. In [12], voltage unbalance and harmonic compensation by centralized control is proposed to share unbalance and harmonic power between the DGs accurately. However, if the communication lines or the centralized controller is failure, there is a disadvantage of very low flexibility and reliability due to the inability to control the microgrid [23, 27].

In recent years, distributed control systems based on consensus algorithm have been studied in various research fields [13,15] and have been applied to solve the above problems in microgrid. In [15], a distributed control method based on a consensus algorithm was used to adaptively control the virtual impedance at fundamental frequency for accurate reactive power sharing. However, it has not been considered for adaptive control of the fundamental negative-sequence virtual impedance or the harmonic virtual impedance under the existence of unbalance or nonlinear loads [25].

The scope of study presented is the development of distributed virtual impedance controller able to proportionally share the unbalance and harmonic power among the DGs, under the mismatched condition of the line.[20, 21]

The main contribution of this paper can be summarized as follows:

First, the concrete principle of voltage unbalance and harmonic compensation is presented and then the method of voltage unbalance and harmonic

compensation using the virtual impedance is proposed.

Secondly, a consensus algorithm-based distributed control is proposed to adaptively adjust not only the fundamental positive-sequence but also the negative-sequence and harmonic virtual impedance according to the power sharing error.

The proposed method can accurately share the unbalance and harmonic power as well as the fundamental reactive power, without knowing the value of the line impedance in the microgrid with both unbalance and nonlinear loads.

The reminder of this paper is organized as follows.

Section 2 presents the principle of voltage unbalance and harmonic compensation, the voltage unbalance and harmonic compensation by virtual impedance are proposed in Section 3, and the distributed control method based on consensus algorithm is proposed for virtual impedance control in Section 4. Section 5 analyzes the simulation results and Section 6 concludes the proposed method.

2. Principle of Voltage Unbalance and Voltage Harmonic Compensation

In the study about voltage unbalance and harmonic compensation problem of microgrid, the unbalance and nonlinear loads can be considered as unbalance and harmonic current sources, respectively [16, 19]. Generally, the DG supplies only fundamental active and reactive power to the load.

First, consider the principle of voltage harmonic compensation. Generally, the DG supplies the load with fundamental active and reactive power. In other words, the droop controller of the DG has power control by the fundamental voltage and current, so the harmonic output voltage ($u_{DG,k}$) of the DG is zero even if a nonlinear load exists in the microgrid. However, in order to compensate the voltage harmonic of PCC through the DG, it is necessary to design so that the harmonic power required to compensate the voltage ($u_{DG,k}$) at the PCC is not zero.

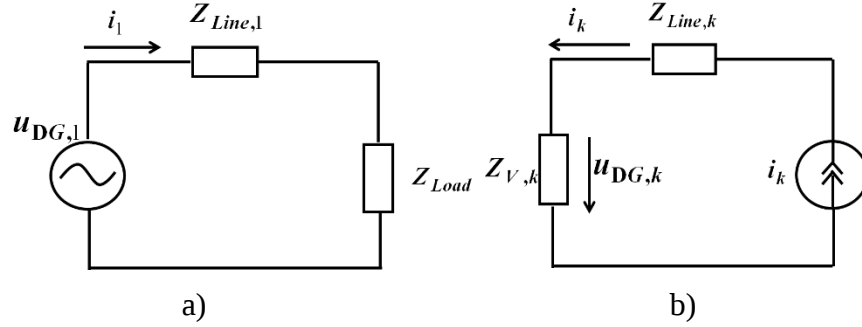


Fig 1. Equivalent circuit of the DG with linear load only (a) and nonlinear load only (b)

The equivalent circuits of the DG with linear load only and with nonlinear load only are shown as Fig. 1, where the subscript “1” denotes the fundamental components, “k” denotes the harmonic components. As shown in Fig. 1, in the case of linear load only, the DG is considered as the fundamental voltage source, meanwhile in the case of nonlinear load only, the DG and the nonlinear load are considered as the load and the current source.

Under the linear and non-linear load conditions, the output voltage of the DG is expressed by

$$u_{DG} = u_{DG,1} + \sum_{k=2}^{\infty} u_{DG,k} = \sqrt{2}E_1 \sin(\omega^* t + \theta_1) + \sum_{k=2}^{\infty} \sqrt{2}E_k \sin(k\omega^* t) \quad (1)$$

where $u_{DG,1}$ -fundamental voltage of the DG, $u_{DG,k}$ - k^{th} harmonic voltage of the DG, ω^* -fundamental rating angle frequency,

E_1 -fundamental reference voltage, E_k - k^{th} harmonic reference voltage, θ_1 -initial phase of fundamental voltage of the DG

On the other hand, the voltage of the PCC can be written as

$$u_{PCC} = u_{PCC,1} + \sum_{k=2}^{\infty} u_{PCC,k} = \sqrt{2}E_{PCC,1} \sin(\omega^* t) + \sum_{k=2}^{\infty} \sqrt{2}E_{PCC,k} \sin(k\omega^* t + \delta_k) \quad (2)$$

Where $u_{PCC,1}$ -fundamental voltage at the PCC, $u_{PCC,k}$ - k^{th} harmonic voltage at the PCC, δ_k -initial phase of k^{th} harmonic voltage

Then, the harmonic current generated by the nonlinear load can be written as

$$i = \sum_{k=1}^{\infty} i_k = \sqrt{2}I_k \sin(k\omega^* t + \phi_k) \quad (3)$$

When the output voltage of the DG contains harmonic component, the voltage balance of the microgrid expressed by complex number at k harmonic is

$$\begin{aligned} \dot{U}_{PCC,k} &= (-\dot{U}_{DG,k}) + \dot{I}_k Z_{Linek} = (-E_k e^{k\omega^* t + \theta_k}) + I_k e^{k\omega^* t + \phi_k} Z_{Linek} e^{j\varphi_k} \\ &= (-E_k e^{k\omega^* t + \theta_k}) + I_k Z_{Linek} e^{k\omega^* t + \phi_k + \varphi_k} \end{aligned} \quad (4)$$

Where φ_k -the phase difference between voltage and current at the line

In the Eq. 4, the negative sign of $\dot{U}_{DG,k}$ means that the additional harmonic voltage generated by the DG is opposite direction in phase with the harmonic voltage at the PCC.

