Iranian Journal of Electrical and Electronic Engineering 03 (2020) 269–278
Special Issue on Smart Grids

Iran University of Science and Technology

Iranian Journal of Electrical and Electronic Engineering

Journal Homepage: ijeee.iust.ac.ir

Research Paper

A New Approach for Voltage Balancing and Appropriate Power-Sharing in Autonomous Microgrids

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Abstract: This paper suggests a new control method to modify the virtual impedance performance in unbalanced conditions. The proposed method compensates the voltage drop that occurred due to the virtual impedance and adjusts the voltage of the point of common coupling at a desirable level. To compensate the voltage drop, the reference voltage in the droop control varies according to the proposed algorithm. Moreover, a modified decoupled double synchronous reference frame is introduced to achieve appropriate active and reactive power sharing and voltage balancing, simultaneously. Finally, the simulation results in MATLAB/Simulink are provided to validate the accuracy and effectiveness of the proposed approach.

Keywords: Power Sharing, Virtual Impedance, Droop Control, Voltage Drop Compensation, Voltage Unbalance.

1 Introduction

ENVIRONMENTAL concerns arising from the use of fossil fuels have led to an increase in the inclination to use Renewable Energy Sources (RES). These resources, such as wind turbines, hydropower, and photovoltaics, are often available as Distributed Generation units (DGs) [1]. To increase the reliability, a number of DG units, and Energy Storage Systems (ESSs), are connected to the load by power electronic converters, and the overall system is widely known as a Microgrid (MG) [2]. Fig. 1 shows the structure of an MG with parallel-connected DG units. MGs have two operating modes: grid-connected and autonomous or islanded [3]. In the grid-connected mode, DGs have the only task to supply portion of the load power and the frequency and voltage regulation is the grid responsibility. However, the autonomous operation is challenging because in this case, in addition to local load supply, other functions such as voltage and frequency control are also undertaken by DGs [3].

Due to the increase of sensitive electronic equipment, the issue of power quality is more pay attention than ever. One of the important parameters of power quality is the voltage unbalance. The imbalance in MGs is inevitable for different reasons, such as single-phase loads or single-phase sources, fault in the system, etc. Unbalanced voltage leads to higher losses, reducing the stability of MGs, and causes problems in the consumer equipment and the operation of MG [4]. Due to the aforementioned drawbacks, the IEC recommends that the voltage imbalance in electrical systems is limited to 2% [5].

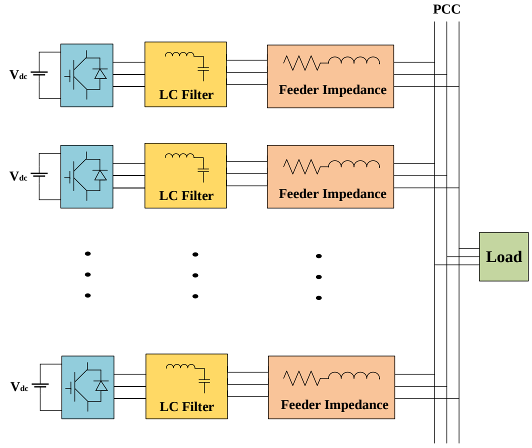

Fig. 1 The structure of MG with several DG units.

