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A New Control Strategy for Voltage Restoration and Voltage Unbalance Compensation in an Islanded Droop-Controlled Microgrid

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Abstract

Low voltage microgrids including sensitive loads often face unbalanced load conditions. Therefore, a compensation procedure should be carried out in order to balance and restore sensitive load's voltage. In this paper, an effective voltage control strategy has been proposed for the autonomous operation of microgrids, under unbalanced load conditions. The proposed strategy balances single-phase sensitive loads by compensating the unbalanced voltage drop of the impedance between the outputs of Distribution Generation (DG) to the Point of Common Coupling (PCC). In addition, this scheme has also shown to be capable of restoring sensitive loads' voltage to nominal values. This method also shares the active and reactive load accurately between Distribution Generation (DG) units, based on their capacity. In order to evaluate the performance of the proposed control strategy, several simulations have been conducted under various states in an islanded microgrid prototype. Obtained simulation results demonstrate the effectiveness of the proposed control strategy in compensation of unbalanced load voltage and voltage restoration.

Keywords: Generation; Sensitive load; Active and reactive power sharing; Voltage control; Voltage unbalance compensation; Islanded microgrid Aggregator.
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1. Introduction

In recent years, the penetration of the DG units in power system has rapidly increased, causing problems for the distributed systems in terms of voltage deviation, voltage fluctuation and reverse power flow. Micrograds can coordinate different types of DG units effectively, by using local power management systems to overcome these problems [1]. Microgrid has the capability of operating in both grid's connected and islanded modes [2]. The conventional P-ω/Q-V droop control method has commonly been employed to control islanded microgrids. In traditional power systems, this method is based on the correlation between frequency and active power flows. High modularity, flexibility and moderate reliability are known advantages of this method [3]. However, the trade-off between reactive power sharing accuracy and system stability [4], inaccuracy in the reactive power sharing among DG units [5] and dependency towards the inverter output impedance[6] are known main setbacks of this approach. Several control methods, including the virtual frame transformation [6], the virtual frequency/voltage frame [7, 8], P-V/Q-f droop [9, 10], secondary control loop[11, 12] and virtual impedance[13-19] have been proposed to improve the performance of micrograds. However, the mentioned methods solely focus on balanced loading conditions.

Unbalanced load conditions are the common case in low voltage microgrids, where the majority of loads are single-phase [20]. The significance of this unbalanced voltage will be more noticeable, when a portion of these single-phase loads is designated as sensitive loads. The unbalanced voltage has noticeable negative influences on sensitive loads that are sensitive to voltage deviations, such as electronic loads, adjustable speed drives and induction motors. The

International Electrotechnical Commission (IEC) recommends the limit of 2% for the Voltage Unbalance Factor (VUF) in electrical systems [21]. Therefore, a control strategy should be designed for the DG units to improve the performance of microgrids under unbalanced loading conditions.

The control of microgrid with droop control method under unbalanced conditions can generate large negative sequence (NS) voltages. The NS voltages can be reduced by a NS output impedance controller [22], injecting a NS compensating voltage [23, 24] or injection NS currents by the DG [25]. However, a decrease of negative sequence impedance or increase of injection NS current or compensation NS voltage can reduce the accuracy of the NS current sharing. Additionally, the proposed method in [24], compensates the voltage unbalance at the DG output. The drawback of this method is the unbalanced voltage at the PCC is not compensated.

Most of the previous research focuses on balancing out the loads or DGs output, while neglecting voltage restoration. Furthermore, reactive power sharing problems with mismatch feeder impedance and inequality of DG capacities scarcely considered. Therefore, the main contribution of this paper is to propose a novel control strategy for an islanded microgrid based on droop control method, which employs communication links to balance and restore sensitive load's voltage. Moreover, this strategy can improve accuracy reactive power sharing and reduce circulating currents, which affect by the feeder impedance mismatch. In this study, inequality of DG capacities is also investigated.

In this control strategy, the P-ω/Q-V droop method has been used to generate frequency and voltage reference for each DG unit. Then, voltage drop across the feeders has been estimated for each phase and added to the voltage reference generated by the Q-V droop control method, that causes to load voltage is balanced. In order to estimate the voltage drop across the feeder impedance, a power reference value for each DG unit is required. The Energy Management System (EMS) calculates the active and reactive power reference values based on the total load. The Low Bandwidth Communication (LBC) has been employed to exchange the data information of the EMS to local controllers of DG units. It should be pointed out that the proposed control strategy does not require knowledge of the feeder impedances. The performance evaluation of the proposed control strategy on an exemplary microgrid with two parallel DG units and a larger network with five DG units have been thoroughly discussed and reported in this paper.

2. The proposed control strategy

The proposed control strategy in islanding mode includes four steps:

First, the active and reactive powers for each phase of DG units' output are required to be calculated. Subsequently, by utilizing the P-ω/Q-V droop control, the reference voltages for DG units are produced.

Second, the voltage drop across the feeder impedance will be compensated, by employing voltage drop estimation.