If the harmonic voltage $u_{DG,k}$ added to the droop controller output voltage of the DG is obtained to be equal to the harmonic voltage drop at the line $Z_{line,k}$, the harmonic voltage present at the PCC voltage can be eliminated. In other words, when the internal harmonic impedance $Z_{V,k}$ of the DG becomes equal to the line harmonic impedance $Z_{line,k}$ connected by the DG and the phase is reversed, the equivalent harmonic impedance of the line becomes zero so that the harmonic voltage of the PCC can be completely compensated. To eliminate the harmonic voltage at the PCC, the harmonic voltage added to the reference voltage of the DG inverter can be written as

$$u_{DG,k} = \sqrt{2}E_k \sin(k\omega^*t) = \sqrt{2}I_k Z_{Line,k} \sin(k\omega^*t) \quad (5)$$

In the presence of an unbalance load in the microgrid, similar to the method to compensate the voltage harmonic, the voltage unbalance at the PCC is compensated by adding a voltage equal in magnitude and opposite in phase to the fundamental negative-sequence voltage drop at the line to the fundamental reference voltage of the DG.

Then, the unbalance voltage of the output of the DG inverter is

$$u_{DG,1}^- = \sqrt{2}E_1^- \sin(-\omega^*t) = \sqrt{2}I_1^- Z_{Line,1}^- \sin(-\omega^*t) \quad (6)$$

In the following section, we describe a virtual impedance control method to reduce the voltage unbalance and harmonic at the PCC using these compensation principles.

3. Voltage Unbalance and Harmonic Compensation Method by Using Virtual Impedance

3.1. Unbalance and Harmonic Droop Control

The DGs can be used to compensate the voltage unbalance and harmonic due to the unbalance or nonlinear loads in the microgrids. When multiple DGs are participated to compensate the voltage unbalance or harmonic, in similar to the conventional droop control, the unbalance and harmonic droop control methods can be adopted as follows [19]:

$$E_{1,i}^- = -n_{1,i}^- \cdot Q_{1,i}^- \quad (7)$$

$$E_{k,i} = -n_{k,i} \cdot Q_{k,i} \quad (8)$$

Where $Q_{1,i}^-$, $Q_{k,i}$ -the fundamental negative-sequence and k^{th} harmonic powers generated by from the i^{th} DG, $n_{1,i}^-$, $n_{k,i}$ -the voltage droop control coefficients for the fundamental negative-sequence and k^{th} harmonic of i^{th} DG

In order to proportionally share the unbalance and harmonic power required for the compensation according to the rated power between the DGs, the equivalent fundamental negative-sequence and harmonic impedances of the DG must be designed to be inversely proportional to the rated power, respectively [17].

$$X_{eq1,1}^- \cdot Q_{1,1}^- = X_{eq1,2}^- \cdot Q_{1,2}^- = \dots = X_{eq1,N}^- \cdot Q_{1,N}^- \quad (9)$$

$$X_{eqk,1} \cdot Q_{k,1} = X_{eqk,2} \cdot Q_{k,2} = \dots = X_{eqk,N} \cdot Q_{k,N} \quad (10)$$

Where $X_{eq1,i}^-$ -the equivalent fundamental negative-sequence inductive reactance of i^{th} DG, $Q_{1,i}^-$ -the reference unbalance power of i^{th} DG, $Q_{k,i}$ -the reference harmonic power of i^{th} DG.

3.2. Virtual Impedance Control Method

Fig 2 shows the relationship between the droop characteristic of one DG and the voltage drop at the line impedance. In Fig.2, the blue line means U - Q droop characteristic and the red line means the voltage drop at the line impedance. As shown in Fig.2, the PCC voltage is related to the no-load voltage E , droop coefficient n_1 of the DG and the line impedance Z_1 .

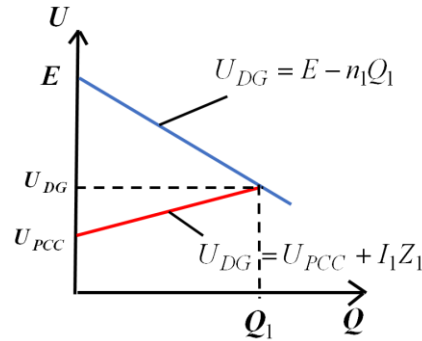


Fig 2. Droop characteristic of one DG with consideration of the line impedance

Under the mismatched condition of the line, the problem facing on the power sharing in the microgrid including multiple DGs is for the load power not to be shared according to the rated power of DGs but according to the value of the line impedance of corresponding DGs.

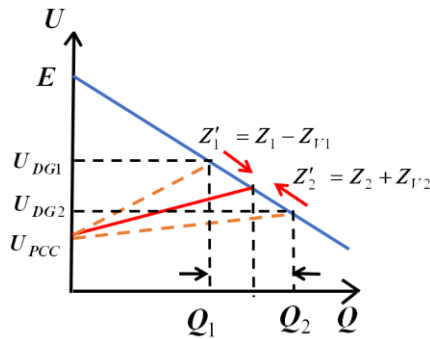


Fig 3. Fundamental reactive power sharing principle between two DGs

Fig. 3 shows the principle of fundamental reactive power sharing under the assumption of two DGs with the same rated power.

As shown Fig. 3, before the adopt of virtual impedance, the power sharing between the two DGs is different each other (the dot red line of Fig. 3), but after the adopt of virtual impedance, the power is equal shared between the two DGs (the red line of Fig. 3).