Iranian Journal of Electrical and Electronic Engineering, 2020.
Paper first received 30 October 2019, revised 10 February 2019, and accepted 13 February 2019.
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Another important issue in the autonomous operation is that the load power should be correctly shared among DG units according to their power ratings [6]. Among the power sharing methods, the droop control is more popular [7-9]. However, under imbalance conditions, conventional methods cannot be effectively exploited. Different techniques have been offered in the past studies for power sharing in unbalanced voltage conditions. In [10], the authors have solved the effects of the unbalanced voltage by generating the negative sequence current. In [11], the virtual resistivity-based control strategy for reactive power sharing is introduced under the inconsistent feeder impedance and nonlinear load and imbalance situation. Although, if the feeder or load is detached, the system will be non-stable, which will limit its practical applications. In [12], the positive sequence power is used to generate voltage reference and the negative sequence reactive power is used to compensate the unbalanced voltage, which enables the power sharing. However, the voltage drop caused by the virtual impedance is not considered. In [13], the authors have proposed an algorithm to compensate the voltage drop, in the balanced load conditions. In [14], a Q-G controller is used for imbalance compensation, but if the impedance of the DG's feeder is different, sharing is not done correctly. The negative sequence current using the negative sequence impedance controller in [15] is fully compensated through the sharing among DGs. In [16], a frequency droop is used to compensate the reactive power sharing errors, imbalance, and harmonic. Using frequency droop control, some active power variation is generated which regulates the virtual impedance of DG unit. A hierarchical control approach for voltage imbalance is suggested by sending appropriate control signals from a central secondary controller to the primary level in [17]. In [18], local DER controllers are divided into primary and secondary levels to compensate the voltage unbalance. The secondary layer collects information from all DERs and provides control rules for controlling the primary level using the averaging technique. In [19], a hierarchical control structure is used to control the Voltage Unbalance Factor (VUF) of the Point of Common Coupling (PCC) and shares a current unbalance among generators. One of the problems regarding to the proposed approaches in [15-19] is that these approaches require a communication link that leads to higher prices and less reliability. The authors in [20] have designed a current sharing controller in a stationary frame for low-voltage grid in islanded mode, which divides the current in the positive, negative, and zero sequences. However, current limiting, in order to prevent DG overload, especially during fault conditions, is a major problem due to the fact that the signals fed to the controllers in the stationary frame must be sinusoidal. The MG unbalanced voltage can be compensated by using a double synchronous reference frame (DSRF) in the d-q reference frame [21]. However, the oscillatory coupling between the positive and negative sequence components degrades the efficiency of the control system [22]. In [23] the Decoupled Double Synchronous Reference Frame (DDSRF) has been introduced for using in the current controller under unbalanced voltage condition to eliminate oscillatory coupling. However, DDSRF is not used for the voltage balancing, as well as it is assumed that the positive and negative sequence of the reference currents are dc and have not the oscillatory component.

In this paper, the DDSRF has been modified to increase the accuracy of the oscillatory component estimation. In addition, this paper proposes that the modified DDSRF can be used in the control system of inverter-interfaced DGs to compensate the unbalanced voltage. So, the load power can be appropriately shared among DGs despite the unbalanced load connection. Moreover, the voltage drop caused by the virtual impedance is also compensated. Furthermore, the proposed method does not require a communication link which increases the reliability.

The main contributions of this paper can be highlighted as:

- Introducing a modified DDSRF to increase the accuracy of the oscillatory component estimation.
- Proposing a control system based on the modified DDSRF to compensate the unbalanced voltage in the d-q reference frame.
- Appropriate power sharing under the unbalanced condition without a communication link.

The remainder of this paper is as follows. In Section 2, a brief description of the droop control, virtual impedance and conventional DDSRF are given. The proposed DDSRF is presented in Section 3. The proposed control strategy for voltage balancing, and the proposed algorithm to compensate the voltage drop caused by the virtual impedance are presented in Section 4. In Section 5, the test system and simulation results are reported. Finally, in Section 6, conclusions are drawn.

2 Basic Principle of Droop Control, Virtual Impedance, and Conventional DDSRF

This paper probes an MG, which comprises two parallel inverter-interfaced DGs that are operated in islanding mode. Each DG is connected to the PCC through an LC filter. In this paper, the main control blocks used in the DGs control system are the droop control, virtual impedance, and conventional DDSRF, which are discussed in brief in the following sections.

2.1 Droop Control

Fig. 2 shows the equivalent circuit of an inverter connected to a load bus. The complex power delivered to the bus are as follows:

$$S = P + jQ \tag{1}$$

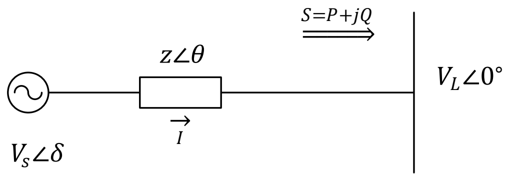


Fig. 2 Equivalent circuit of an inverter connected to a load bus.

wherein

$$P = \frac{V_S^2}{Z}\cos\theta - \frac{V_S \times V_L}{Z}\cos\left(\theta+\delta\right) \tag{2}$$

$$Q = \frac{V_S^2}{Z}\sin\theta - \frac{V_S \times V_L}{Z}\sin\left(\theta+\delta\right) \tag{3}$$