Third, the virtual impedance loop is used to make the output impedance of the DG unit more inductive and hence improve the load sharing. Finally, the voltage and current control loops have been used to generate reference voltages for the PWM. Fig. 1 illustrates the block diagram of the proposed method.

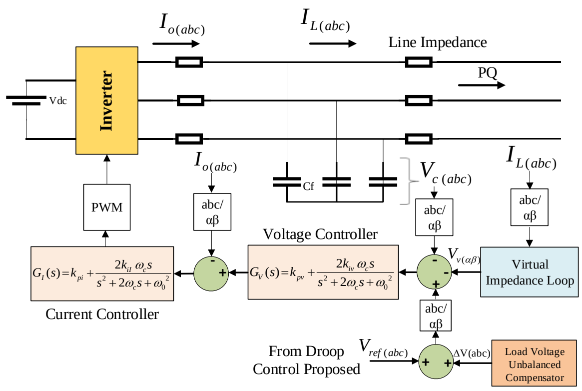


Fig. 1. Block diagram of the proposed control strategy

A) *Calculation of P and Q for Each Phase*

The active and reactive powers for each phase of DG units' output have been obtained based on the stationary and orthogonal αβ reference frame for per phase.

In this scheme, each phase of the original three-phase system can be considered as three independent two-phase systems. Therefore, for each phase, a second fictitious phase should be generated by a given phase shift of π/2 lead or π/2 lag [24]. For the purpose of generating the fictitious phase, the SOGI [25] has been implemented.

The actual DG output voltages and currents have been considered as α-axis quantities, whereas the π/2 lag voltages and π/2 lag currents of the DG output have been considered as β-axis quantities. For phase-a, the DG output voltage and current in α–β coordinates can be represented by π/2 lag as:

$$\begin{bmatrix} v_{oa\_\alpha} \\ v_{oa\_\beta} \end{bmatrix} = \begin{bmatrix} v_{oa}(\omega t) \\ v_{oa}(\omega t - \pi/2) \end{bmatrix} = \begin{bmatrix} V_{om}\cos(\omega t) \\ V_{om}\sin(\omega t) \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} i_{oa\_\alpha} \\ i_{oa\_\beta} \end{bmatrix} = \begin{bmatrix} i_{oa}(\omega t + \varphi_i) \\ i_{oa}(\omega t + \varphi_i - \pi/2) \end{bmatrix} \quad (2)$$

Where $v_{oa}(\omega t)$ and V_{om} represent the reference DG output voltage and desired DG output voltage magnitude, respectively. Considering phase-a, by using the voltage ($v_{oa\_\alpha\beta}$) and current ($i_{oa\alpha\beta}$) of phase-a in the $\alpha\beta$-axis, the instantaneous active power (p_a) and reactive power (q_a) can be represented by [26].

$$p_a = v_{oa\_\alpha}\, i_{oa\_\alpha} + v_{oa\_\beta}\, i_{oa\_\beta} \tag{3}$$

$$q_a = v_{oa\_\beta}\, i_{oa\_\alpha} - v_{oa\_\alpha}\, i_{oa\_\beta} \tag{4}$$

Subsequently, p_a and q_a are processed by low-pass filter in order to eliminate the double frequency ripples of the power components. Similarly, for phase-b and phase-c can also be defined as a two-phase system in α–β coordinates and instantaneous active and reactive power can be calculated for each phase separately.

B) The P-ω/Q-V droop control method

The droop control method has been known as a primary, autonomous, and wireless control method. The voltage references of DG by P-ω/Q-V droop control defined as follows:

$$\omega_i = \omega_{0i} - D_{pi}[P_{0i} - (P_{ai} + P_{bi} + P_{ci})] \tag{5}$$

$$V_i = V_{0i} - D_{qi}[Q_{0i} - (Q_{ai} + Q_{bi} + Q_{ci})] \tag{6}$$

The P_0, Q_0 from each DG are set by the EMS.

C) Load Voltage Unbalanced Compensation

Under the unbalanced loading conditions, power consumption of the single-phase loads in microgrid systems will not be identical and hence; currents flow in each phase will be different. In conventional droop control method, DG output voltage is balanced, due to the presence of unbalanced voltage drop throughout the feeder's impedance, load voltage will be unbalanced. Therefore, in this paper, for the purpose of balancing load voltage, voltage drop across the feeders has been estimated for each phase and added to voltage reference generated by the Q-V droop control method, which will lead to a balanced load voltage. Furthermore, this method can improve accuracy reactive power sharing, which affect by the feeder impedance mismatch. If resistance and reactance of the feeder impedances are not the same, as a result, the voltage drop on the feeder is not equal and accuracy reactive power sharing is reduced. But, with proposed control method, the voltage drop mismatch is compensated. For this purpose, a simple microgrid with two DG units, supplying three single-phase loads has been shown in Fig. 2.

