Journal of Electrical Power & Energy Systems, 2023, 7(2), 47-53
https://www.hillpublisher.com/journals/jepes/
ISSN Online: 2576-053X
ISSN Print: 2576-0521

Voltage Harmonic Compensation Using Virtual Harmonic Impedance Regulation in Islanded Microgrids

Sunghyok Kim*, Songchol Hyon, Jinsong Choe, Wisong Jong

Department of Electrical Engineering, Kim Chaek University of Technology, Pyongyang, Democratic People's Republic of Korea.

How to cite this paper: Sunghyok Kim, Songchol Hyon, Jinsong Choe, Wisong Jong. (2023) Voltage Harmonic Compensation Using Virtual Harmonic Impedance Regulation in Islanded Microgrids. *Journal of Electrical Power & Energy Systems*, 7(2), 47-53.
DOI: 10.26855/jepes.2023.12.001

Received: October 29, 2023
Accepted: November 28, 2023
Published: December 30, 2023

***Corresponding author:** Sunghyok Kim, Department of Electrical Engineering, Kim Chaek University of Technology, Pyongyang, Democratic People's Republic of Korea.

Abstract

The load power sharing and voltage quality are more challenging in islanded microgrids with nonlinear loads. Distributed generations (DGs) can be used to improve the power quality in the microgrids. However, the conventional droop control can cause poor harmonic power sharing among the DGs due to mismatched line impedance. This paper proposes a harmonic power-sharing control method using the adaptive regulation of the virtual harmonic impedance. Consensus algorithm is used to adaptively regulate the virtual harmonic impedance with consideration of mismatched line impedance. The consensus-based distributed control does not require prior knowledge of the line impedance. Simulation results are presented to demonstrate the proposed method in achieving accurate harmonic power sharing while reducing the voltage distortion at the point of common coupling (PCC).

Keywords

Microgrid, distributed generation, harmonic power sharing, distributed control, virtual harmonic impedance, consensus algorithm

1. Introduction

Microgrids, which have been developed to cope with the penetration of renewable energy systems, can provide a promising solution to integrate renewable and distributed energy resources and distributed energy storage systems in [1] and [14]. The microgrids now play a more crucial role than ever before concerning the power system stability, reliability, and power quality requirement in [2] and [3]. In microgrids with nonlinear loads, the current harmonics may induce the voltage distortion of PCC. Active power filters (APFs) can be used to compensate for harmonic current [4]. However, this leads to an increase in cost. An alternative to the use of APF is to use the DGs as APF, to improve the microgrid's power quality.

The harmonic power-sharing methods among the DGs using the virtual impedance in the droop control have been reported to reduce voltage distortion [6-9]. The virtual positive and negative sequence impedances are regulated to overcome the impact of mismatched line impedance causing the voltage distortion. However, these methods worsen the voltage quality in some cases and require prior knowledge of the line impedance.

The centralized control methods have been proposed to improve the PCC voltage quality and share the harmonic power with the help of the low-bandwidth communication line in [10] and [11]. However, these methods usually require prior knowledge of the line impedances and the number of DGs. Also, the system reliability and the control performance can be greatly reduced due to communication link failures.

Accordingly, distributed harmonic power sharing should be researched to overcome several drawbacks of the centralized control methods. The consensus control facilitates the coordination among a large number of distributed agents. In recent years, consensus-based distributed control strategies have been applied to compensate for the voltage unbalance and share the active and reactive power among the DGs in the microgrids in [12] and [13].

This paper mainly focuses on accurate harmonic power sharing and the improvement of the voltage quality at PCC in the islanded microgrids. Each DG and neighbor's harmonic powers are discovered by using a consensus algorithm. The virtual harmonic impedance is adaptively regulated according to the harmonic power sharing error among the DGs. and then the harmonic power is accurately shared among the DGs.