Whenever the output impedance of the inverter is inductive, (2) and (3) can be simplified as follows:

$$\cos\theta \approx 0 \Rightarrow \begin{cases} P = \dfrac{V_S \times V_L}{X}\sin\delta \\ Q = \dfrac{V_S^2}{X} - \dfrac{V_S \times V_L}{X}\cos\delta \end{cases} \tag{4}$$

These equations indicate that in this state, there is a straight relationship between the frequency and the active power and as well as between the voltage amplitude and the reactive power, which is the principle of droop control operation. Actually, droop control is an imitation of the steady-state treatment of synchronous generator (SG) [24]; where by increasing demand for the active power, the frequency is reduced and vice versa. The main advantage of the droop method is that it does not require a communication link for the load sharing which increases the reliability of the system. The droop control characteristics can be expressed as:

$$\omega = \omega_0 - m_P\left(P - P_0\right) \tag{5}$$

$$E = E_0 - n_Q\left(Q - Q_0\right) \tag{6}$$

where ω and E are the measured angular frequency and voltage amplitude, respectively, P and Q, are the measured active and reactive powers, respectively, ω_0 and E_0, are the nominal angular frequency and voltage amplitude, respectively, P_0 and Q_0, are the active and reactive powers in the nominal angular frequency and voltage amplitude, respectively, and n_Q and m_P are the droop coefficients.

2.2 Virtual Impedance

Generally, the impedance between each DG and the PCC (including transmission line impedance and the output impedance of DGs) is different due to the diversity in the places of installation of RESs. Therefore, resulting in unequal power sharing among DGs [25]. In addition, the impedance is not essentially inductive. Consequently, in this condition, the droop controllers are no longer effective. In order to overcome these problems the virtual impedance is used. The most important advantage of the virtual impedance is the tuning of DG output impedance. This means that by employing the virtual impedance, not only the output impedance of the parallel DGs will be equal, the inductive property will be enhanced as well. Fig. 3 shows the block diagram of the DG control system based on the virtual impedance. As shown in this figure, the virtual impedance is an outer control loop and changes the reference voltage. By adding the virtual impedance, the value of the reference voltage is changed as follows:

$$V_o^* = V_{ref} - Z_D . i_o \tag{7}$$

where Z_D is the virtual impedance, V_o^* is the new reference voltage and i_o is the output current.

2.3 Conventional DDSRF

The injection of the positive and negative sequences of the current is essential to compensate the unbalanced networks. So the positive and negative sequence currents must be separated. To extract the positive and negative sequence, the Park's transformation over $i_{\alpha\beta}$ is applied with the positive-sequence and the negative-sequence angles.

$$i_{dq}^{+} = \left[e^{-j\theta^{+}}\right].i_{\alpha\beta} = \underbrace{\overline{i_{dq}^{+}}}_{\text{dc term}} + \underbrace{e^{-j\left(\theta^{+}-\theta^{-}\right)}.\overline{i_{dq}^{-}}}_{\text{AC term}} \tag{8}$$

$$i_{dq}^{-} = \left[e^{-j\theta^{-}}\right].i_{\alpha\beta} = \underbrace{\overline{i_{dq}^{-}}}_{\text{dc term}} + \underbrace{e^{-j\left(\theta^{-}-\theta^{+}\right)}.\overline{i_{dq}^{+}}}_{\text{AC term}} \tag{9}$$

which that $\theta^{+} = \omega t + \varphi^{+}$ and $\theta^{-} = -\omega t + \varphi^{-}$. The park's transformation is given by

$$\left[e^{j\theta}\right] = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \tag{10}$$

In which φ^{+} and φ^{-} represent the initial phases of the positive and negative sequence voltage, respectively.

From (8) and (9), and according to (10), it can be seen that the positive and negative sequence currents consist a dc component and an ac component with the frequency of 2ω. In DDSRF, this ac coupling is eliminated using the estimated positive and negative components according to the following equations.

$$i_{dq}^{+\prime} = \underbrace{\overline{i_{dq}^{+}}}_{\text{dc term}} + \underbrace{e^{-j\left(\theta^{+}-\theta^{-}\right)}.\underbrace{\overline{i_{dq}^{-}}}_{\text{dc term}}}_{\text{AC term}} \underbrace{- e^{-j\left(\theta^{+}-\theta^{-}\right)}.\underbrace{i_{dq}^{-}}_{\text{dc term}}}_{\text{Cross Coupling term}} \tag{11}$$

$$i_{dq}^{-\prime} = \underbrace{\overline{i_{dq}^{-}}}_{\text{dc term}} + \underbrace{e^{-j\left(\theta^{-}-\theta^{+}\right)}.\underbrace{\overline{i_{dq}^{+}}}_{\text{dc term}}}_{\text{AC term}} \underbrace{- e^{-j\left(\theta^{-}-\theta^{+}\right)}.\underbrace{i_{dq}^{+}}_{\text{dc term}}}_{\text{Cross Coupling term}} \tag{12}$$