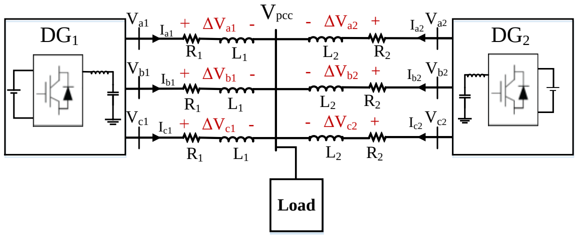


Fig. 2. Simplified model of microgrid with two DG and load

Considering phase-a, the phase-a output current of DG unit i can be calculated according to Eq. (7).

$$I_{ai} = \frac{V_{ai} - V_{a\,pcc}}{Z_i} = \frac{\Delta V_{ai}}{Z_i} \tag{7}$$

where V_{apcc}, Z_i are the PCC Voltage and feeder impedance, respectively.

Complex power injection of phase-a is as follows:

$$S_{ai} = V_{ai} \,.\, I_{ai}{}^* \tag{8}$$

When equation (7) is substituted in (8).

$$S_{ai}^* = V_{ai}^* \cdot \frac{\Delta V_{ai}}{Z_i} \tag{9}$$

$$\Delta V_{ai} = \frac{S_{ai}^* . Z_i}{V_{ai}^*} \tag{10}$$

$$|\Delta V_{ai}| = \frac{|S_{ai}^*|.|Z_i|}{|V_{ai}^*|} \tag{11}$$

The voltage drop across the phase-a feeder impedance depends on the phase-a apparent power of the DG output and feeder impedance. However, the feeder impedance is often not readily available. Therefore, this voltage drop must be estimated without the knowledge of the feeder impedance. The gain k_{vi}, in accordance with Eq. (12), has been defined as the increase factor of output voltage of each DG unit i.

$$k_{vi} = \frac{|\Delta V_i|}{|S_{0i}|} = \frac{|Z_i|}{|V_i|} \tag{12}$$

Where $|S_{0i}|$ is apparent power reference for DG unit i, which calculate by EMS.Provided that the reference for Q_i is available to the local controllers, the gain k_{vi} can be easily obtained. According to Eq. (5), if reactive power output of the DG_i with the reactive power reference (Q_{0i}) is equal, so, the output voltage of the DG_i and the voltage magnitude reference (V_{0i}) will be equal. Therefore, the difference between the DG output voltage and PCC voltage is actually the PI controller's output ($Q_{0i} - Q_i$). A PI controller set k_v for each unit by regulating Q indirectly to match

Q_0. The objective of this controller is not to regulate reactive power directly but to set k_v in order to compensate the voltage drop across feeders. A low-pass filter (LPF) with the cut-off frequency 5Hz is employed to smoothen the achieved coefficient (k_v).

The reactive power reference from each DG has been set by the EMS. Through the communication link, each DG unit sends information to EMS regarding generation capacity. The EMS based on this information, and the data regarding forecasts and historical data calculate the proper share of reactive power for each DG unit (Q_0) and send it back to each unit, along with a controller enable signal. The Q_0 does not show any signs of alteration considering the transients in the reactive power output of each unit. Only variations in the total load reactive power can change these values. To avoid constantly varying power reference values, a sampler with 5Hz sampling rate was use.

The proposed strategy only requires that the EMS exchange data periodically at a slow rate, low-bandwidth communication links are sufficed for this application. If the communication channel becomes unavailable, as long as the load does not change, the voltage unbalance compensation and power sharing accurately done. This way, the control system reliability is improved, since compensation is not dependent on the presence of high communication bandwidth. The proposed controller has been illustrated in Fig. 3(b).

Therefore, the phase-a voltage drop across the feeder impedance is presented as follows:

$$\left|\Delta V_{ai}\right| = k_{vi} . \left|S_{ai}\right| \tag{13}$$

where $|S_{ai}|$ is the phase-a output apparent power of DG unit i.

Similarly, the voltage drop across the feeder's impedance for phase-b and phase-c can also be calculated.

$$\left|\Delta V_{bi}\right| = k_{vi} . \left|S_{bi}\right| \tag{14}$$

$$\left|\Delta V_{ci}\right| = k_{vi} . \left|S_{ci}\right| \tag{15}$$

The Eq. 13 to 15 compensates the voltage drop magnitude from the feeder impedance and does not have an effect on the voltage drop angle. At a power factor close to the unit, the voltage drop angle is negligible and it can be ignored. But in the power factor less than 0.85, these equations must be corrected.

