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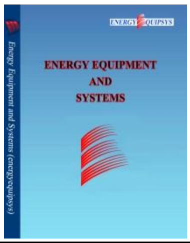

Accurate power sharing for parallel DGs in microgrid with various-type loads

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ABSTRACT

Microgrids are nowadays used to produce electric energy with more efficiency and advantage. However, the use of microgrids presents some challenges. One of the main problems of the microgrids widely used in electrical power systems is the control of voltage, frequency and load sharing balance among inverter- based distributed generators (DGs) in islanded mode. Droop method performance degrades when the feeder impedances of two DGs are different and thereby, further modification is required. In this article, a new method based on virtual impedance and compensating voltage is proposed and simulation results show that this method combined with droop control results in balanced power sharing with negligible voltage and frequency drop. Simulation results have been extracted from the Simulink, MATLAB and showed that the proposed method has a good performance in equal load sharing between two DGs with different feeder impedances; both in equal and different droop gains, and with different loads such as nonlinear or unbalanced ones.

Keywords: Microgrid, Compensating Voltage, Power Sharing, Inverter, Virtual Impedance, Nonlinear-Unbalanced Load.

1. Introduction

Changes in climate and consumption pattern imposes a great effect on electricity generation methods. A significant number of countries have focused on reducing greenhouse gasses up until 2020 [1]. In distribution level, renewable resources such as photovoltaic, wind turbine, fuel cell and other resources, can connect to the main grid and produce a great amount of electric energy and thus these resources are called Distributed Energy Resources (DERs) or distributed generators (DGs). Nowadays, increase in fuel cost and geographic problems presents a scope to use these DERs in electric power systems. So, microgrid is defined as the set of DERs in an electrical power system including DGs, storage systems, and linear, unbalanced or nonlinear loads, that can be connected to the main grid or be islanded.

The presence of several DGs in a microgrid yields some challenges that can affect the system performance. When a microgrid is connected to the main grid, the voltage and frequency are supported by the grid. One of the main challenges is the frequency and voltage control of microgrid in islanded mode, especially when various loads are connected or disconnected. Voltage and frequency drop may be common in this status and voltage and frequency distortion cannot be avoided. So, the voltage and frequency control of microgrid was considered to be a major research problem in many scientific studies.

The main aspect of microgrid control is the stability of voltage and frequency. Low frequency stability due to power demand

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changes is discussed in [2], wherein, low frequency displacement to the new status due to power demand changes has affected relative stability of the system. Robust stability of voltages and currents for islanded DGs was analyzed in [3] where discrete- time slipping mode control was used. In [4], small signal stability analysis is done by a combination of droop control and power averaging method for power sharing of several islanded DGs. Droop control is one of the most pertinent and useful control methods based on the behavior of synchronous generator of power systems. In this method, the control of real and reactive power sharing is adjusted using output frequency and voltage adjustment, respectively. Droop control does not need communication links. Some advantages (such as simplicity) and disadvantages (such as compromise between voltage adjustment and load sharing) of droop method are discussed in [5-7]. In Some studies such as [8, 9], the control of the real and reactive power of electronic-interfaced DGs in a microgrid was investigated. Robust control with harmonic suppression in islanding mode and power control without coupling in the grid-connected mode were discussed in [10, 11]. The load sharing using inherently oscillatory droop control was improved by the PI control in [12]. Transient sharing was also improved and resulted in better stability of frequency and current. In [13], the transient power sharing was improved using virtual impedance current limiting.

It is desirable in microgrids that all DGs respond similarly to the load steps to avoid overloading of some lead or lag DGs. When the impedances of two inverter-based DGs are not equal, the DG with smaller impedance responds more quickly to load steps and picks more power shared. To overcome the droop control drawbacks in load sharing of different DGs, modifications were applied in some researches. To correct the compromise of voltage adjustment and load sharing, feedback control [14, 15], dynamic coefficients [16, 17] and phase droop instead of frequency droop [18] have been used. For harmonic load sharing correction, the method of the extra loop for bandwidth [19] and virtual impedance [20-23] were proposed. Also, cooperative harmonic filtering was suggested in [24]. For coupling inductors degradation, virtual impedance method [20], variable virtual impedance [21, 22], and a method based on virtual power for real and reactive power decoupling for droop-controlled parallel inverters [25] were previously stated. For the problem of feeder impedances, an extra loop for grid impedance estimation was used in [26]. For a slow dynamic response, phase droop [27], adaptive decentralized droop [28], droop based on coupling filter parameters [29], and adaptive droop gains [30] have been proposed. For assembly of DGs, nonlinear droop control [31], a combination of droop control and MPPT [32] and power management of DGs [33] have been applied so far.

Some researches applied integrated control strategies called hierarchical structures which usually included primary, secondary and tertiary control [34-36]. In [37] a multitier hierarchical control of self-sustaining energy infrastructure with islanding and demand response capabilities for microgrids is presented. Hierarchical control strategy for enhancing the economics and the resilient operation of DC microgrid is stated in [38]. Hierarchical cooperative distributed control is also proposed in [39] that uses voltage, real and reactive power regulators to adjust voltage and frequency of inverters. Some new challenges for the frequency control and stability of power systems with the deregulation of power system in an electric vehicle(EV) are discussed in [40]. In this method, EV charging is controlled and, when necessary, EV battery is discharged in the grid. Also, an optimized fuzzy controller is used to control EVs.

In this paper, our purpose is to equalize the power sharing between two DGs by control of the voltage and frequency of the test microgrid in islanded mode. This paper uses a new method including two steps: virtual impedance and compensating voltage. Virtual impedance is used for transient power sharing. Compensating voltage step is used to model and estimate the relation of impedance differences and real and reactive powers and so the voltage drop difference is compensated in steady state. Therefore, this approach equalizes the real and reactive power sharing between two inverters with different feeder impedances. Simulation results verify this method.

The remainder of this paper is organized as follows; in section 2 the test microgrid model is proposed and the proposed method is discussed in section 3. In section 4, simulation results have been shown while in section 5, total harmonic distortion (THD) is discussed. Finally, the conclusion is stated in the last section of this paper, section 6.

2. SYSTEM MODEL

A simple microgrid model is assumed in Fig.1. In this figure, two inverter-based DGs with different feeder impedances are shown to feed the loads. Reference pulses produced from the control unit of each DG are injected to PWM of each inverter to adjust the output voltage and current of inverters. RC filter has been used for the two DGs to eliminate the harmonics. To control the microgrid frequency and voltage, droop control is used with following equations [41]:

$$\omega = \omega_s - mP \tag{1}$$

$$V = V^* - nQ \tag{2}$$

where m and n are the droop gains and ω_S is the synchronous frequency and V^* is the magnitude of reference output voltage of inverter. ω is the output voltage frequency, and P and Q are real and reactive power of inverter, respectively. Per these equations, the frequency is controlled by real power and the voltage is controlled by the reactive power of the DGs. If the feeder impedances of the two inverters are equal, i_{inv1} and i_{inv2} are equal too and the power sharing is similar. But in general cases, the feeder impedances are different and that impacts the power sharing.

3. PROPOSED METHOD

The control system of an inverter can be implemented in the synchronous reference frame (dq coordinates) or natural reference frame (abc coordinates).

In the abc coordinates, variables are sinusoidal but in dq coordinates, they are DC values, and PI control can be applied. The phase angle used by the abc to dq transformation module must be extracted from the grid voltages. The phase-locked loop (PLL) method is the state of art method in extracting the phase angle of the grid voltages.