In (11) and (12), symbol "^" denotes the estimated

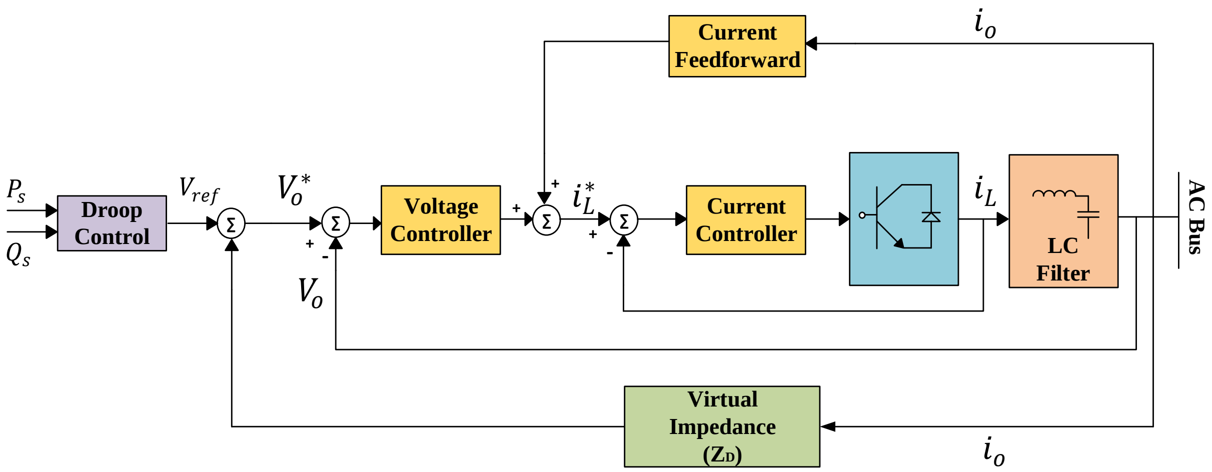


Fig. 3 DG control system based on the virtual impedance.

signals. The positive and negative dc terms are estimated as follows [23]:

$$i_{dq}^{+} = i_{dq}^{+*} - \left(i_{dq}^{+*} - i_{dq}^{+\prime}\right)\frac{\omega_f}{S+\omega_f} \quad (13)$$

$$i_{dq}^{-} = i_{dq}^{-*} - \left(i_{dq}^{-*} - i_{dq}^{-\prime}\right)\frac{\omega_f}{S+\omega_f} \quad (14)$$

In (13) and (14), ω_f is the cutoff frequency of a first-order low-pass filter, and it is assumed that the reference currents, i_{dq}^{+*} and i_{dq}^{-*}, are completely dc and non-oscillatory.

3 Proposed DDSRF

Since in the unbalanced conditions, the reference currents can also comprise the oscillatory component, so the estimation of the oscillatory components using the reference currents does not have the required efficiency. Therefore, as shown in Fig. 4, in the proposed DDSRF, the measured currents and two notch filters are used, to estimate the oscillatory components. The notch filters are tuned to suppress the second-order harmonic component. Thus, in the proposed DDSRF, the positive and negative dc terms are estimated as follows:

$$i_{dq}^{+} = i_{dq}^{+\prime}\cdot\frac{S^2+\omega_n^2}{S^2+2\xi\omega_n+\omega_n^2} \quad (15)$$

$$i_{dq}^{-} = i_{dq}^{-\prime}\cdot\frac{S^2+\omega_n^2}{S^2+2\xi\omega_n+\omega_n^2} \quad (16)$$

In (15) and (16), ω_n and ξ are the natural frequency and damping ratio of the notch filter, respectively.