Considering phase-a, the PCC voltage is calculated as follow.

$$V_{aPCC} = V_a - ZI_a = V_a - (RI_a + jXI_a) \tag{16}$$

The microgrid is mainly resistive (R>>X) in low voltage distribution network lines[27]. If the effective line impedance is purely resistive, $Z=R$ then

$$\Delta V_a = Z\ I_a \approx R\ I_a \tag{17}$$

Therefore, ΔV_a is in phase with I_a. As a result, the PCC voltage is equal to

$$V_{aPCC} = V_a - ZI_a \approx V_a - RI_a = V_a - \Delta V_a \tag{18}$$

Therefore, in order to take into account the voltage drop angle, the voltage drop across the feeder impedance is presented as follows.

$$\Delta V_{ai} = \frac{k_{vi} . \left|S_{ai}\right| . i_{ai}}{\left|i_{ai}\right|} \tag{19}$$

$$\Delta V_{bi} = \frac{k_{vi} . \left|S_{bi}\right| . i_{bi}}{\left|i_{bi}\right|} \tag{20}$$

$$\Delta V_{ci} = \frac{k_{vi} . \left|S_{ci}\right| . i_{ci}}{\left|i_{ci}\right|} \tag{21}$$

Finally, the voltage drops have been added to the reference voltage achieved by the Q-V droop control method. Hence, the new reference voltage can be defined as

$$V_{0ai}^{new} = V_{0i} + \Delta V_{ai} \tag{22}$$

$$V_{0bi}^{new} = V_{0i} + \Delta V_{bi} \tag{23}$$

$$V_{0ci}^{new} = V_{0i} + \Delta V_{ci} \tag{24}$$

The proposed method to determine the reference voltage has been illustrated by Fig. 3.

D) Virtual impedance loop

In the presented paper, the virtual impedance is considered to enhance the performance of the droop controllers. The voltage drop of the virtual impedance in αβ axis are derived as

$$\begin{aligned} V_{v\alpha} + jV_{v\beta} &= (R_v + j\omega L_v)(i_{0\alpha} + j\,i_{o\beta}) \\ V_{v\alpha} &= R_v . i_{0\alpha} - \omega L_v i_{o\beta} \\ V_{v\beta} &= R_v . i_{0\beta} + \omega L_v\, i_{0\alpha} \end{aligned} \tag{25}$$

where R_v and L_v are the virtual resistance and inductance values, respectively.

E) Voltage and current control loops

The voltage and current controllers have been implemented on a stationary frame and the proportional resonant controllers (*P*R) have been employed in the *α–β* frame by using the following transfer function [28]

$$G_V(s) = k_{pv} + \frac{2k_{iv}\,\omega_c s}{s^2 + 2\omega_c s + \omega_0{}^2} \tag{26}$$

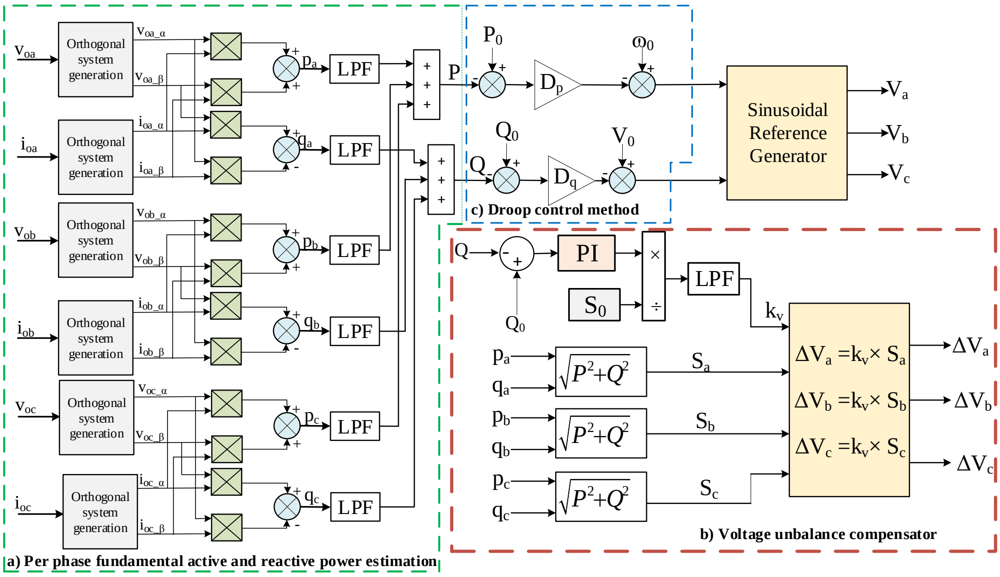


Fig. 3. Block diagram of the proposal voltage control strategy. a) Per phase fundamental active and reactive power of DG output, b) The voltage drop estimation, c) Droop control method.

$$G_i(s)=k_{pi}+\frac{2k_{iI}\,\omega_c s}{s^2+2\omega_c s+\omega_0^{\,2}} \quad (27)$$

where k_{PV} and k_{Pi} are the proportional gains, k_{iv} and k_{iI} represent the resonant gains for the resonant peak adjustment and ω_c the cutoff frequency for resonant bandwidth control.

3. Simulation Results

Simulation results have been carried out in Matlab/Simulink environment. In order to verify the effectiveness of the proposed control strategy, two case studies are conducted.