2. Conventional Harmonic Power Sharing in Islanded Microgrids

For the islanded microgrids, the inaccurate sharing of load reactive power causes the circulating current among the DGs. Therefore, to ensure accurate reactive power sharing, the inductive reactance should be in inverse proportion to the reactive power rating [13].

$$X_1 Q_1 = X_2 Q_2 = \cdots = X_N Q_N \tag{1}$$

where X_1 to X_N are the inductive reactance of DG_1 to DG_N at the fundamental frequency, Q_1 to Q_N are the reactive power rating of DG_1 to DG_N at fundamental frequency.

Similar to the situation of reactive power sharing, when there are nonlinear loads at the PCC, the harmonic inductive reactance should be in inverse proportion to the harmonic power rating to ensure accurate harmonic power sharing.

$$X_{har,1} Q_{har,1} = X_{har,2} Q_{har,2} = \cdots = X_{har,N} Q_{har,N} \tag{2}$$

where $X_{har,1}$ to $X_{har,N}$ are the harmonic reactance of DG_1 to DG_N, $Q_{har,1}$ to $Q_{har,N}$ are the harmonic power rating of DG_1 to DG_N.

From equation (2), the harmonic inductive reactance of all DGs should be equal to accurately share the load harmonic power when all DG units have the same power ratings.

3. Proposed Harmonic Power Sharing

3.1 Adaptive Regulation of Virtual Harmonic Impedance

In reality, the corresponding line impedances of all DGs are mismatched in the microgrid. Therefore, to satisfy equation (2), the virtual harmonic impedance should be added to the droop control loop to overcome the impact of the mismatched DG unit line impedances.

The equivalent harmonic inductive reactance X_{har}, which includes the line inductive reactance $X_{harline}$, the static virtual harmonic inductive reactance X^*_{Vhar}, and the adaptive virtual harmonic inductive reactance ΔX_{Vhar}, is written as

$$X_{har} = X_{harline} + X^*_{Vhar} + \Delta X_{Vhar} \tag{3}$$

In equation (3), the line inductive reactance $X_{harline}$ should be obtained to design and apply the virtual harmonic impedance. However, it is difficult to obtain the line inductive reactance in reality.

Therefore, to satisfy equation (2) regardless of the mismatched line impedance, this paper proposes the adaptive regulation method of virtual harmonic impedance based on the consensus algorithm.

It should be noted that when the DGs do have not the same power ratings, the load harmonic power should be shared by DGs proportional to their power rating.

3.2 Distributed Virtual Harmonic Impedance Control

In order to accurately share the load harmonic power with consideration of the mismatched line impedance, a consensus algorithm is applied to design the communication law to make the harmonic power of each DG converge at the average value of the harmonic powers of all DGs. Then the harmonic power correction term $\delta_{HQ,i}$, which is fed to the PI control loop, can be obtained from the designed communication law based on the consensus algorithm.

$$\delta_{HQ,i} = -\left(k_p + \frac{k_I}{s}\right) \cdot C_{HQ} \sum_{j=N_i} a_{ij} (Q_{har,i} - Q_{har,j}) \tag{4}$$

where $Q_{har,i}$ and $Q_{har,j}$ are the harmonic power of DG$_i$ and DG$_j$, respectively; a_{ij} is the connection status between DG$_i$ and DG$_j$; k_p and k_I are the proportional and integral coefficients of the PI control loop, respectively; C_{HQ} is the coupling coefficient.

From the obtained harmonic power correction term $\delta_{HQ,i}$, the virtual harmonic reactance and the virtual resistance at the hth harmonic frequency are corrected as follows;

$$\Delta X_{Vhar,i} = h\omega\left(L^*_{Vhar} - k_L \delta_{QH,i}\right) \tag{5}$$

$$R_{Vhar,i} = R^*_{Vhar} - k_R \delta_{QH,i} \tag{6}$$

where k_L and k_R are the proportional coefficients for adjusting the virtual harmonic inductance and the virtual resistance, respectively; L^*_{Vhar}, and R^*_{Vhar} are the static virtual harmonic inductance and the virtual resistance, respectively. Here the virtual resistance is adopted to provide some damping effect to the microgrids.