4 Proposed Control System

Fig. 5 shows the structure of the proposed control strategy. According to the proposed control strategy, first, the positive and negative sequence components of

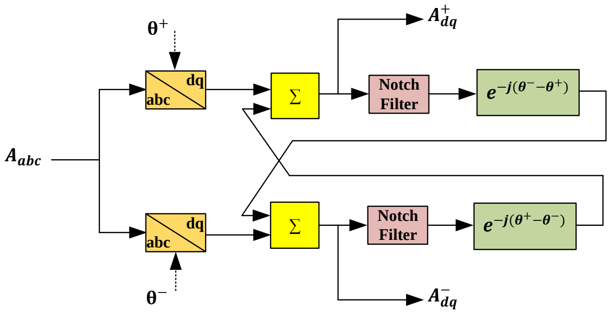


Fig. 4 Structure of the proposed DDSRF.

the DG and the line currents, and the DG voltage are separated by using the proposed DDSRF. After extracting the positive and negative sequence components, the negative sequence components are sent to the voltage and current control loops of negative sequence to compensate the unbalanced voltage. The positive sequence components are also sent to the power calculator block and the voltage and current control loops of the positive sequence.

Based on the theory of instantaneous power, the delivered active and reactive power to the ac system at the PCC is given by the following equations:

$$P^{+}(t) = \frac{3}{2}\left[V_{sd}^{+}(t)i_d^{+}(t) + V_{sq}^{+}(t)i_q^{+}(t)\right] \quad (17)$$

$$Q^{+}(t) = \frac{3}{2}\left[-V_{sd}^{+}(t)i_q^{+}(t) + V_{sq}^{+}(t)i_d^{+}(t)\right] \quad (18)$$

The low-pass filter is used to obtain the dc value of the powers, So:

$$P_s^{+}(s) = P^{+}(s).LPF(s) \quad (19)$$

$$Q_s^{+}(s) = Q^{+}(t).LPF(s) \quad (20)$$

The measured active and reactive power then are used in the modified droop control block. According to (7), the existence of the virtual impedance in the control

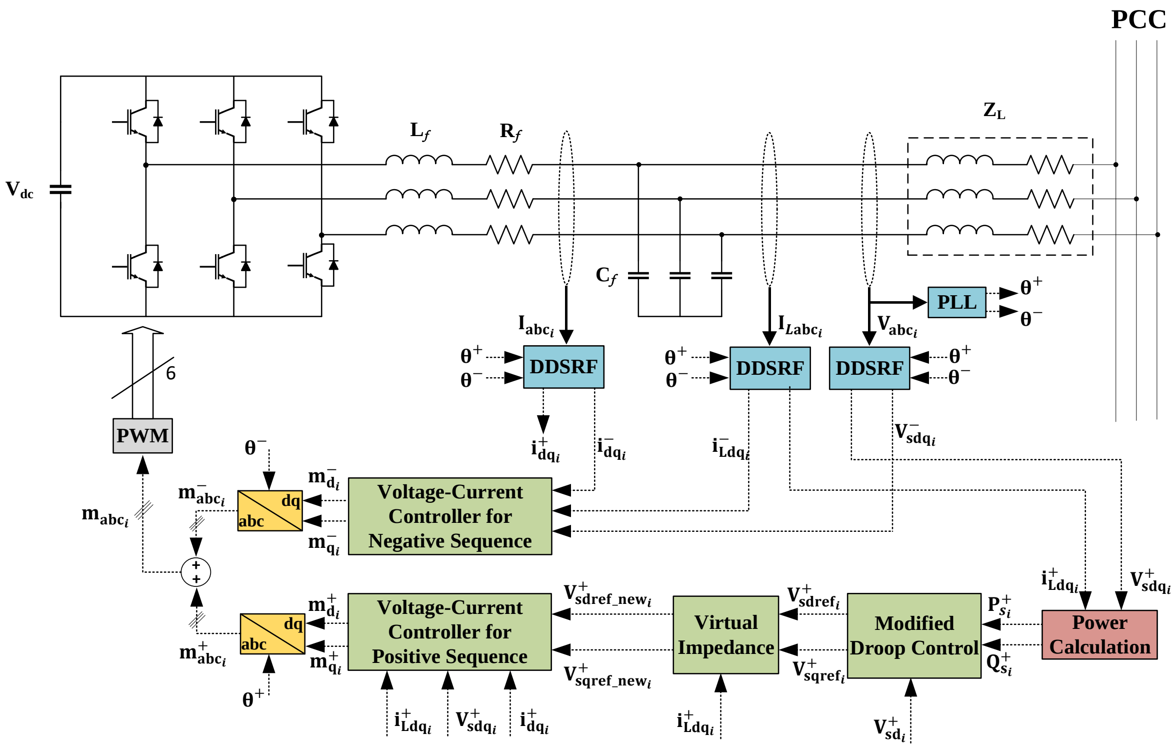


Fig. 5 Proposed control strategy for DG$_i$.