The droop control method is one of the most applicable and simplest one for voltage and frequency control in microgrids system. But the main defect of this method is unbalanced initial load sharing between DGs during a load change in the system. In Fig.1feeder impedances of two DGs are not equal, and DG with smaller impedance picks more power relative to another DG with

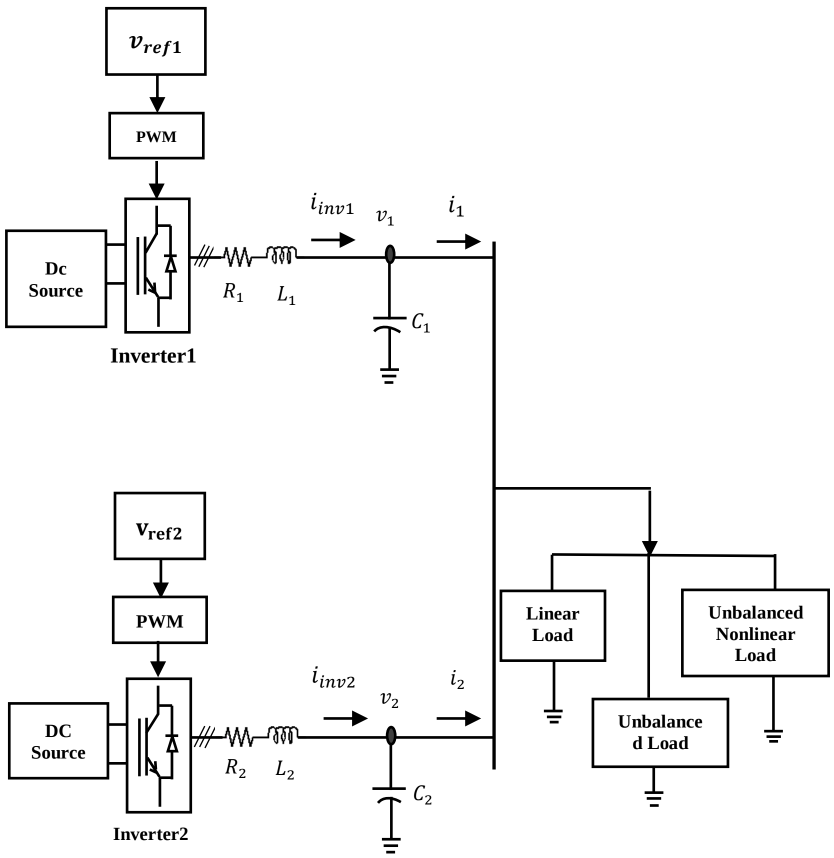


Fig.1. Simple microgrid model

greater impedance. Some researchers suggest the use of transient droop or adaptive droop to overcome this effect but these methods degrade the load sharing and voltage and frequency in the steady state. In this article, a control method is suggested, in which load sharing would be equalized between two DGs in both transient and stable mode, and frequency and voltage drop would be also negligible.

In order to apply the proposed method, dq coordinates are used. Thus, all voltages and currents in the control unit were transformed from abc to dq and also the real and reactive powers were calculated in this coordination. The Proposed method consists of two steps discussed below:

A. Virtual impedance

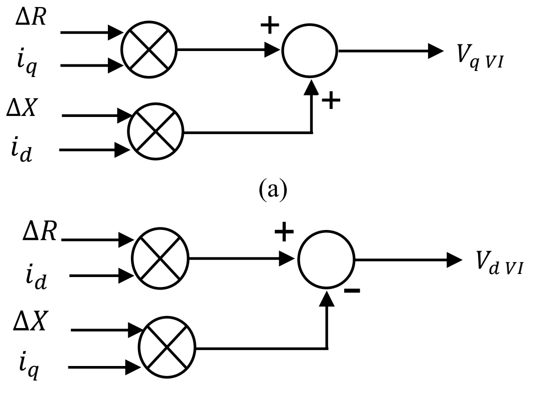
In the first step, the voltage drop on DG with smaller impedance must be modified. In other words, it is obvious that the voltage of DG with greater impedance cannot be reduced because that is not available. So, the impedance of DG with smaller impedance can be increased virtually in the control unit to equalize the voltage loss in both the DG feeder circuits. If there is a method to equalize the impedances, the voltage drops will be equal and that will ensure the similarity of the load sharing between two DGs. The difference between two impedances especially affects reactive power sharing because the reactive power is justified by the voltage. In this paper, it is assumed the impedance of DG1 is smaller. As mentioned, it is impossible to apply the real impedance in the feeder of DG1 so the virtual impedance must be used to modify the difference of voltage drops. The virtual impedance effect is more obvious in transient load sharing and less effective in stable mode. So, in the first step, the virtual impedance can be used as follows [42, 43]:

$$\Delta Z_{VI} = \Delta R_{VI} + j\Delta X_{VI} \quad (3)$$

$$V_{d\,VI} = \Delta R_{VI} i_d - \Delta X_{VI} i_q \quad (4)$$

$$V_{qVI} = \Delta R_{VI} i_q + \Delta X_{VI} i_d \quad (5)$$

These equations are depicted in Fig.2.



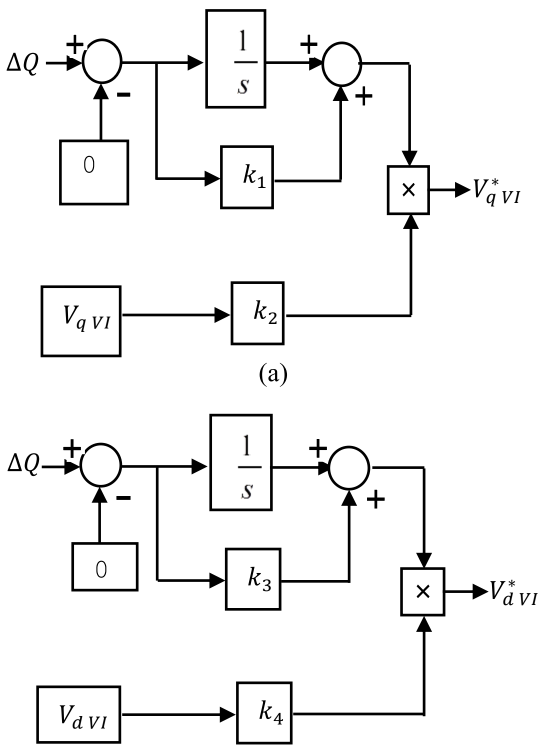
(a) (b)

Fig. 2. Virtual impedance in a) q-axis b) d-axis

For stability of the proposed method in transient power sharing, the least sensitivity to the change of feeder impedances and change of load types (such as common linear, unbalanced and nonlinear - unbalanced loads) the coefficient of applied virtual impedance is updated according to the equation below (in the case of equal droop gain):

$$\Delta Q = Q_1 - Q_2 \quad (6)$$

Then, this difference is controlled by PI controller to remain close to zero in the transient mode as shown in Fig.3.



(a) (b)

Fig.3. Block diagram for automatically adjusting virtual impedance in a) q-axis and b) d-axis

It is noticeable that the values of ΔR and ΔX are only the initial values or initial guesses of feeder impedance differences and the exact values are not really considered. In fact, the real values of feeder impedances are not available [44]. This does not raise a concern, because the feedback structure of Figure 3 is sufficient for stability and convergence of the transient mode of control circuit.

In the case of different droop gains (e.g., if droop gain of inverter 1 becomes double) the Eq.(6) changes as below:

$$\Delta Q = 2Q_1 - Q_2 \tag{7}$$

The above equation means that the inverter 1 picks more power of load, double the load sharing of the inverter 2.

The virtual impedance is calculated proportional to the voltage drop from above equations and directly decreases the voltage reference of the control unit of inverter 1. With this approach, the transient load sharing is improved between two DGs. This step has a great effect on proper transient load sharing of DG1 and DG2 and reduces voltage differences as shown in the next section. The modification of steady state load sharing will be done in the second step of the proposed algorithm.