Fig. 4 shows the principle of the voltage compensation of one DG and the unbalance power sharing between two DGs with the same rated power. In Fig. 4a, the reference voltage of the DG is controlled to have the minus value for the unbalance voltage of the PCC to become zero. Also, as shown in Fig. 4b, the unbalance equivalent line

impedances z'_1 and z'_2 become equal by controlling of added virtual impedances z_{V1} and z_{V2} . Consequently, the unbalance powers Q_1^- and Q_2^- are equally shared between two DGs.

In similar, the harmonic power can be proportionally shared by controlling the harmonic virtual impedance.

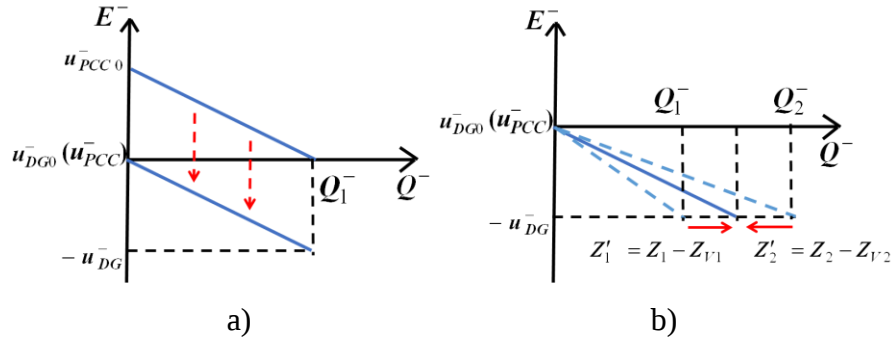


Fig 4. Principle of the PCC voltage unbalance compensation and the unbalance power sharing.

a) the PCC voltage unbalance compensation b) the unbalance power sharing.

In practice, because the values of the line impedance connecting the DGs to the microgrid are different each other, Eq. 9 and Eq. 10 are not satisfied and consequently the mismatch of these line impedance affects the unbalance and harmonic power sharing, resulting in the fundamental negative-sequence and harmonic circulating currents. To overcome this problem, a method of adjusting the equivalent line negative-sequence and harmonic impedances is proposed, where the fundamental negative and harmonic virtual impedances are added into the local controller of the DGs.

The equivalent line impedances, including the line impedance and the virtual impedance in the DG, can be written for fundamental negative-sequence and harmonic as follows:

$$X_{eq1,i}^- = X_{Line1,i}^- + X_{V1,i}^- \quad (11)$$

$$X_{eqk,i} = X_{Linek,i} + X_{Vk,i} \quad (12)$$

Where $X_{Line1,i}^-$, $X_{Linek,i}$ -the inductive reactance of the line at the fundamental negative-sequence and k^{th} harmonic of the i^{th} DG, respectively. $X_{V1,i}^-$, $X_{Vk,i}$ -the virtual inductive reactance at fundamental negative-sequence and k^{th} harmonic of the i^{th} DG, respectively.

If the rated power of all DGs are the same and the virtual impedances added to the local controller are adjusted to equalize the equivalent negative-sequence and harmonic impedances of the line, the unbalance and harmonic power are equally shared so that the unbalance and harmonic circulating currents are eliminated.

In order to obtain the same equivalent negative-sequence and harmonic impedances under the mismatched line impedance, the value of the line should be accurately measured. Then the virtual negative-sequence and harmonic virtual impedances can be regulated for the equivalent impedances to be the same. However, in practice, because it is difficult to accurately measure the value of the line impedance, the virtual impedance cannot be regulated for satisfying Eq. 9 and Eq. 10. Accordingly, the virtual impedance should be adaptively regulated according to the power sharing error regardless the prior knowledge of the line impedance.

4. Distributed Control of Virtual Negative-Sequence and Harmonic Impedances using Consensus Algorithm

Since it is difficult to measure the line impedance accurately in practice and the control objective is the proportional sharing of reactive power, the virtual impedance must be adaptively controlled based on the reactive power generated each DG. As mentioned above, it is necessary to share the information of each DG in order to share the reactive power proportionally, which is realized in this paper by distributed control rather than a low-reliability centralized control. Considering each DG as an agent, the communication layer between the DGs in the distributed control architecture can also be represented by a directed graph like the structure model of the microgrid.[26, 27]

Applying the graph theory in [14, 24], the amount of the negative-sequence power from each DG is denoted by Q_i^- and the controller receives the information from neighboring DGs as low-bandwidth communication and updates it to the following value.

$$n_{1,i}^- \dot{Q}_{1,i}^- = - \sum_{j \in N_i} a_{ij} (n_{1,i}^- Q_{1,i}^- - n_{1,j}^- Q_{1,j}^-) \quad (13)$$

Where a_{ij} -element showing the connectivity of each DGs in the neighborhood matrix.

To analyze the above equation, the weight factor $w_{ij} = \frac{a_{ij}}{\sum_{k=1}^N a_{ik}}$ is defined as

$$\tau_i (n_{1,i}^- \dot{Q}_{1,i}^-) = -n_{1,i}^- Q_{1,i}^- + \sum_{j \in N_i} w_{ij} (n_{1,j}^- Q_{1,j}^-) \quad (14)$$

Where $\tau_i = \frac{1}{\sum_{j=1}^N a_{ij}}$, $w_{ij} > 0$, $\sum_{j=1}^N w_{ij} = 1$

From Eq. 14, the negative-sequence power Q_i^- approaches the weighted average of the adjacent negative-sequence powers Q_j^- with a weighting factor w_{ij} with a time constant equal to τ_i .

Adaptive control of virtual negative-sequence impedances also collects local information about unbalance powers of adjacent DGs, using the consensus control theory of multi agent system(MAS), such as the distributed virtual impedance control in the fundamental positive-sequence described in Section 3.