If the DG$_i$ shares the harmonic power less than the needed one, the obtained harmonic power sharing correction term $\delta_{HQ,i}$ increases by the harmonic power sharing control based on the consensus algorithm. Then, the virtual harmonic inductance decreases correspondingly. Under a stable state, the harmonic power sharing error $e_{HQ,i}$ converges to zero, and accordingly, the load harmonic power is shared equally among the DGs. The harmonic power sharing control scheme using adaptive virtual harmonic impedance is represented in Fig. 1. The local controller of each DG includes the droop control loop, voltage and current control loop, and the virtual 5th and 7th harmonic impedance loop. The virtual harmonic impedance is adaptively regulated by using the consensus algorithm. The voltage drop $V_{Vhar,i}$ across the virtual harmonic impedance is added to the reference output voltage $V_{ref,i}$ of the DG$_i$.

4. Simulation Results

The simulations on the microgrid with 120V/60Hz have been performed by the MATLAB/Simulink. As shown in Fig. 2, the microgrid has three DGs and loads. The communication topology is a ring-shape with the three DGs.

In the microgrid system, the DGs have the same power rating of 20kW. The droop coefficients of the frequency and voltage droop controllers are 2×10^{-5}Hz/W and 1×10^{-3}V/var, respectively. The corresponding line impedances of the three DGs are Z_{line1}=0.3+j0.131Ω, Z_{line2}=0.2+ j0.226Ω, and Z_{line3}= 0.175+j0.358Ω, respectively. Three-phase linear balance load and three-phase rectifier which includes a resistance of 2.5 Ω and capacitor of 5 μF are connected to the PCC. Some results are represented in detail as follows.

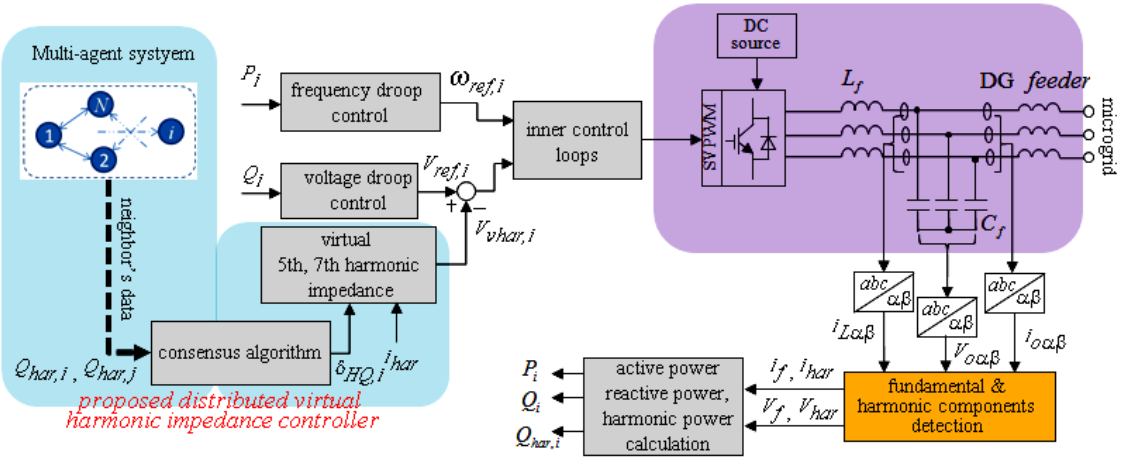


Figure 1. Complete block diagram of proposed control method.

Firstly, to analyze the performance of harmonic load sharing, the three-phase rectifier is added at the PCC. Fig. 3 shows the simulation results on the performance of load harmonic power sharing.