A) Case studies: microgrid with two DG units

A microgrid with two DG units has been chosen, which in Fig. 2 is shown. In this study, the rating DG_1 is twice that of DG_2. The feeder impedances of the two DG units are Z_1=2+j0.565 Ω and Z_2=4+j1.31 Ω. In this case, because the rated power of DG_2 is half of that of DG1, the virtual impedance of DG_2 is twice those of DG_1. The control and system parameters are same as that of previous study. The utilized system parameters for simulation have been demonstrated in Table 1. Three single-phase loads are connected to the PCC for consideration of voltage unbalance conditions. In this respect, the active and reactive power at the rated voltage and frequency in each phase has been demonstrated in Table 2. The load of phase-c has been categorized as a sensitive type, where the voltage should be adjusted at the nominal value. To evaluate the proposed control strategy against load changes, a balanced three-phase load with P=1000 W and Q= 300 VAr at *t* = 3 seconds has been inserted, in parallel with previous load.

Table.1.
System parameters with their values

Symbol	*Quantity*	*Value*
V_{dc}	DC Voltage	650
V_0	Grid Voltage Amplitude (RMS)	230 v
ω_0	Grid frequency	2π50 rad/s
C_f	Filter capacitance	25 µF
L_f	Filter Inductance	1.8 mH
D_p , D_q	Frequency and voltage droop slopes	0.0001rad/s/W, 0.0001 V/Var
R_v , L_v	Virtual impedance loop	0.2 Ω , 2 mH
k_{pv}	Voltage proportional term	0.155
k_{iv}	Voltage integral term	15
k_{pI}	Current proportional term	30
k_{iI}	Current integral term	1000
ω_f	Cut-of frequency of power calculation	10
ω_c	Cut-off frequency for resonant bandwidth control	5

Table.2.
The active and reactive power of each phase of the load

Power of the three loads	*Load of the phase-a*	*Load of the phase-b*	*Load of the phase-c*
Active power	800 W	800 W	2400 W
Reactive power	200 Var	200 Var	600 Var

The three-phase voltage and current waveforms from DG_1 and DG_2 output and load have been compared between the proposed scheme and conventional droop control method (Figs. 4 and 5). Power demand of sensitive loads at phase-c is greater than other two phases, which results in a higher current level as well. In conventional droop control method, the output voltage of DG units is

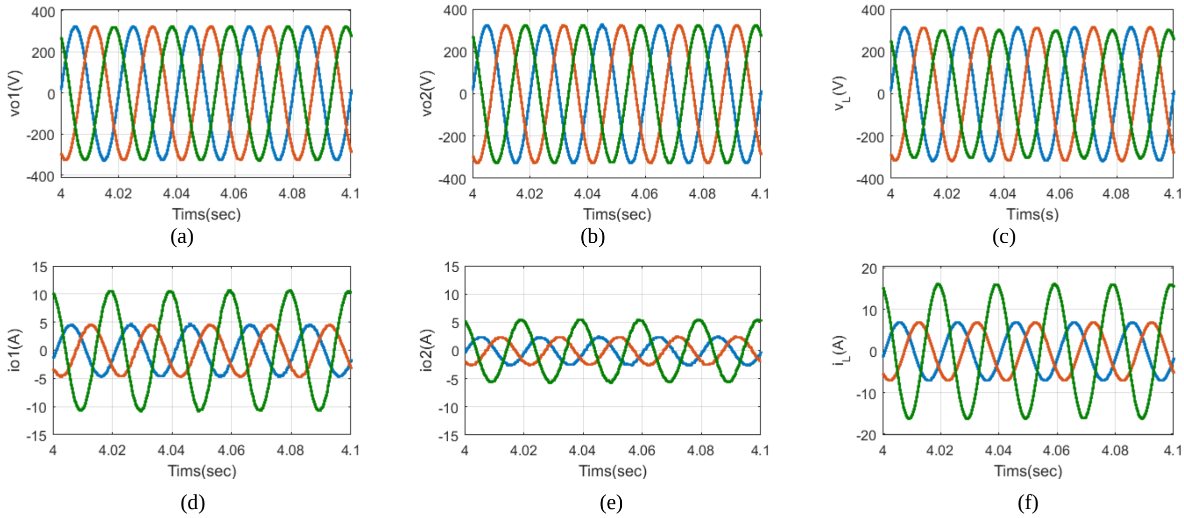


Fig. 4. Results of the microgrid system with conventional droop control method and voltage and current loops. (a) Output voltages of DG1. (b) Output voltages of DG2. (c) Voltages of load. (d) Output currents of DG1. (e) Output currents of DG2. (f) Currents of Load