B. Compensating Voltage

In step 2, the goal is a proper load sharing in steady state with negligible voltage and frequency drops from the reference values. The feeder impedance difference between two inverters is dependent on the powers and feeder impedances as follows [45, 46]:

$$\Delta Z = \frac{\Delta RP + \Delta XQ}{P + jQ} \tag{8}$$

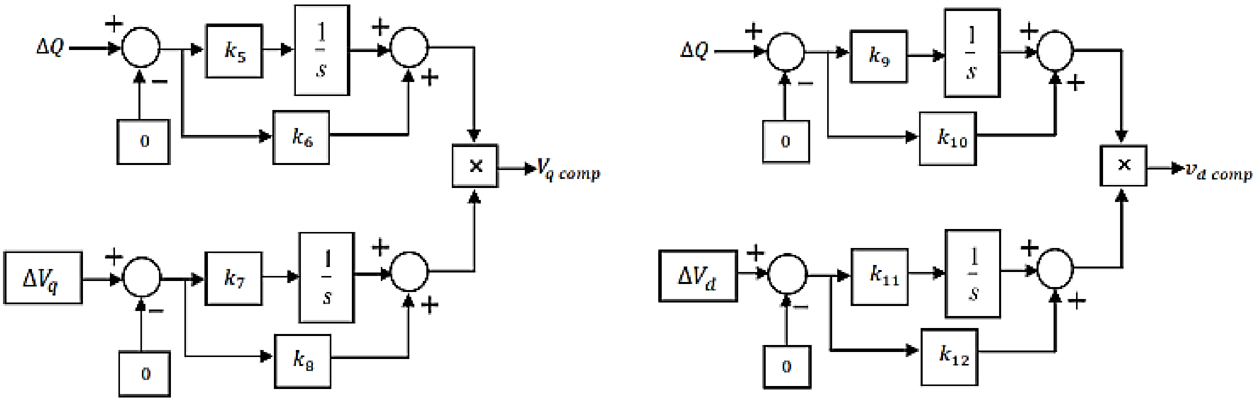
So, in order to define the compensating voltage, and due to the voltage and current relation in the power circuit, this impedance can be multiplied by d and q-axis currents to produce the required compensating voltage in two axes as below:

$$\begin{cases} \Delta V_d = \dfrac{(\Delta RP + \Delta XQ)}{P+Q}(i_q + i_d) \\ \Delta V_q = \dfrac{(\Delta RP + \Delta XQ)}{P+Q}(i_q - i_d) \end{cases} \tag{9}$$

This compensating voltage is needed to implement with known values of real and imaginary parts of feeder impedances; but as stated before, these values are not available [44]. Also, the proposed controller must be independent of feeder impedances, therefore the compensating voltage calculation is done based on reactive power differences (ΔQ) as shown in Eqs. (10) and (11) and implemented as Fig.4. The final compensating voltage calculation is done based on the initial guess of compensating voltage (as ΔV_q, ΔV_d) and reactive power differences (ΔQ). The gains α and β are updated automatically using PI controller and ΔQ.

$$\begin{cases} V_{qcomp} = \alpha\left[[\int k_7(\Delta V_q - 0)] + k_8(\Delta V_q - 0)\right] \\ \alpha = \left[[\int k_5(\Delta Q - 0)] + k_6(\Delta Q - 0)\right] \end{cases} \tag{10}$$

$$\begin{cases} V_{d\,comp} = \beta\left[[\int k_{11}(\Delta V_d - 0)] + k_{12}(\Delta V_d - 0)\right] \\ \beta = \left[[\int k_9(\Delta Q - 0)] + k_{10}(\Delta Q - 0)\right] \end{cases} \tag{11}$$



(a) (b)

Fig.4. a) The block diagram of $V_{q\ comp}$
b) The block diagram of $V_{d\ comp}$

By applying the PI controller, the same as virtual impedance, the weighted $V_{q\,comp}$ and $V_{d\,comp}$ can be automatically updated according to the new value of feeder impedances and for any kind of loads.

The general control unit of the proposed algorithm including voltage and frequency control of DG1 is shown in Fig.5.

The virtual impedance and compensating voltage will not be applied to the control circuit of inverter 2 since it is assumed the feeder impedance of inverter 1 is smaller than that in inverter 2.

Finally, the reference voltage signal in abc coordinates, v_{ref} is produced and used as a command signal for the PWM of the inverter to control the voltage and frequency of each DG.

The flowchart of system and control unit is shown in Fig.6.

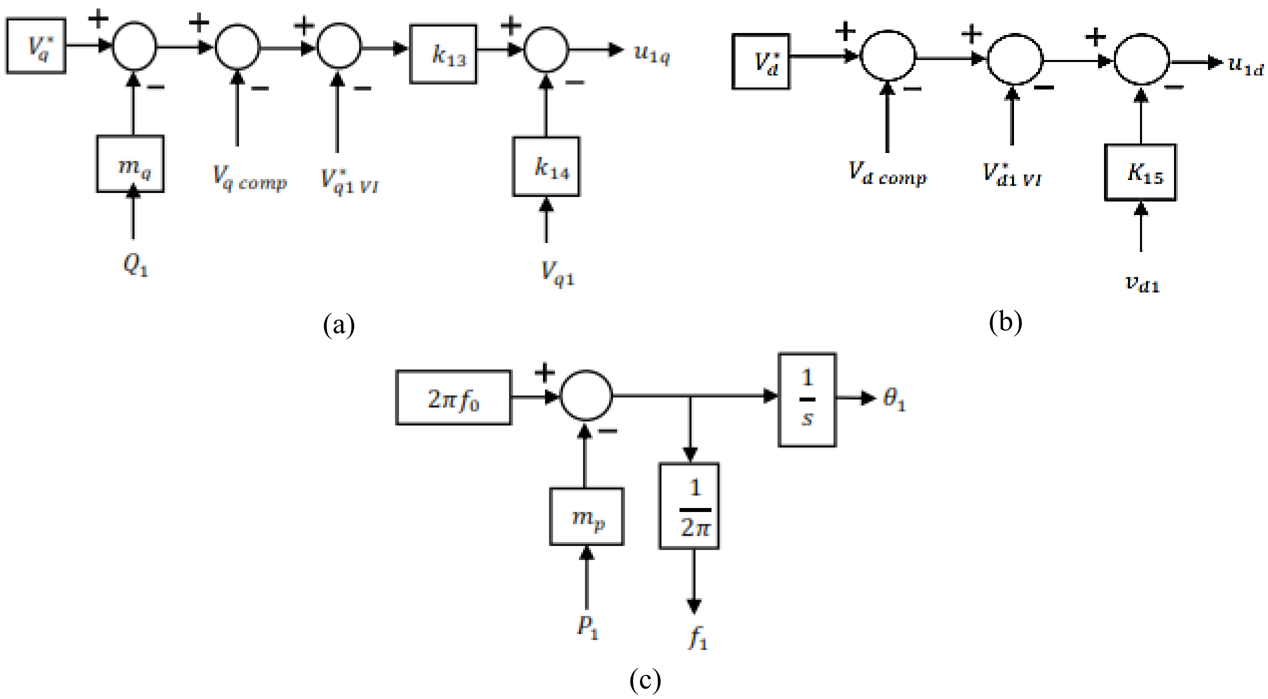


Fig.5. Control unit of DG_1 a) q-axis voltage control b) d-axis voltage control c) frequency control