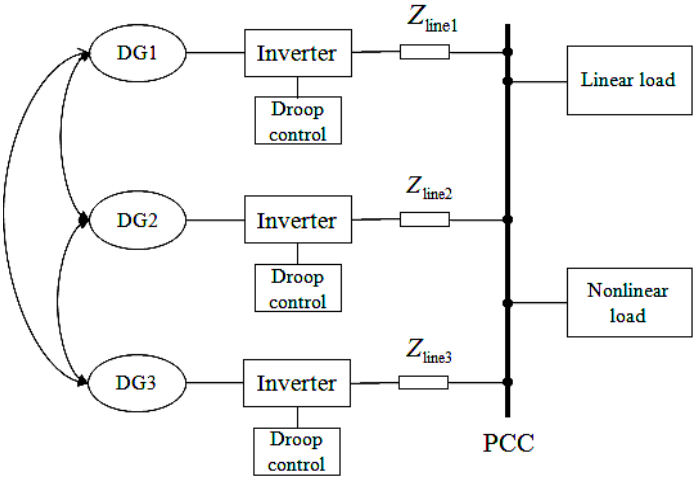
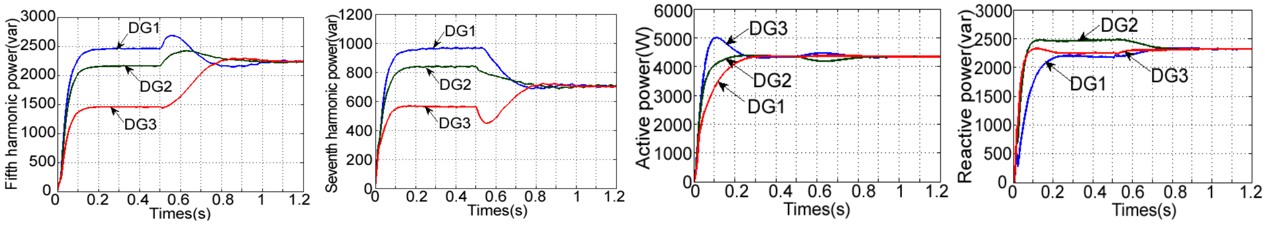


Figure 2. Block diagram of islanded microgrids with nonlinear load.



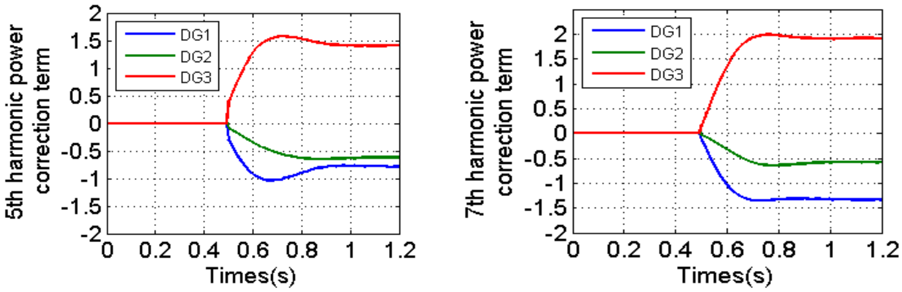
(a) (b) (c) (d)

Figure 3. Simulation results of power sharing. (a) 5th harmonic power sharing. (b) 7th harmonic power sharing. (c) Active power sharing. (d) Reactive power sharing.

As shown in Fig. 3(a) and (b), although the power ratings of the three DGs are the same, the 5th and 7th harmonic power could not be accurately shared in proportion to their power ratings among the three DG units with the conventional droop control method. The three DGs share different amounts of the harmonic power before *t*=0.5s. This is mainly caused due to mismatched line impedances of the three DGs. After *t*=0.5s, the proposed method is adopted. The 5th and 7th harmonic powers are shared equally among the DG units. Meanwhile, the proposed method does not affect the active power and reactive power sharing as shown in Fig. 3(c), and (d).