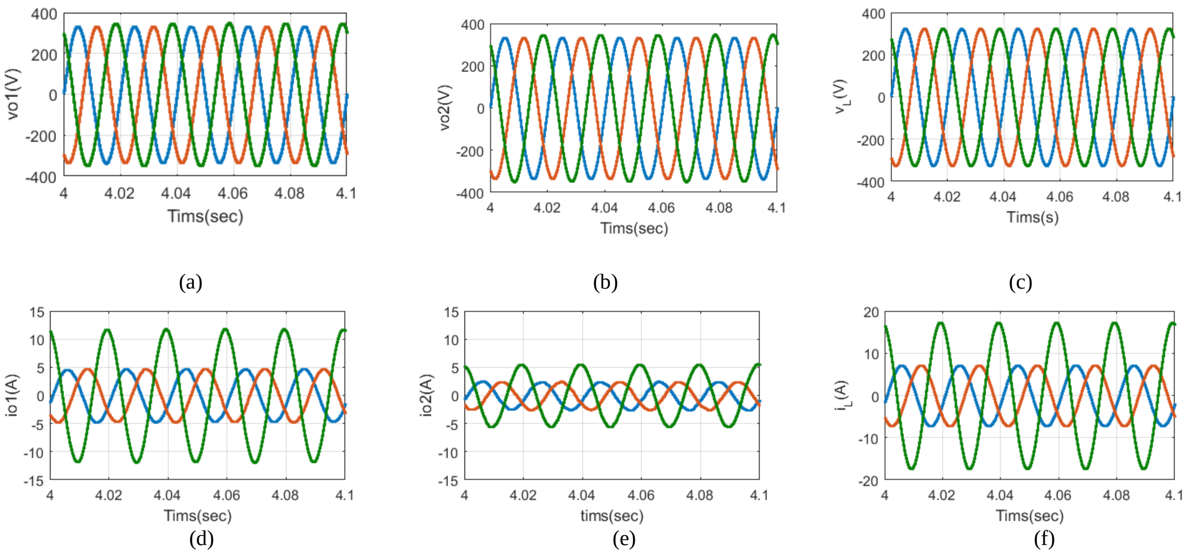


Fig. 5. Results of the microgrid system with using the proposed control method. (a) Output voltages of DG1. (b) Output voltages of DG2. (c) Voltages of load. (d) Output currents of DG1. (e) Output currents of DG2. (f) Currents of Load.

balanced. Therefore, due to the rather high rate of current at phase-c, voltage drop across feeder impedance of phase-c will be greater and lead to a lower load voltage from this phase in comparison to other phases, as presented by Fig.4(c). However, by using the voltage drop estimation of the feeder impedance for each phase separately, and the addition to the reference voltage generated by droop control, load voltage has been balanced and set at nominal values, without balancing phases currents. The waveforms of the balanced load voltages have been shown by Fig. 5(c). These figures illustrate the effectiveness of the proposed compensation method in balancing out load voltages.

In this paper, all the three-phase waveforms shown by the colors blue, red and green represent phase-a, phase-b and phase-c, respectively. The RMS voltage of three single-phase loads using the proposed control strategy and conventional droop control method along with appropriate voltage and current loops has been presented by Fig. 6. Judging by Fig. 6(a), it can be observed that the loads' voltage has declined using the conventional droop control scheme, hence, the loads' voltage connected to phase-a and phase-b is at about 223 volts, whereas the sensitive load voltage connected to phase-c is around 217 volts. That being said, taking into account the proposed control strategy, voltages have been set in close proximity to the nominal value, illustrated by Fig. 6(b). By employing this strategy, a balanced and restored voltage has been achieved. The %VUF is defined as follows in Eq. (28)

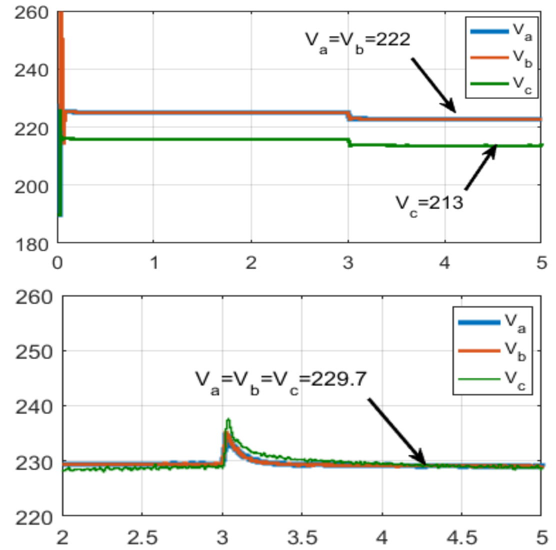


Fig. 6. The RMS values of three-phase load voltages. (a) with conventional droop control method. (b) with using the proposed control method.

$$\%VUF=\frac{\text{negative sequence V component}}{\text{positive sequence V component}}\times 100 \qquad (28)$$

As it can be seen in Fig. 7(a), the %VUF of the load voltage with conventional droop control method is about 1.4%, whereas the proposed control strategy shows values about 0.3%. As a result, load voltage unbalanced is decreased, while the DG voltage output becomes unbalanced. Considering that $Z_2=2Z_1$, the VUF of DG_2 should be a little higher, which in Fig. 7(b) is shown. The VUF of the DG units is increased whereas the load voltage unbalanced is decreased as a result of unbalanced compensation.In Fig. 8, the active and reactive power sharing among DG units with conventional droop control method and proposed control strategy have been shown. As previously mentioned, the capacity of the DG_1 is twice DG_2 and according to Fig. 8, active power has been distributed properly among DG units, but reactive power is not correctly divided based on DG units' capacity. It can be observed in Fig. 8(b), by, the active and reactive powers are properly shared among DG units based on their capacity, and the amount of the Q_1 supplied by DG_1 is accurately twice of the supplied by DG_2.