Then, the unbalance power sharing error between the DGs can be expressed as

$$e_{1,i}^- = \sum_{j \in N_i} a_{ij} (n_{1,i}^- Q_{1,i}^- - n_{1,j}^- Q_{1,j}^-) \quad (15)$$

Similarly, the harmonic power sharing error between the DGs can be expressed as

$$e_{k,i} = \sum_{j \in N_i} a_{ij} (n_{k,i} Q_{k,i} - n_{k,j} Q_{k,j}) \quad (16)$$

The unbalance and harmonic power sharing errors obtained using Eq. 15 and Eq. 16 input to the proportional-integral (PI) controller. Then the correction terms NQ_i and HQ_i of the negative-sequence and harmonic virtual impedances are obtained from PI controller as follows:

$$NQ_i = -\left(k_{pNQ} + \frac{k_{iNQ}}{s}\right)e_{1,i} \quad (17)$$

$$HQ_i = -\left(k_{pHQ} + \frac{k_{iHQ}}{s}\right)e_{k,i} \quad (18)$$

Where k_{pNQ} , k_{iNQ} -proportional and integral coefficients of PI controller for the unbalance power sharing error compensation, respectively, k_{pHQ} , k_{iHQ} -proportional and integral coefficients of PI controller for the harmonic power sharing error compensation, respectively. NQ_i , HQ_i -correction terms of the fundamental negative-sequence and k^{th} harmonic controlled according to the unbalance and harmonic power sharing errors in the i^{th} DG, respectively.

Thus, the negative-sequence and harmonic impedances are adaptively adjusted to eliminate the unbalance and harmonic power sharing error by the correction term (NQ_i , HQ_i) obtained by Eq. 17 and Eq. 18.

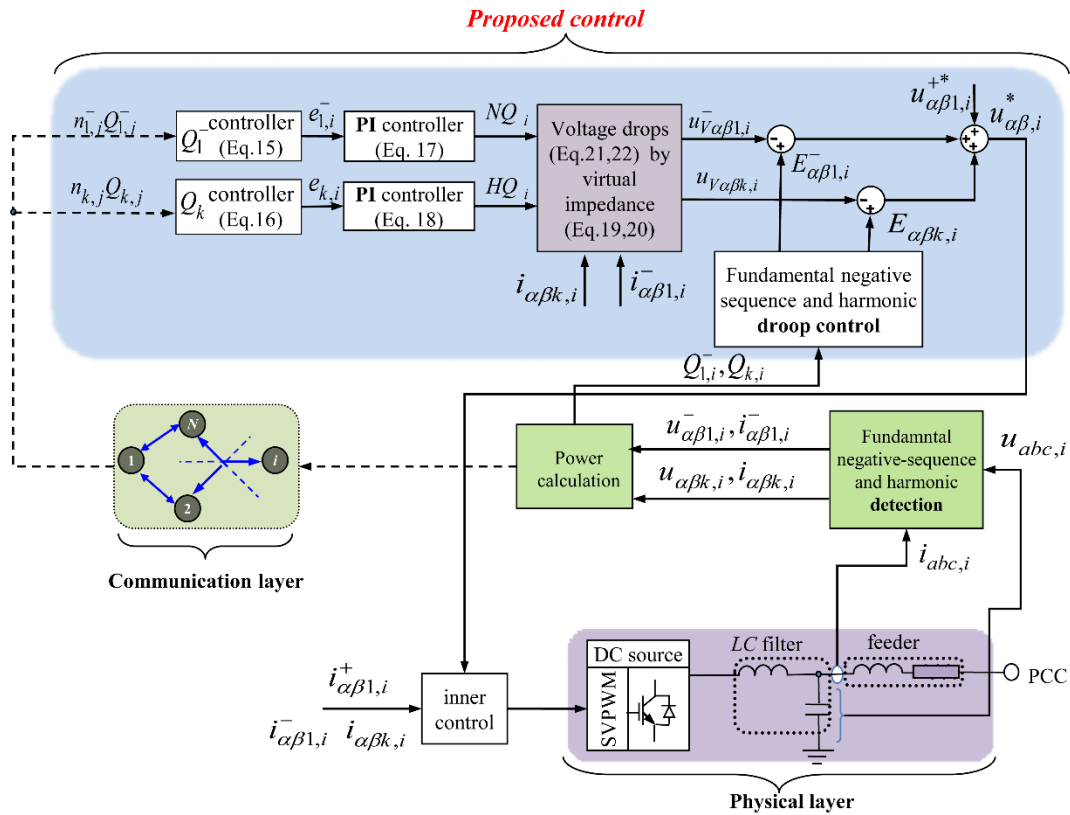


Fig. 5 Block diagram for proposed distributed control

To adaptively adjust the virtual negative-sequence and harmonic impedances of the DGs according to the unbalance and harmonic power sharing error, correction terms (NQ_i , HQ_i) of the fundamental negative-sequence and k^{th} harmonic are reflected the negative-sequence and harmonic virtual impedances as follows:

$$X_{V1,i}^- = X_{V1,i}^{-*} + \Delta X_{V1,i}^- = (-\omega^*)(L_{V1,i}^{-*} - k_{1,i}^- NQ_i) \quad (19)$$

$$X_{Vk,i} = X_{Vk,i}^* + \Delta X_{Vk,i} = k\omega^*(L_{Vk,i}^* - k_{k,i} HQ_i) \quad (20)$$

Where $X_{V1,i}^{-*}$, $X_{Vk,i}^*$ -static virtual inductive reactance for fundamental negative-sequence and k^{th} harmonic of the i^{th} DG, respectively, $\Delta X_{V1,i}^-$, $\Delta X_{Vk,i}$ -variable virtual inductive reactance for fundamental negative-sequence and k^{th} harmonic of the i^{th} DG, respectively. $L_{V1,i}^{-*}$, $L_{Vk,i}^*$ -static virtual inductive reactance for fundamental negative-sequence and k^{th} harmonic of the i^{th} DG, respectively. $k_{1,i}^-$, $k_{k,i}$ - proportionality factor to adjust the fundamental negative-sequence and the virtual impedance at the k^{th} harmonic of the i^{th} DG, respectively.