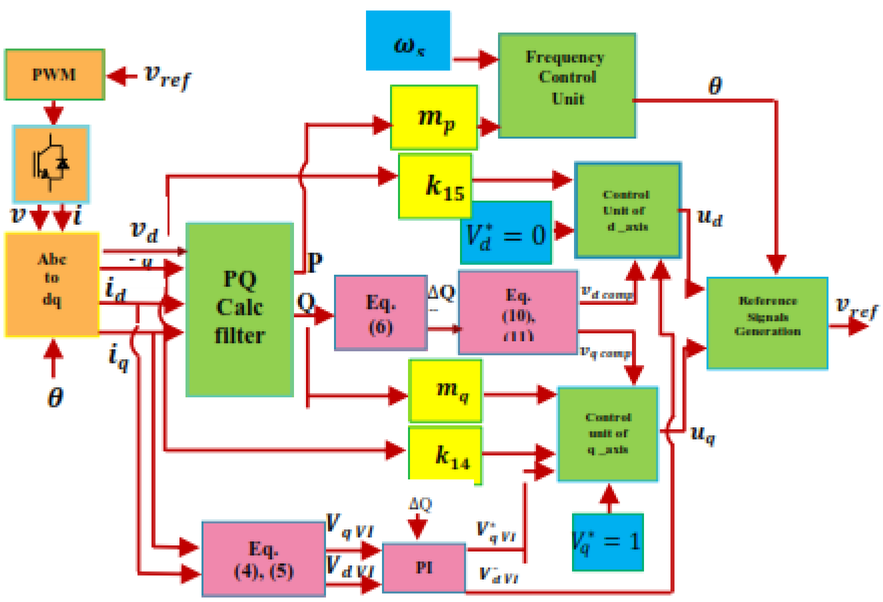


Fig.6. The flowchart of system and control unit

The proposed algorithm, as is shown in the next section has a good performance in real and reactive power sharing in both transient and stable modes.

4.Simulation Results

The proposed algorithm was simulated with Simulink/MATLAB using simpower toolbox. The simulation parameters are described in Table 1.

Before discussion of the results, it should be noted that the values are stated in per unit (P.U.).

In the simulation results, first we have investigated power sharing with linear, unbalanced and nonlinear - unbalanced loads separately in different interval times. Then the power sharing is analyzed in the case of these three loads simultaneously connected to the test microgrid in combination. In the following subsection, the simulation results of reactive power sharing are discussed first and then the same is done for the real power sharing.

In the simulation results, first we have investigated power sharing with linear, unbalanced and nonlinear - unbalanced loads separately in different interval times. Then the power sharing is analyzed in the case of these three loads simultaneously connected to the test microgrid in combination. In the following subsection, the simulation results of reactive power sharing are discussed first and then the same is done for the real power sharing.

A. Equal Droop Gain

1) Reactive Power Sharing

1-1) Power Sharing with Virtual Impedance

Figure 7 shows the reactive power sharing with V_{VI} (step 1 of the algorithm). As shown in this figure, it can be concluded that V_{VI} affects transient power sharing and by applying V_{VI} , transient part remains balanced and two inverters track each other without any overshoot in transient case. Also, it is

Table 1. Simulation Parameters

Parameters	Value
Frequency (Hz)	60
Voltage (Volt)	220
$S_{b1}(DG_1)$(KVA)	7
$S_{b2}(DG_2)$ (KVA)	9
Frequency droop slope ((rad/s)/ P_{pu}), m_p	2π
Voltage droop slope (V_{pu}/P_{pu}), m_q	0.05
k_1= k_3 (PI proportional virtual impedance Gain, inv1, q-axis and d-axis, respectively)	1
k_2 (virtual impedance Gain, inv1, q-axis)	0.1
k_4 (virtual impedance Gain, inv1, d-axis)	0.05
k_5=k_9 ($V_{q\ comp}$ PI integration Gain, inv1, q-axis and d-axis, respectively)	30
k_6 =k_8 ($V_{q\ comp}$ PI proportional Gain, inv1, q-axis)	2
k_7=k_{11} ($V_{q\ comp}$ PI proportional Gain, inv1, q-axis and d-axis, respectively)	500
k_{10}=k_{12} ($V_{d\ comp}$ PI proportional Gain, inv1, d-axis)	2
k_{13} (PI proportional voltage Gain, inv1, d-axis)	0.95
k_{14} =k_{15} (output voltage Gain, inv1, q-axis and d-axis, respectively)	0.1
Feeder impedance 1	1.1+j1.5
Feeder impedance 2	1.6+j2.45
RC filter	C=15µf, R=20

observed that the steady state part is not balanced, because the feeder impedances are different, and this difference causes an error in steady state reactive power sharing even with equal droop gains of two DGs.

1-2) Power Sharing with Proposed Method

The reactive power sharing result using the proposed method (virtual impedance and compensating voltage) has been shown in Figure 8. Both transient and steady state load sharing are balanced between two DGs and inverters track each other. Although with different feeder impedances, the proposed method by addition of the V_{comp} has compensated the voltage drop difference and the reactive power sharing is equalized.

2) Real Power Sharing

2-1) Power Sharing with Compensating Voltage

The real power sharing using (compensating voltage has been shown in Fig.9. The steady state mode becomes balanced. Thus, compensating voltage has affected steady state mode in real power sharing. From this figure, it can be suggested that only transient power sharing is degraded especially for linear and nonlinear-unbalanced loads, due to impedance differences between two DGs. In fact, inverter 1 overshoots when a load is connected initially and picks more power. As the transient time passed, the load sharing becomes approximately equalized.

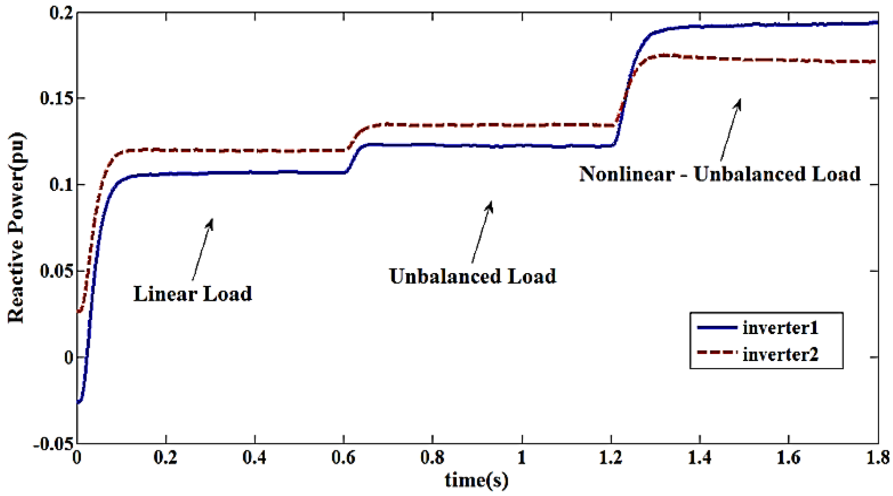


Fig.7. Reactive power sharing using the virtual impedance

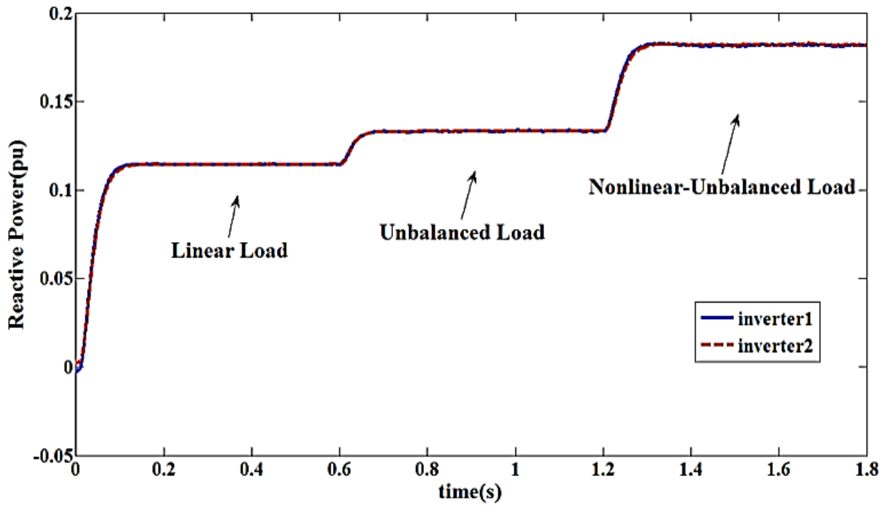


Fig.8. Reactive power sharing using the proposed algorithm

2-2) Power Sharing with Proposed Method

In Fig.10, it is shown that using the proposed method (virtual impedance and compensating voltage), both transient and steady state real power sharing become balanced and two DGs track each other with equal droop gains and different feeder impedances. It can be concluded that virtual impedance influences transient mode and compensating voltage influences steady-state mode.