B) Case studies: microgrid with five DG units

In order to show the performance of the proposed method, the comprehensive simulations are done on a larger network with 6 buses and 5 DG units. Fig. 9 illustrates the single-line diagram of the investigated microgrid. To prove the effectiveness of the proposed control strategy in balancing the microgrid phase voltage, all loads are assumed single phase loads.

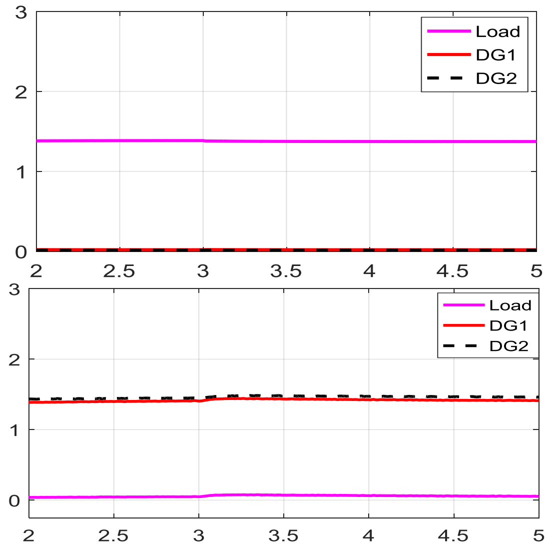


Fig. 7. VUF at load and DGs output. (a) with conventional droop control method. (b) with using the proposed control method.

Ratings and power factor for all loads and DG units are shown in Fig. 9. System parameters of this microgrid in [29] is given. The load 3 is sensitive load and phase voltages must be balanced. The proposed control strategy is used for all distributed generations.

Fig. 10 shows three-phase voltages of Bus3 using the proposed control strategy and conventional droop control method. As shown, with conventional droop control method, the three-phase voltages are lower than the rated values (Va3=215.8 V, Vb3=209.5 V, and Vc3=215.8 V). For the proposed control method, the Bus 3 three-phase voltages are equal to the rated value (Va3=Vb3=Vc3=220 V). The active and reactive power sharing among DG units has been illustrated by Fig. 11. As shown, loads share between DG units, based on their capacity.

4. Conclusion

This paper presents a novel power control strategy for voltage unbalance compensation in an islanded microgrid consisting of the power-electronics-interfaced DG units and unbalanced loads. This strategy is not only capable of balancing load voltages, but also can share the active and reactive power between DG units, based on their capacity. The proposed control strategy includes four steps. In the first step, with the droop control method, the voltage references for DG units are generated. Second, voltage drop estimation has been employed to compensate voltage declines across feeder impedance for each phase, separately. The active and reactive power references from each DG are set and transmitted by the EMS, based on the capacity of DG units and the total load. The power reference has been employed in estimating voltage drop across feeder impedance. In the proposed control strategy, the knowledge of the feeder impedances is not a necessity. Third, the virtual impedance loop is used. Finally, by adopting voltage and current control loops, active and reactive powers are shared among the DG units. Simulations have been performed, and the results have shown that the proposed control scheme is an effective way to be used in the microgrid implementations.