The voltage drops in the controller using the above virtual impedances can be expressed as follows

$$\begin{bmatrix} u_{V\alpha1,i}^- \\ u_{V\beta1,i}^- \end{bmatrix} = \begin{bmatrix} R_{V1,i}^- & -X_{V1,i}^- \\ X_{V1,i}^- & R_{V1,i}^- \end{bmatrix} \begin{bmatrix} i_{\alpha1,i}^- \\ i_{\beta1,i}^- \end{bmatrix} \quad (21)$$

$$\begin{bmatrix} u_{V\alpha k,i} \\ u_{V\beta k,i} \end{bmatrix} = \begin{bmatrix} R_{Vk,i} & -X_{Vk,i} \\ X_{Vk,i} & R_{Vk,i} \end{bmatrix} \begin{bmatrix} i_{\alpha k,i} \\ i_{\beta k,i} \end{bmatrix} \quad (22)$$

Where $i_{\alpha1,i}^-$, $i_{\beta1,i}^-$ and $i_{\alpha k,i}$, $i_{\beta k,i}$ are the α , β components of fundamental negative-sequence and harmonic currents of i^{th} DG, $u_{V\alpha1,i}^-$, $u_{V\beta1,i}^-$ and $u_{V\alpha k,i}$, $u_{V\beta k,i}$ are the α , β components of fundamental negative-sequence and harmonic voltage drops of i^{th} DG

In detail, if the unbalance and harmonic power supplied by the i^{th} DG is less than the required unbalance and harmonic power, the virtual unbalance and harmonic impedance correction terms NQ_i and HQ_i are increased by unbalance and harmonic power sharing error control. Then, the virtual negative-sequence and harmonic impedances decrease adaptively with the increase of NQ_i , HQ_i .

If the unbalance and harmonic power sharing errors are zero, according to Eq. 19 and Eq. 20 which give the designed unbalance and harmonic power sharing rules, each DG will share the unbalance and harmonic powers exactly proportionally.

Fig. 5 shows the distributed power sharing control circuit with the fundamental and harmonic virtual impedances adaptively tuned by the consensus algorithm of MAS. The method acquired the fundamental positive-sequence reference voltage $u_{\alpha\beta1,i}^{+*}$ by the adaptive control of the virtual impedance has been already addressed in [15]. Therefore, here it

is not mentioned again.

As shown in the Fig.5, the proposed control method is a fully distributed control method, which overcomes the shortcomings of the centralized control method, effectively enhances the flexibility and reliability of the system, and realizes an accurate proportional sharing of the unbalance and harmonic powers required as well as fundamental reactive power.

5. Simulation Results

The simulations are carried out on the islanded microgrid with 120V/60Hz by MATLAB/Simulink. as shown in the Fig. 6, the simulation analysis system consists of three DGs and linear, unbalance and nonlinear loads. Each DG has the same power rating of 20 kW and output filter parameters with a 1.8mH coil and 122 μ F capacitor, respectively. Also, the parameters of the frequency and voltage droop controller are $2.18 \cdot 10^{-5}$ Hz/W and $1 \cdot 10^{-3}$ V / var. The line impedances corresponding to

the three DGs are $Z_{Line1} = 0.27 + j0.188\Omega$, $Z_{Line2} = 0.3 + j0.226\Omega$, and $Z_{Line3} = 0.175 + j0.358\Omega$, respectively. The simulation is performed with the conventional droop control method before 0.5s and the proposed method after 0.5s.

First of all, the voltage compensation of the PCC is considered when the unbalance and nonlinear loads are connected, respectively, and then, the power sharing is considered with both the loads.

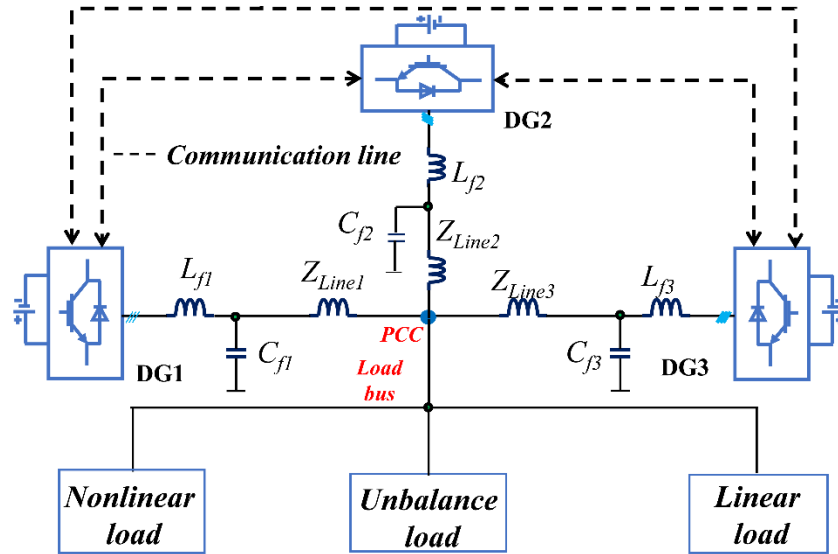
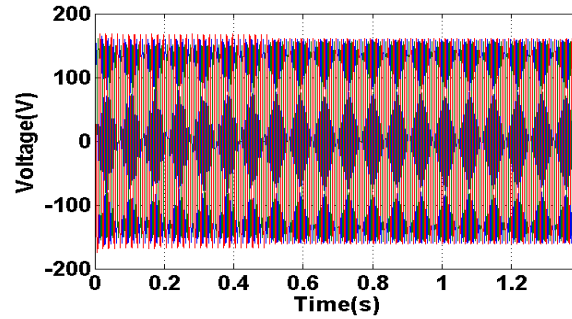


Fig. 6. The islanded Microgrid with linear, unbalance and nonlinear loads

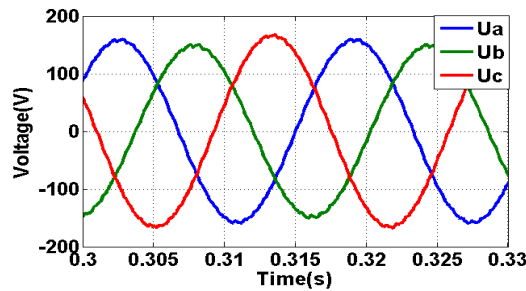
5.1. Voltage unbalance compensation with only the unbalance load