B. Different Droop Gain

In this section, the behavior of the test microgrid under different feeder impedances and different droop gains is discussed. The simulation results show the real and reactive power is shared between two DGs proportional to their droop gains. The simulation parameters are the same as in Table 1.

1) Power Sharing Accuracy

To investigate the accuracy of power sharing of proposed method in different droop gains, the accuracy error is defined and analyzed as below:

$$accuracy\ error\% = \frac{Q_{ref} - Q_0}{Q_{ref}} \times 100 \quad (12)$$

where Q_{ref} and Q_o are the planned and output reactive power of inverter, respectively. It can be seen that when the various loads are connected to the microgrid in methods other than the proposed one, the accuracy error increases. But by applying the proposed method, the accuracy of power sharing is not degraded and it is bound to a small value near to zero.

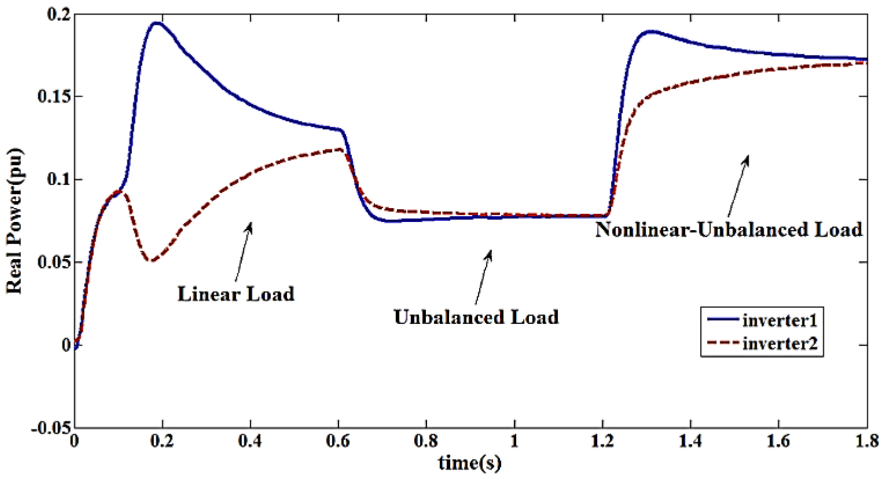


Fig.9. Real power sharing with compensating voltage

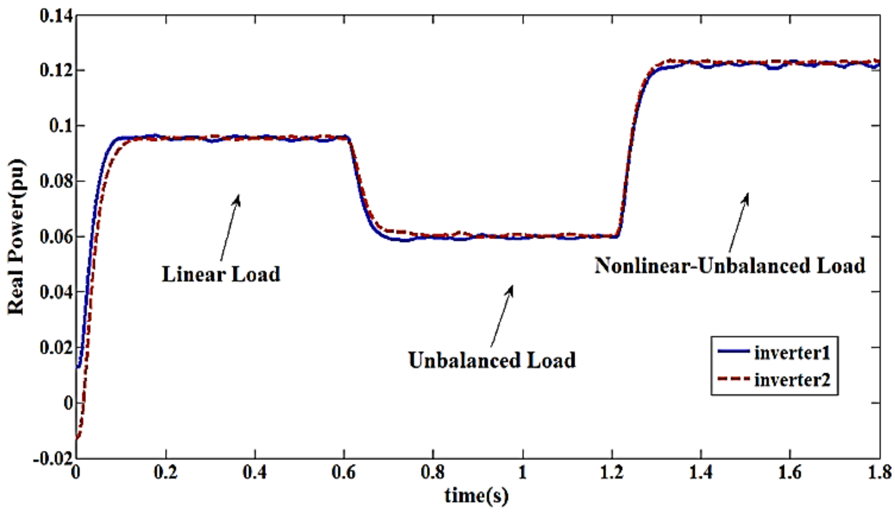


Fig.10. Real power sharing using the proposed method

2) Reactive Power Sharing

2-1) Power Sharing with Virtual Impedance

The reactive power sharing with the application of the first step of the proposed method (virtual impedance) has been shown in Fig.11 when droop gains ratio is 2:1. From this figure, it can be concluded that transient sharing of two inverters approximately track each other. But in steady state mode, reactive power sharing between two DGs is not divided proportionally to the droop gains and the accuracy error is high.

The accuracy error for linear, unbalanced and nonlinear-unbalanced load is 18.42%, 22.4% and 8.63% for inverter 1, and -36.84%, -44.79% and -17.25% for inverter 2, respectively.

2-2) Power Sharing with Proposed Method

The reactive power sharing result using the proposed method (virtual impedance and compensating voltage) has been shown in Fig. 12. Both the transient and steady state load sharing are balanced between two DGs and the inverters track each other proportional to their droop gains. So even with different feeder impedances, compensating voltage affects the steady state sharing to improve it. Addition of the V_{comp} to virtual impedance has modified the voltage drop difference and the reactive power sharing is done according to the droop gains. The accuracy errors for linear, unbalanced and nonlinear-unbalanced load are 1.8%, 0.33% and 0.0% for inverter 1 and 0.9%, 0.1% and 0.0% for inverter 2, respectively.