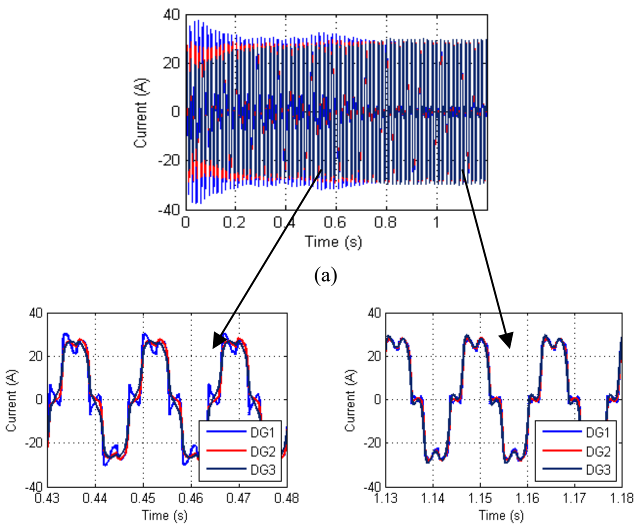
Fig. 4(a) and (b) show the 5th and 7th harmonic power sharing correction terms obtained from the consensus algorithm for the accurate harmonic power sharing after *t*=0.5s.

Following, in order to demonstrate the effectiveness of the proposed method, the load current sharing of the three DGs is simulated. Fig. 5 shows the output current sharing among the three DGs. The phase-A output currents of the DGs are not the same, that is, their amplitudes and phases are different before *t*=0.5s (Fig. 5(b)). However, after *t*=0.5s, the output currents are changed to be the same by the proposed method as shown in Fig. 5(c).



(a) (b)

Figure 4. Harmonic power-sharing correction terms. (a) 5th harmonic. (b) 7th harmonic.

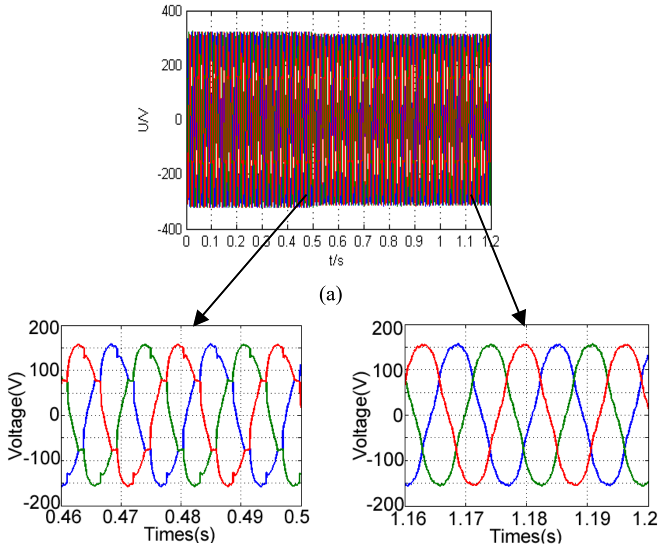


(a)

(b)

(c)

Figure 5. Output currents of three DGs. (a) Output currents. (b), (c) Expanded currents before and after application of proposed method.

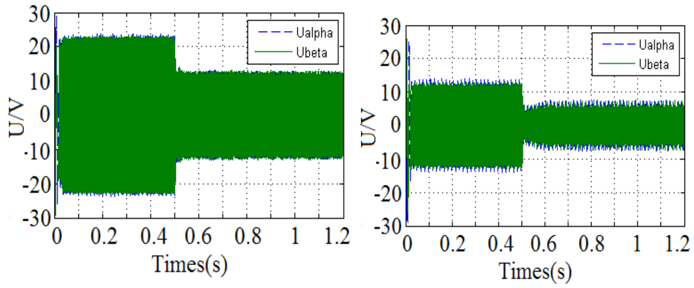


(a)

(b)

(c)

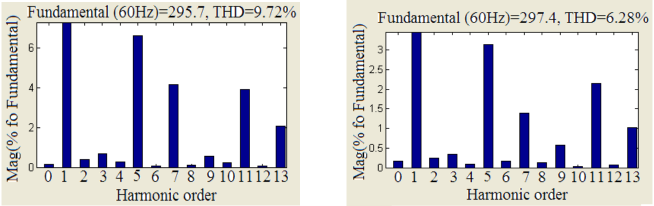
Figure 6. Three-phase voltage at PCC. (a) PCC voltage. (b), (c) Expanded voltage before and after application of the proposed method.