Fig. 7 shows the three-phase voltage waveforms in the PCC when the unbalance load is connected. Fig. 7(b) shows the voltage waveform at $t < 0.5s$, before applying the proposed method, and Fig. 7(c) shows the one at $t > 0.5s$ after applying the

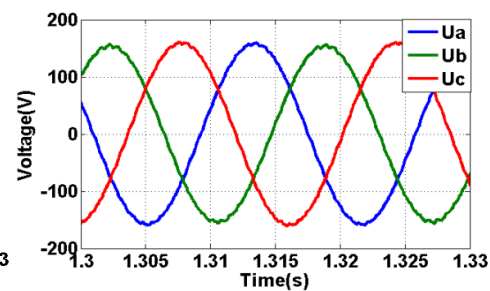
proposed method. As can be seen, before applying the proposed method (Fig. 7(b)), the amplitude of the three-phase voltage is not the same, the amplitude of U_c is large and the amplitude of U_b is relatively small due to the fundamental negative-sequence voltage. However, after applying the proposed method (Fig. 7(c)), the amplitudes of the three-phase voltages become almost the same.



a)



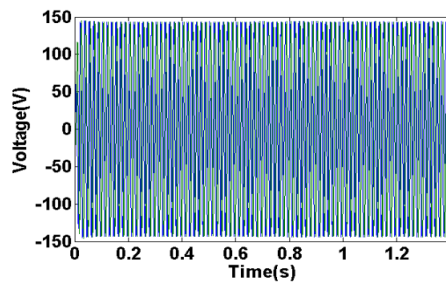
b)



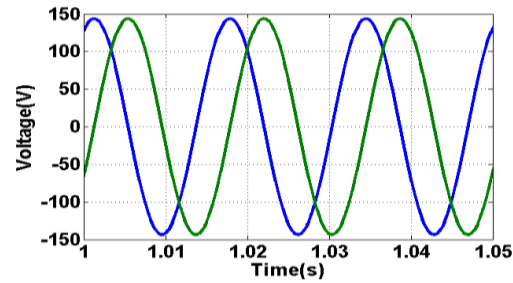
c)

Fig 7. Voltage waveforms with the unbalance load at the PCC.

a) Total voltage waveform, b) Enlarged voltage waveform by the conventional method, c) Enlarged voltage waveform by the proposed method



a)



b)

Fig. 8. Positive-sequence voltage waveforms of two-axis stationary reference frame

a) Total waveform, b) Enlarged waveform

Fig. 8 shows the fundamental positive-sequence waveform in the two-axis stationary reference frame. As can be seen, the proposed method does not affect the fundamental positive-sequence component of the PCC voltage. Whereas, Fig. 9 shows the fundamental negative-sequence waveform in the two-axis

stationary reference frame. As can be seen, the fundamental negative-sequence voltage in the two-axis stationary reference frame is 8.4 V before the proposed method (Fig. 9(b)), but it decreased to 2.5 V after the proposed method (Fig. 9(c)). This indicates that the voltage unbalance factor (VUF) has

been reduced from 6% to about 2%, so the proposed method effectively compensates the negative-sequence voltage at the PCC due to the unbalance

load under the condition of the mismatched line impedance.

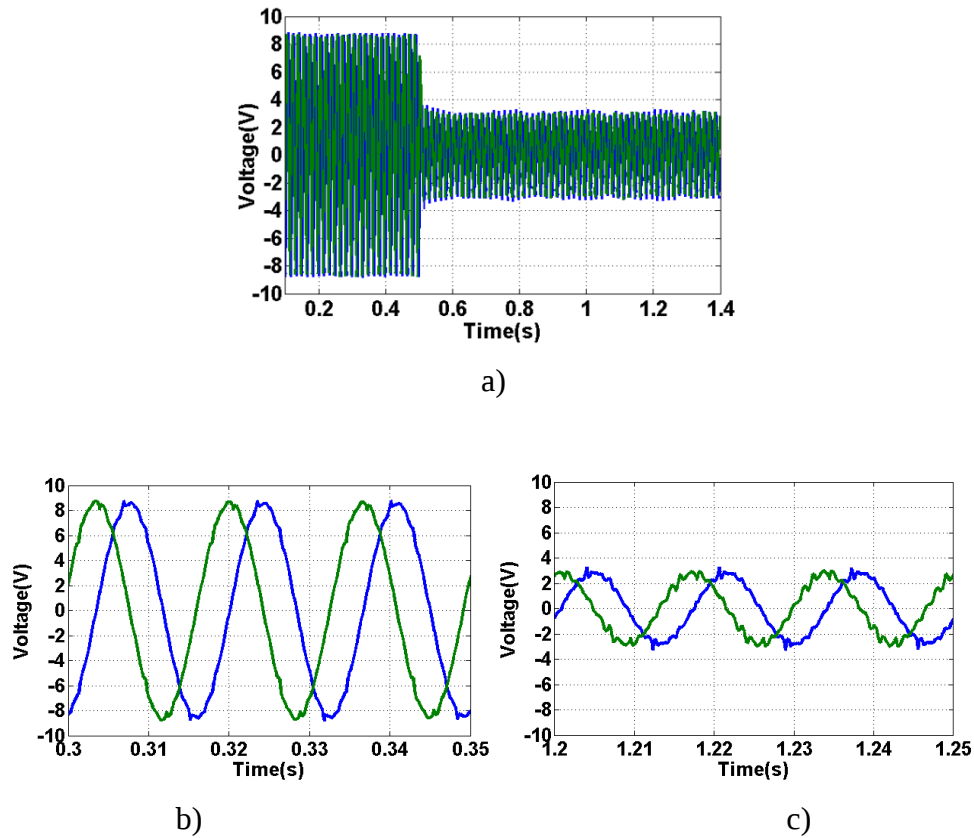
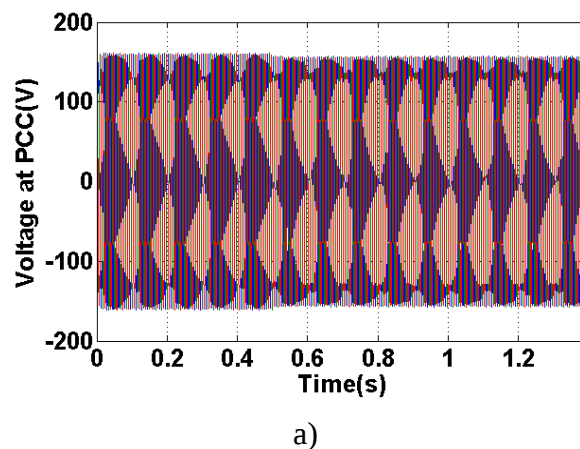