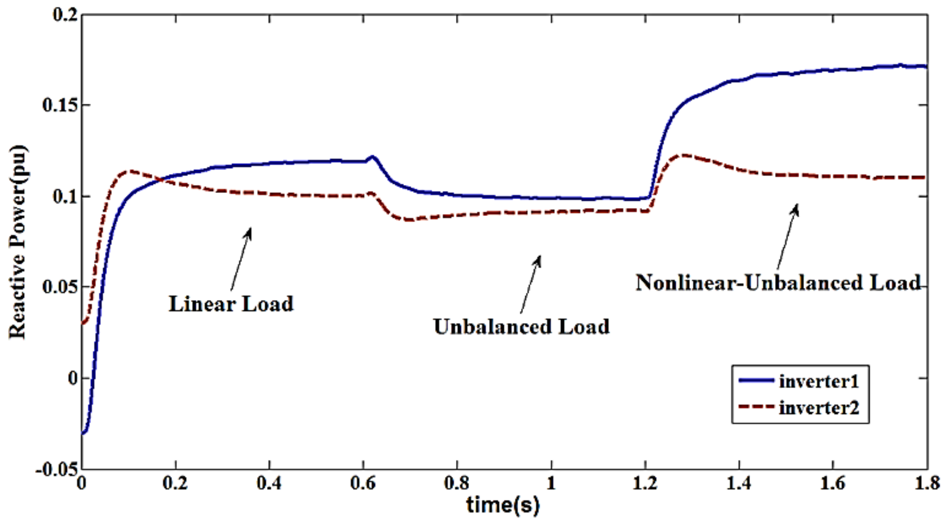


Fig.1. Reactive power sharing with virtual impedance in droop gain 2:1

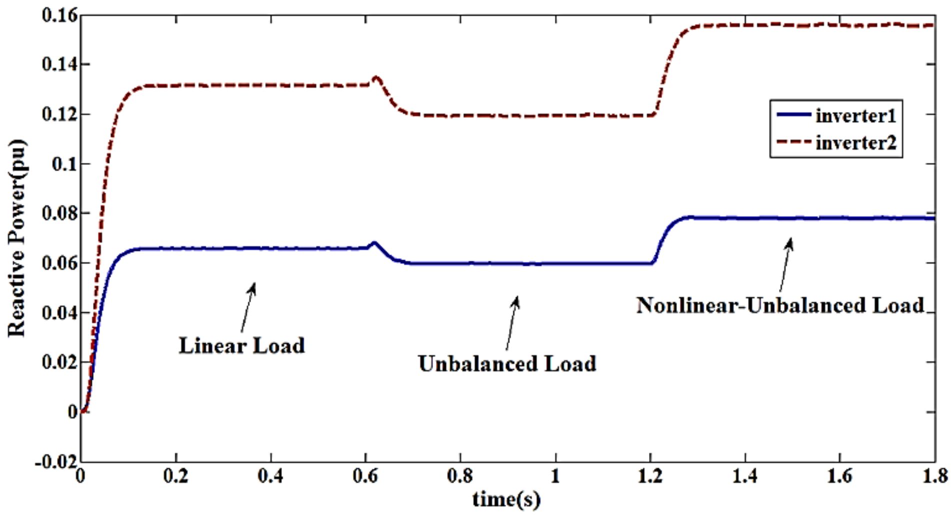


Fig.12. Reactive power sharing using the proposed method with droop gain 2:1

3) Real Power Sharing

3-1) Power Sharing with Compensating Voltage

Figure 13 shows the real power sharing with only the step 2 of the proposed method. As shown and expected, when the transient time passed, the compensating voltage affects the stable mode of real power sharing and it is divided approximately in the ratio of 2:1. Also, we can see the transient power sharing is degraded due to the impedance difference between two DGs. In fact, DG2 overshoots when the load is connected and picks more power to support the load because of the smaller impedance. The respective accuracy error of inverter 1 for linear, unbalanced and nonlinear - unbalanced load is -12%, -0.31% and 0.8% and it is 0.06%, 0.15% and -0.44% for inverter 2.

3-2) Power Sharing with Proposed Method

In Fig.14, it is shown that using the proposed method, both the transient and steady state parts of real power are shared accurately according to a droop gain ratio of 2:1. It is shown that with different feeder impedances, two inverters track each other so that inverter 2 picks twice the power compared to inverter 1. Also, using the virtual impedance, the transient part of Fig.13 is modified and the result is improved. The accuracy errors for linear, unbalanced and nonlinear-unbalanced load are -0.03%, -0.1% and -0.1% for of inverter 1 and are 0.06%, 0.36% and 0.23% for inverter 2, respectively.

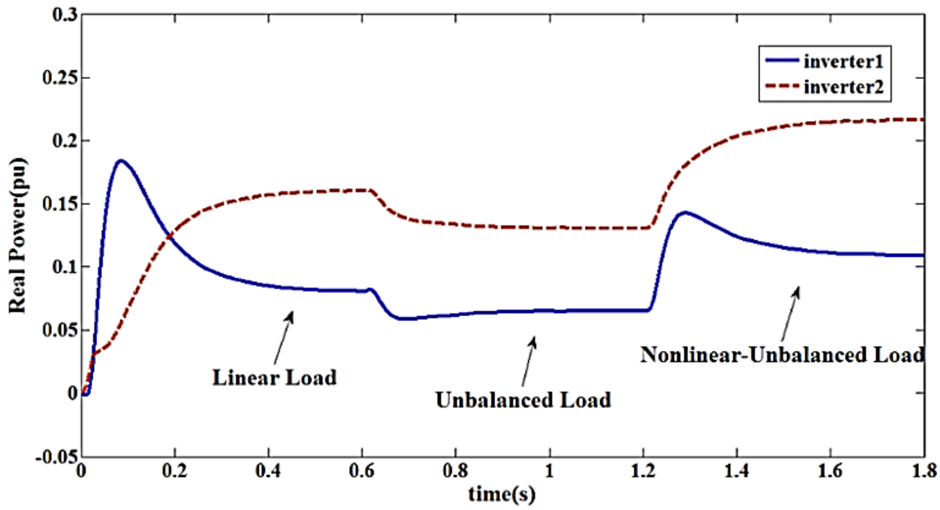


Fig.13. real power sharing with using compensating voltage in droop gain 2:1

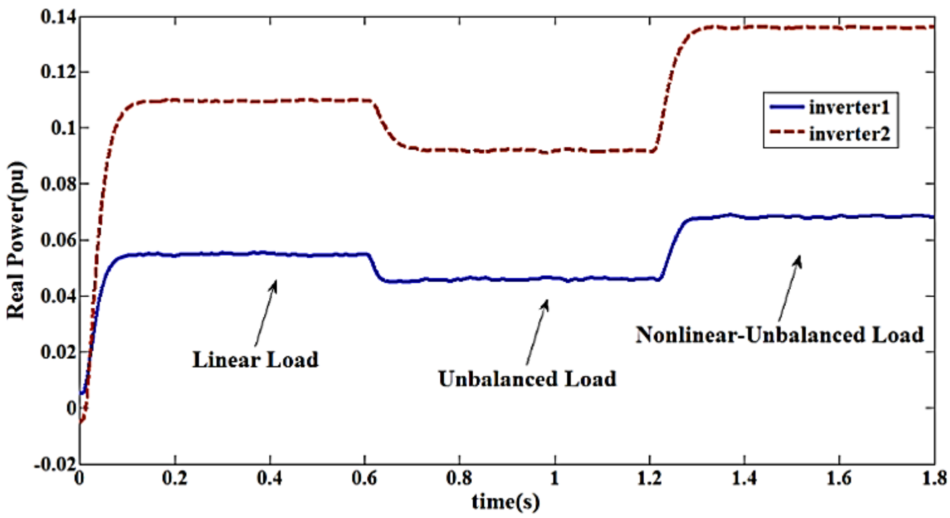


Fig.14. Real power sharing using the proposed method in droop gain 2:1

C. Investigation of Feeder Impedance Change on Power Sharing

1)Reducing Feeder Impedance of Inverter 1 (20 Percent)

In this section, the robustness of the proposed method in case of a higher difference between the feeder impedances of two inverters is evaluated. First, the feeder impedance of inverter 1 (with smaller impedance) is again reduced about 20 percent from its first value while the feeder impedance of inverter 2 is not changed. Thus, the impedance difference of two inverters is increased and the results are shown in Figs. 15 and 16 for reactive and real power, respectively. The reactive power sharing errors for linear, unbalanced and nonlinear-unbalanced load are 0.06%, -0.08% and 0.0% for inverter 1 and are 0.0%, -0.08% and 0.0% for inverter 2, respectively.

The real power sharing errors for linear, unbalanced and nonlinear-unbalanced load are -0.2%, 0.0% and -0.56% for inverter 1 and are 0.12%, 0.0% and 0.28% for inverter 2, respectively.

2) Increasing Feeder Impedance of Inverter 2 (20 Percent)

In this test case, the feeder's impedance of inverter 2 is increased up to 20 percent when the feeder impedance of inverter 1 remains fixed. Figures 17 and 18 show reactive and real power sharing between the two inverters. The results verify the robustness of the proposed method to change of feeder's impedance.

5. Conclusion

In this article, following a description of a conventional droop control method, an implementation of transient power sharing is explained. A new robust droop control for microgrid's inverters has been developed using virtual impedance and compensating voltage control loops.

The proposed method was verified by three case studies: different droop gains, nonlinear and unbalanced load and different feeder impedance.