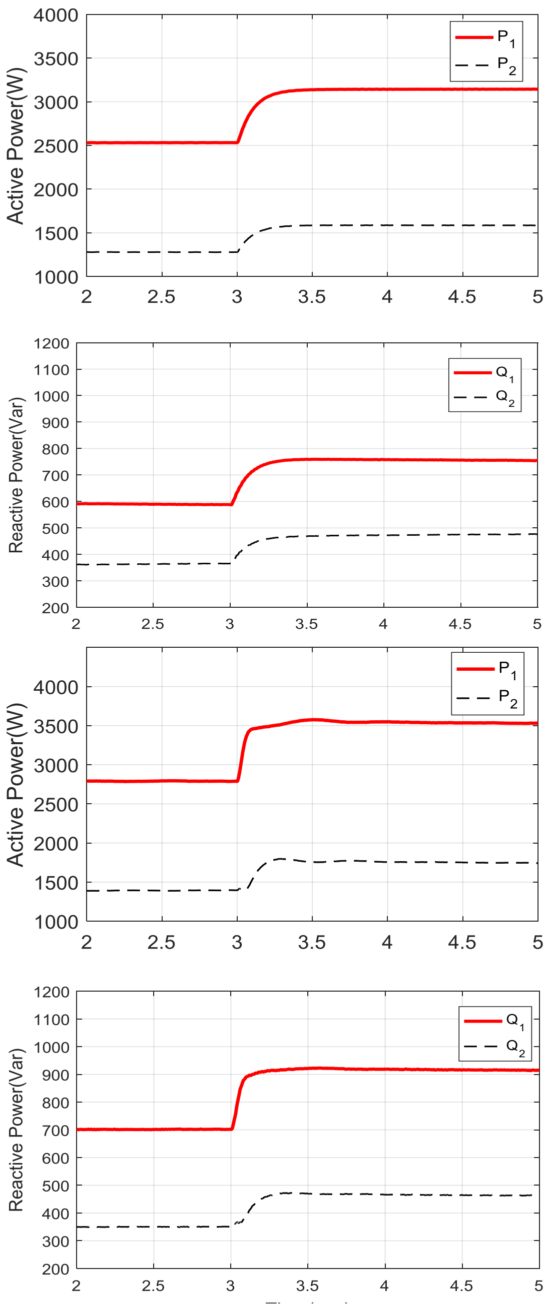


Fig. 8. Power sharing performance. (a) with droop control method. (b) with proposed control strategy.

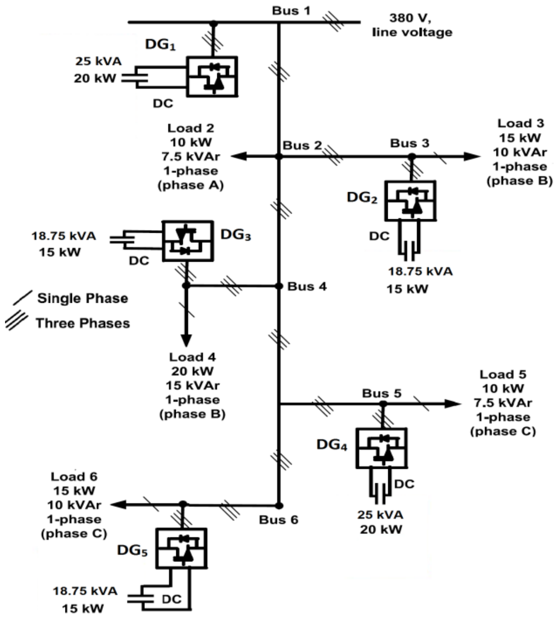


Fig. 9. Single line diagram of the investigated microgrid

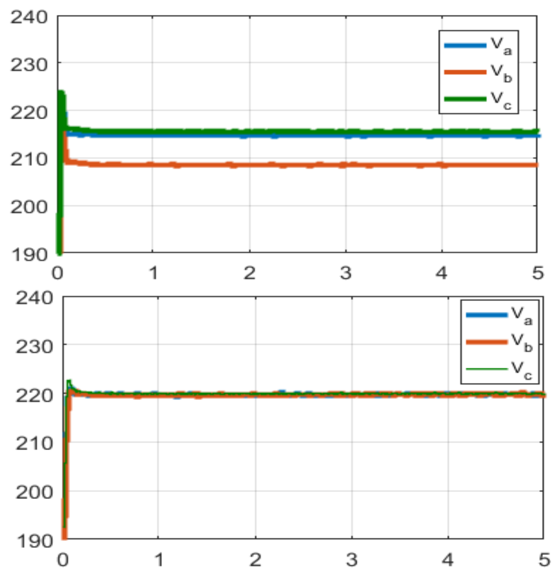
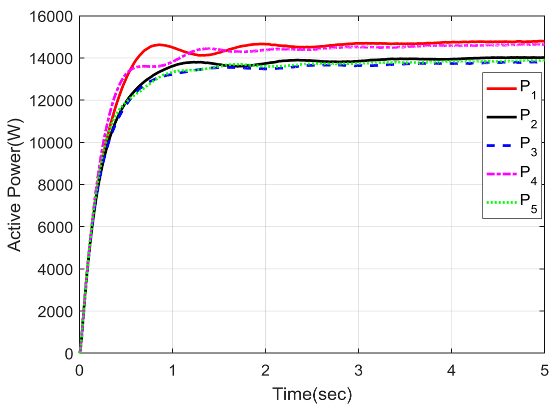


Fig. 10. Bus 3 three phase voltages. (a) with conventional droop control method. (b) with using the proposed control method.



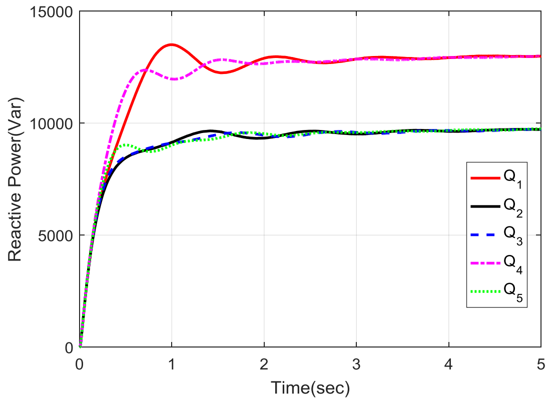


Fig. 11. Power sharing performance with proposed control strategy. (a) active power sharing. (b) reactive power sharing.

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