Fig 9. Negative-sequence voltage waveform of two-axis stationary reference frame.

a) Total waveform, b) Enlarged waveform by the conventional method, c) Enlarged waveform by the proposed method

5.2 Voltage harmonic compensation with only the nonlinear load.



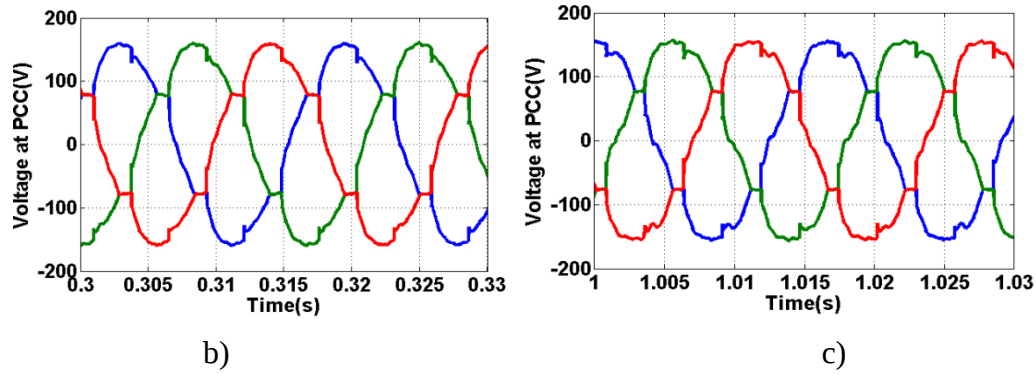


Fig 10. Voltage waveforms with the nonlinear load at the PCC.

a) Voltage waveform b) Enlarged waveform by the conventional method c) Enlarged waveform by the proposed method

Here, the distortion at the PCC voltage is analyzed when the nonlinear load is connected in the microgrid. Fig. 10 shows the three-phase voltage waveforms at the PCC with the nonlinear load. As can be seen, the voltage waveform was distorted before the proposed control method (Fig. 10(b)), but the voltage waveform is improved after the application of the proposed method (Fig. 10(c)).

The effectiveness of the proposed control method is better demonstrated by the following simulation results on total harmonic distortion (THD) of the

PCC voltage. Fig. 11 shows the voltage THD at the PCC with the nonlinear load. As shown in the Fig. 11, before applying the proposed method, the voltage THD at the PCC is 8.94%, but it decreased to 4.94% after application of the proposed method. On the other hand, Fig. 12 shows the voltage THD of the DG1 typically. The voltage THD of the DG1 was raised from 3.14% to 5.84% before and after applying the proposed method. This indicates that the THD of PCC voltage is reduced as compensation to the voltage THD increasing of each DGs.

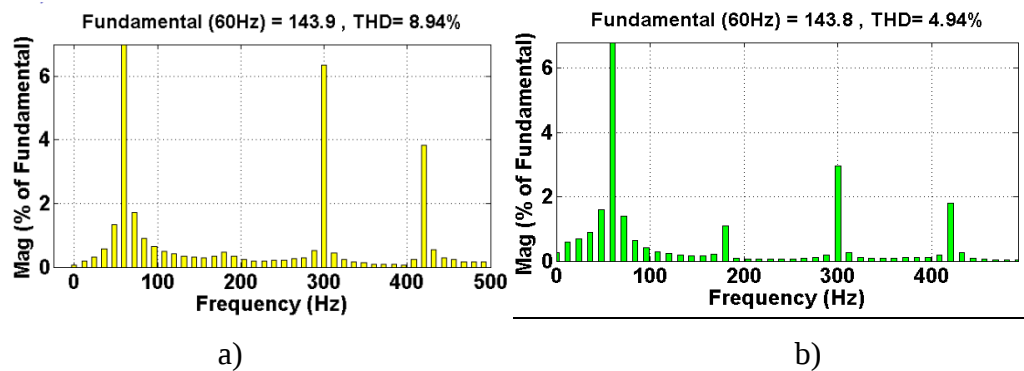


Fig 11. Voltage THD at the PCC.