The results show an improvement in the

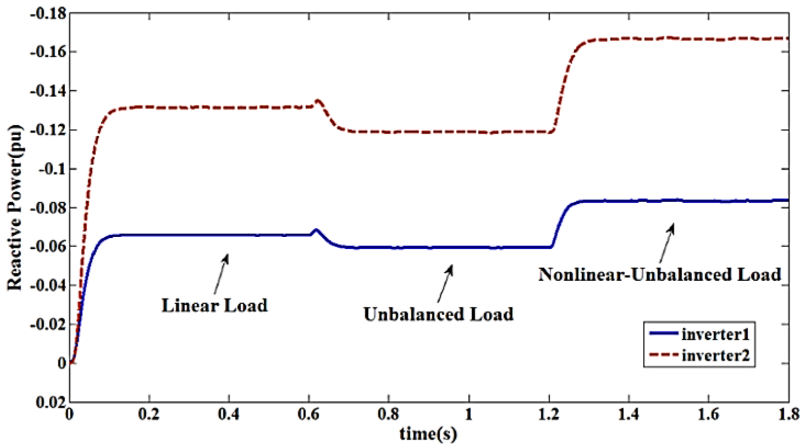


Fig.15. Reactive power sharing using the proposed method with 20 percent reduction in feeder impedance of inverter 1

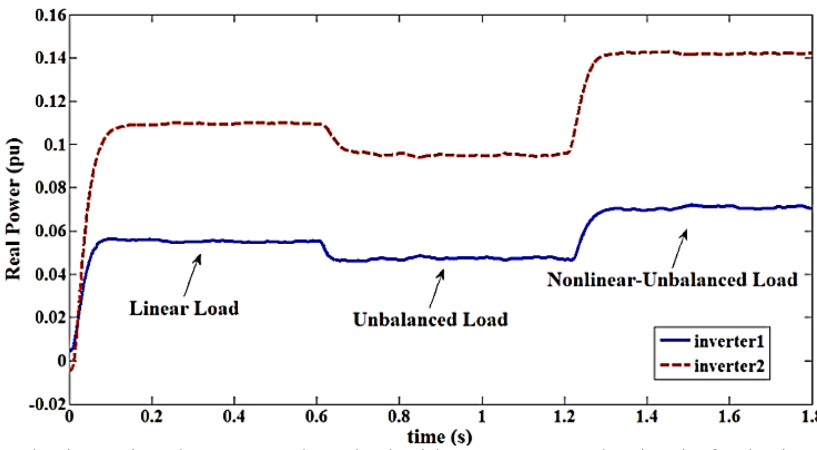


Fig.16. Real power sharing using the proposed method with 20 percent reduction in feeder impedance of inverter 1

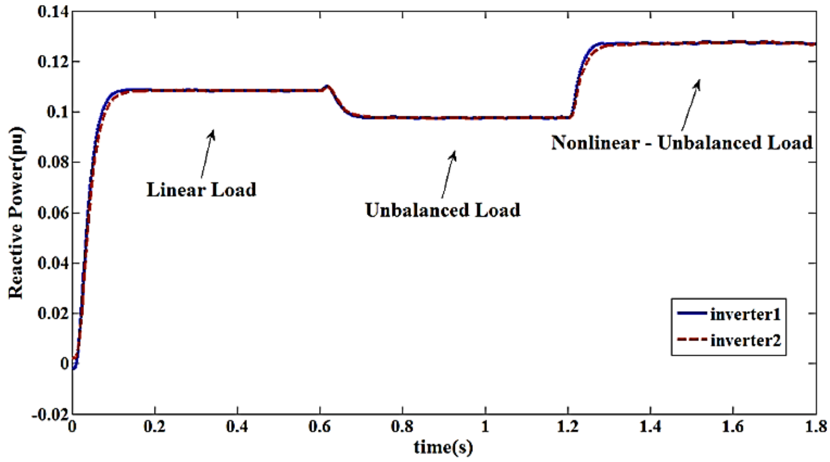


Fig.17. Reactive power sharing using the proposed method with 20 percent addition in feeder impedance of inverter 2

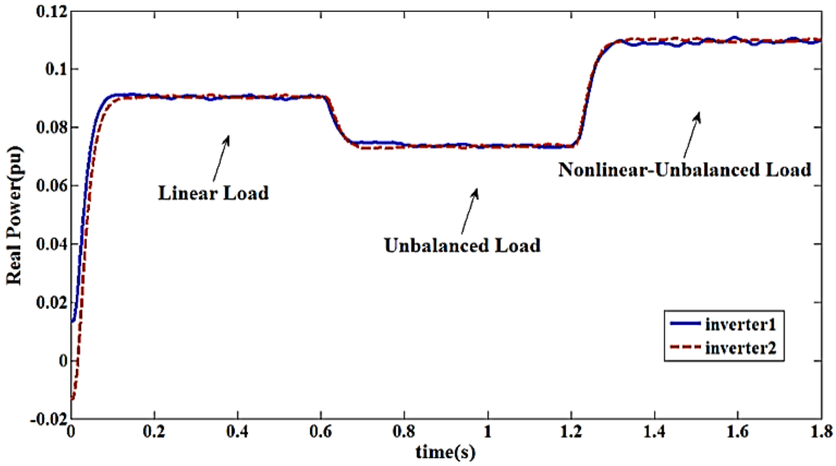


Fig.18. Real power sharing using the proposed method with 20 percent addition in feeder impedance of inverter 2

power-sharing accuracy and system robustness when compared with the previous control method. This control method could also be applied well for microgrids with multiple DGs.

References

[1] Majumder R., Modeling Stability Analysis and Control of Microgrid, Ph. D. Thesis, Queensland University of Technology (2010).

[2] Vilathgamuwa D. M., Loh P. C., Li Y., Protection of Microgrids During Utility Voltage Sags, IEEE Transactions on Industrial Electronics (2006) 53: 1427-1436.

[3] Marwali M. N., Dai M., Keyhani A., Robust Stability Analysis of Voltage and Current Control for Distributed Generation Systems, IEEE Transactions on Energy Conversion (2006) 21(2): 516-526.

[4] Marwali M. N., Dai M., Keyhani A., Stability Analysis of Load Sharing Control for Distributed Generation Systems, IEEE Transactions on Energy Conversion (2007) 22(3):737-745.

[5] Chandorkar M., Divan D., Decentralized Operation of Distributed ups Systems International Conference on Power Electronics, Drives and Energy Systems for Industrial Growth (1995) 1: 565–571.

[6] Guerrero J., Berbel N., Vicuna L. de, Matas J., Miret J., Castilla M., Droop Control Method for the Parallel Operation of Online Uninterruptible Power Systems using Resistive Output Impedance, IEEE Applied Power Electronics Conference and Exposition (APEC)(2005)1716–1722.

[7] Guerrero J., Vicuna L. de, Matas J., Castilla M., Miret J., Output Impedance Design of Parallel-Connected ups Inverters with Wireless Load-Sharing control, IEEE Transactions on Industrial Electronics (2005)52(4): 1126–1135.

[8] Katiraei F., Iravani M. R., Power Management Strategies for a Microgrid with Multiple Distributed Generation Units, IEEE Transactions on Power Systems (2006)21: 1821-1831.

[9] Azim M. I., Hossain M. A., Hossain M. J., Pota H. R., Effective Power Sharing Approach for Islanded Microgrids, Smart Grid Technologies - Asia (ISGT ASIA), IEEE Innovative, Bangkok(2015)1-4.

[10]Reza M., Sudarmadi D., Viawan F. A., Kling W. L., Van Der Suis L., Dynamic Stability of Power Systems with Power Electronic Interfaced DG, In Power Systems Conference and Exposition, PSCE06, IEEE PES (2006) 1423-1428.

[11]Zhong Q. C., Robust Droop Controller for Accurate Proportional Load Sharing Among Inverters Operated in Parallel, IEEE Transactions on Industrial Electronics (2013) 60(4):1281-1290.

[12]Guerrero J., Vicuna L. de, Castilla J. M., Miret J., A Wireless Controller to Enhance Dynamic Performance of Parallel Inverter in Distributed Generation Systems, IEEE Transactions on Power Electronics (2004) 19:1205-1213,.