(a)

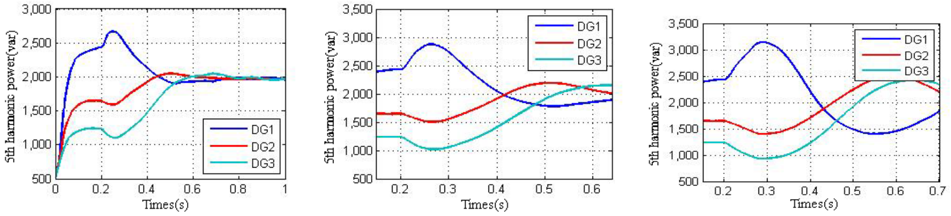
(b)

Figure 7. PCC voltage on *αβ* coordinates. (a) 5th harmonic voltage. (b) 7th harmonic voltage.



(a) (b)

Figure 8. THD of PCC voltage. (a) Conventional method. (b) Proposed method.



(a) (b) (c)

Figure 9. 5th harmonic power consensus of three DGs with communication time-delays. (a) 20ms. (b) 41.8ms. (c) 100ms.

Finally, the voltage distortion of PCC is analyzed. Fig. 6 shows the three-phase voltage of PCC and Fig. 7 shows the components of the 5th negative sequence and the 7th positive sequence of PCC voltage on $\alpha\beta$ coordinates without and with the proposed method, respectively. Also, Fig. 8 shows THD of PCC voltage without and with the proposed method, respectively.

Before t=0.5s, the voltage of PCC is seriously distorted (THD=9.72%) shown in Fig. 6(b) and Fig. 7. However, after t=0.5s, the proposed method is implemented in the three DGs, and then the voltage quality at PCC is obviously improved (THD=6.28%) shown in Fig. 6(c) and Fig. 7. It should be noted that the voltage harmonics at PCC are not quite eliminated with consideration of the 5th and 7th harmonic frequencies. If other harmonic frequencies could be considered in the control loops, the voltage quality of PCC would be better.

In reality, the communication time-delay may affect the performance of the proposed harmonic power-sharing control system and even result in instability. Therefore, the effect of the communication time-delay should be considered for the application of the proposed method. According to the control system settings, the maximum time-delay is $\tau_{\max}$=41.8ms with the maximum eigenvalue of Laplacian matrix $\lambda_{\max}$=3 and the coupling coefficient C_{HQ}=12.5. In this case, the communication time-delay τ is set to be 20ms, 41.8ms and 100ms, respectively. Fig. 9 shows the responses of the 5th harmonic power of the DGs when the consensus controllers are applied at t= 0.2s. It can be seen that the harmonic power consensus is achieved for the case of τ=20ms shown in Fig. 9(a). The DG output harmonic powers can also converge to the consensus for the case of τ= 41.8ms, but they have oscillation until the harmonic power consensus is achieved shown in Fig. 9(b). For the case of τ=100ms $>\tau_{\max}$, the system cannot be maintained stable, and the power-sharing consensus is not achieved shown in Fig. 9(c). It should be noted that the response of the 7th harmonic power is similar to the 5th harmonic power, thus it is not presented in the paper.

5. Conclusion

The accurate harmonic power-sharing control method has been investigated in this paper. To accurately share the load harmonic power regardless of the mismatched line impedance, the virtual harmonic impedance is adaptively regulated to eliminate the harmonic power sharing error. The harmonic power-sharing error is discovered by the consensus algorithm. The proposed method does not need the measuring value of the line impedance. The validity of the proposed method has been proved by the simulation results.

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