a) THD by the conventional method b) THD by the proposed method

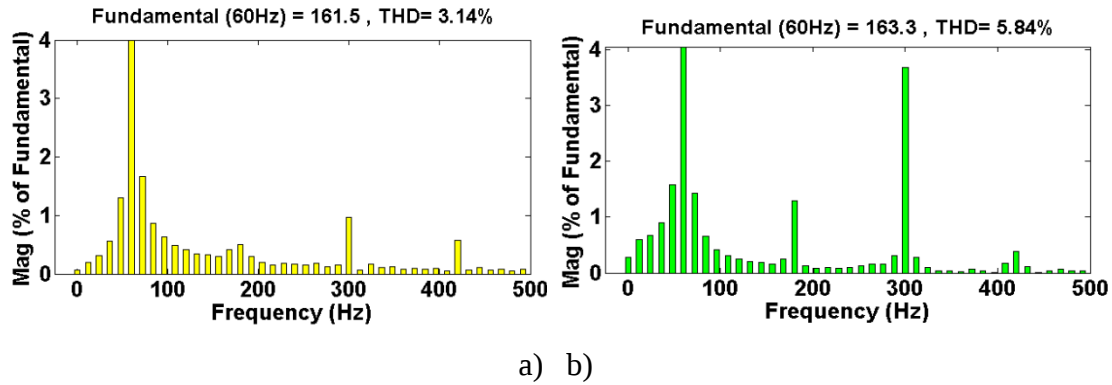


Fig 12. Voltage THD at the DG1

a) Voltage THD by the conventional method b) Voltage THD by the proposed method

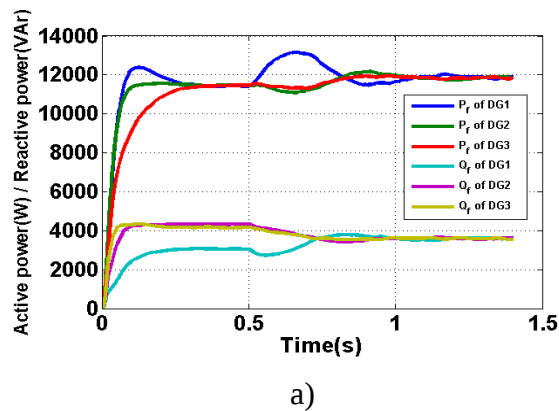
5.3 Power sharing with both unbalance and nonlinear loads

The impact on the active and reactive power sharing by the proposed method is analyzed. And then the unbalance power, the 5th harmonic power and 7th harmonic power sharing is analyzed for the voltage unbalance and harmonic compensation under the condition with both unbalance and nonlinear loads.

As shown in Fig. 13(a), the three DGs share the active power and the reactive power equally regardless of

before and after application of the proposed method. This means that the proposed method does not affect the sharing of active power and the reactive power.

In Fig.13(b) and Fig. 13(c), using the conventional droop control method at $t < 0.5s$, the unbalance and harmonic powers are not equally shared. After applying the proposed distributed control method at $t > 0.5s$, the negative-sequence and harmonic virtual impedance are adaptively adjusted and accordingly the equal unbalance, 5th and 7th harmonic power sharing are achieved.



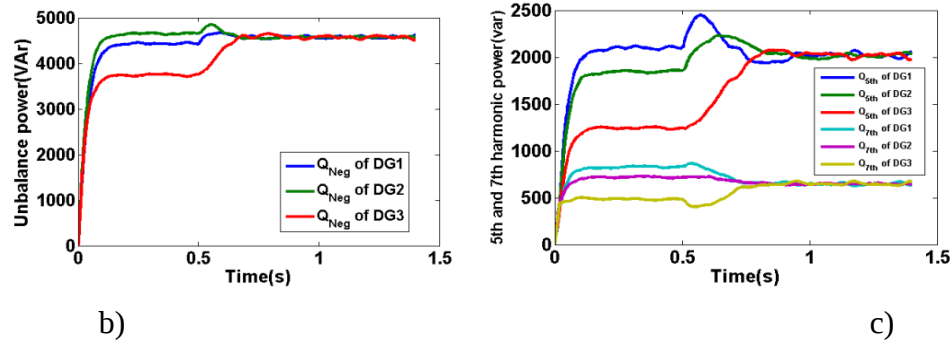


Fig 13. Power sharing with both the unbalance and nonlinear load

a) Active and reactive power sharing b) Unbalance power sharing c) 5th and 7th harmonic power sharing

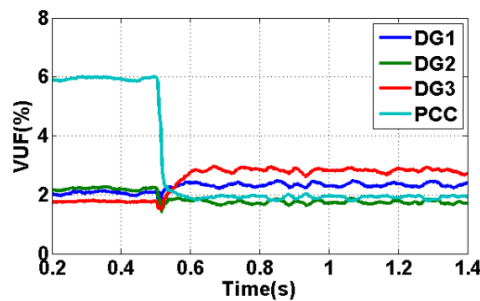


Fig 14. Voltage unbalance factor

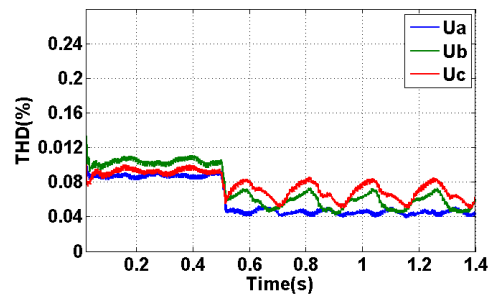


Fig 15. Voltage THDs of three phases at the PCC

Fig. 14 shows the voltage unbalance factor (VUF) when the generalized load including the unbalance and the nonlinear loads is connected at the PCC. As shown in Fig. 14, the VUF of each DG increases slightly, whereas the VUF at the PCC decreases significantly, satisfying the VUF criterion proposed by IEEE Std.519 [28] that the VUF should be less than 2%. This means that in order to compensate the VUF of the PCC, the VUFs of the three DGs are worse a little rather than a previous balance voltage. Also, Fig. 15 shows the voltage THDs of three phases at the PCC. As can be seen, the voltage harmonic at the PCC is effectively compensated by the proposed method.

6. Conclusions

In this paper, the voltage unbalance and voltage harmonic compensation method at the PCC have been investigated in the islanded microgrid with

multiple DGs. Based on the detailed discussion of the voltage unbalance and harmonic compensation principle at the PCC, a power sharing method using the combination of the droop control and the virtual impedance control has been proposed. A distributed control method based on a consensus algorithm has been applied to the virtual impedance control to share accurately the unbalance and harmonic powers according to the rated power of the DGs without knowing the exact value for the line impedance. As a result, the unbalance and harmonic power is shared equally, the voltage quality at the PCC is improved. The effectiveness of the proposed method was proved through the analysis of simulation results.

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