[13] Paquette A. D., Divan D. M., Virtual Impedance Current Limiting for Inverters in Microgrids with Synchronous Generators, IEEE Transactions,Industry Applications (2015) 51(2):1630-1638.

[14]Kim J., Guerrero J. M., Rodriguez P., Teodorescu R., Nam K., Mode Adaptive Droop Control with Virtual Output Impedances for an Inverter-Based Flexible AC Microgrid, IEEE Transactions on Power Electronics (2011) 26(3): 689–701.

[15] Katiraei F., Iravani R., Hatziargyriou N., Dimeas A., Microgrids Management, IEEE Transactions on Power (2008) 6:54–65.

[16] Diaz G., Gonzalez-Moran C., Gomez-Aleixandre J., Diez A., Scheduling of Droop Coefficients for Frequency and Voltage Regulation in Isolated Microgrids, IEEE Transactions on Power Systems (2010)25:489–496.

[17] Lee C. T., Chu C.-C., Cheng P.-T., A New Droop Control Method for the Autonomous Operation of Distributed Energy Resources Interface Converters, IEEE Transactions on Power Electronics (2013) 28(4):1980–1993.

[18]Sao C. K., Lehn W., Autonomous Load Sharing of Voltage Source Converters, IEEE Transactions on Power Del (2005)20:1009–1016.

[19]Sao C. K., Lehn W., Control and Power Management of Converter Fed Microgrids, IEEE Transactions on Power Systems (2008) 23: 1088–1098.

[20]Marwali M. N., Jung J. W., Keyhani A., Control of Distributed Generation Systems–Part II: Load Sharing Control, IEEE Transactions on Power Electronics (2004) 19: 1551–1561.

[21] Lee T. L., Cheng P. T., Design of a New Cooperative Harmonic Filtering Strategy for Distributed Generation Interface Converters in an Islanding Network, IEEE Transactions on Power Electronics (2007) 22: 1919–1927.

[22] Vasquez J. C., Guerrero J. M., Luna A., Rodriguez P., R. Teodorescu, Adaptive Droop Control Applied to Voltage-Source Inverters Operating in Grid-Connected and Islanded Modes, IEEE Transactions on Industrial Electronics, (2009) 56: 4088–4096.

[23] HeJ., Li Y. W., Guerrero J. M., An Islanding Microgrid Power Sharing Approach Using Enhanced Virtual Impedance Control Scheme, IEEE Transactions on Power Electronics, (2013) 28(11):5272-5282.

[24] Li Y., Li Y. W., Power Management of Inverter Interfaced Autonomous Microgrid Based on Virtual Frequency-Voltage Frame, IEEE Transactions Smart Grid (2011) 2: 30–40.

[25]Wu T., Liu Z., Liu J., Wang S., You Z., A Unified Virtual Power Decoupling Method for Droop-Controlled Parallel Inverters in Microgrids, In IEEE Transactions on Power Electronics (2016) 31(8): 5587-5603.

[26]Yao W., Chen M., Matas J., Guerrero J. M., Qian Z., Design and Analysis of the Droop Control Method for Parallel Inverters Considering the Impact of the Complex Impedance on the Power Sharing, IEEE Transactions on Industrial Electronics (2011) 58: 576–588.

[27]Yazdani D., Bakhshai A., Joos G., Mojiri M., A Nonlinear Adaptive Synchronization Technique for Grid-Connected Distributed Energy Sources, IEEE Transactions on Power Electronics (2008) 23: 2181–2186.

[28]McGrath B. P., Holmes D. G., Galloway J. J. H., Power Converter Line Synchronization using a Discrete Fourier Transform (DFT) Based on a Variable Sample Rate, IEEE Transactions on Power Electronics(2005) 20: 877–884.

[29]Lee S. J., Kim H., Sul S. K., Blaabjerg F., A Novel Control Algorithm for Static Series Compensators by use of PQR Instantaneous Power Theory, IEEE Transactions on Power Electronics (2004) 19: 814–827.

[30]Yazdani A., Iravani R., A Unified Dynamic Model and Control for the Voltage Source Converter under Unbalancedd Grid Conditions, IEEE Transactions on Power Del (2006) 21: 1620–1629.

[31] Savaghebi M., Jalilian A., Vasquez J. C., Guerrero J. M., Secondary Control Scheme for Voltage Unbalanced Compensation in an Islanded droop-Controlled Microgrid, IEEE Transactions Smart Grid (2012) 3(2): 797-807.

[32]Vanthournout K., Brabandere K. D., Haesen E., Driesen J., Deconinck G., R. Belmans, Agora, Distributed Tertiary Control of Distributed Resources, In Proceedings 15th Power Systems Computation Conference (2005) 1–7.

[33] Setiabudy R., Bs H., Budiyanto, Development Energy Management Strategy to Optimize Battery Operation in Islanding Microgrid using Zero One integer programming," Quality in Research (QiR), 2015 International Conference on, Lombok (2015) 125-128.

[34]Guerrero J. M., Vasquez J. C., Matas J., Hierarchical Control of Droop-Controlled AC and DC Microgrids—A General Approach Toward Standardization, IEEE Transactions on Industrial Electronics, (2011) 58(1):158-172.

[35]Guerrero J. M., Loh P., Chandorkar M., Advanced Control Architectures for Intelligent MicroGrids−Part I, Decentralized and Hierarchical Control, IEEE Transactions on Industrial Electronics (2013) 60(4):1254-1262.

[36]Zhang Y., Xie L., Ding Q., Interactive Control of Coupled Microgrids for Guaranteed System-Wide Small Signal Stability," in IEEE Transactions on Smart Grid (2016) 7(2):1088-1096.

[37]Khodayar M., Shahidehpour M., Cutting Campus Energy Costs with Hierarchical Control: The Economical and Reliable Operation of a Microgrid," IEEE Electrification Magazine (2013) 1(1):40-56.

[38]Che L., Shahidehpour M., DC Microgrids, Economic Operation and Enhancement of Resilience by Hierarchical Control, IEEE Transactions on Smart Grid (2014) 5(5): 2517-2526.

[39] Nasirian V., Shafiee Q., Guerrero J. M., Lewis F. L., Davoudi A., Droop-Free Distributed Control for AC Microgrids," in IEEE Transactions on Power Electronics (2016) 31(2):1600-1617.

[40]Falahati S., Taher S., M Shahidehpour, Smart Deregulated Grid Frequency Control in Presence of Renewable Energy Resources by EVs Charging Control, IEEE Transaction on Smart Grid (2016).

[41]Chandorkar M. C., Divan D. M., Adapa R., Control of Parallel Connected Inverters in Standalone ac Supply Systems, IEEE Transactions Industry Applications (1993) 29(1).

[42]Rocabert J., Luna A., Blaabjerg F., Rodriguez P., Control of Power Converters in AC Microgrids, IEEE Transactions on Power Electronics (2012) 27:4734-4749,.

[43] Brabandere K. De, Voltage and Frequency Droop Control in Low Voltage Grids by Distributed Generators with Inverter Front-End, Ph.D. Dissertation, Faculteit Ingenieurswetenschappen, K.U. Leuven, Belgium (2006).

[44]Mahmood H., Michaelson D., Jiang J., Accurate Reactive Power Sharing in an Islanded Microgrid Using Adaptive Virtual Impedances, IEEE Transactions Power Electronics (2015) 30 (3):1605-1617.

[45]Li Y. W., Kao C. N., An Accurate Power Control Strategy for Power Electronics-Interfaced Distributed Generation Units Operating in a Low Voltage Multibus Microgrid, IEEE Transactions on Power Electronics (2009)24 (12): 2977–2988.

[46]He J., Li Y. W., An Enhanced Microgrid Load Demand Sharing Strategy, IEEE Transactions on Power Electronics (2012) 27(9):3984–3995.