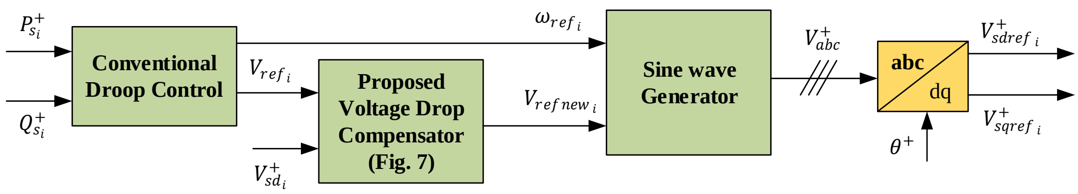


Fig. 6 Modified droop control.

loop causes the output voltage drop. In this paper, for compensating the voltage drop a voltage drop compensator, as shown in Fig. 6, has been proposed. By using the proposed voltage drop compensator, the new reference voltage V_{refnew_i} is produced from the conventional droop control output voltage V_{ref_i} and the positive sequence voltage $V^+_{sd_i}$. This compensation is performed according to the algorithm shown in Fig. 7. In this algorithm, the difference between V_{ref_i} and $V^+_{sd_i}$ is calculated (dV) and compared with the maximum permissible voltage drop V_k, and so, the value of voltage deviation from the allowed value V_ε is obtained. If the voltage drop exceeds the permissible limit, V_ε is considered equal to zero. Otherwise, dV is evaluated. In this case, if the value of dV is positive, V_ε is added to ΔV, else if the value of dV is negative, V_ε is subtracted from ΔV. Finally, the ΔV amount is added to V_{ref_i}. Consequently, the output voltage of the conventional droop control is modified.

In the proposed control strategy to increase the inductive property of the line impedance, the virtual impedance has been used in the positive control loop (see Fig. 5). After construction of the new reference voltages in the dq axes, they are sent to the voltage and current control loops. The voltage and current control loops for the positive and negative sequences are shown in Figs. 8(a) and 8(b), respectively. It is important to note that the reference voltages in the negative control loop are equal to zero. Eventually, the positive and negative modulation signals are collected together, and are sent to PWM block to generate suitable switching signals.

5 Simulation Results

To demonstrate and prove the validity and accuracy of the proposed control strategy, the simulation has been performed in the MATLAB/Simulink environment. Fig. 9 shows the studied system and some key parameters are given in Table 1. The three-phase balanced load is a constant power load with 100kW active power and 50kvar reactive power. The unbalanced load is a constant impedance load with the resistance of 2Ω and

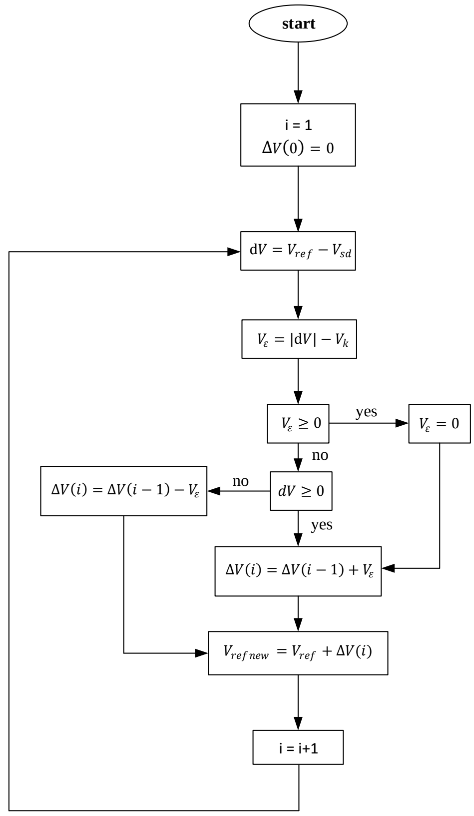


Fig. 7 Proposed algorithm for compensating the voltage drop.

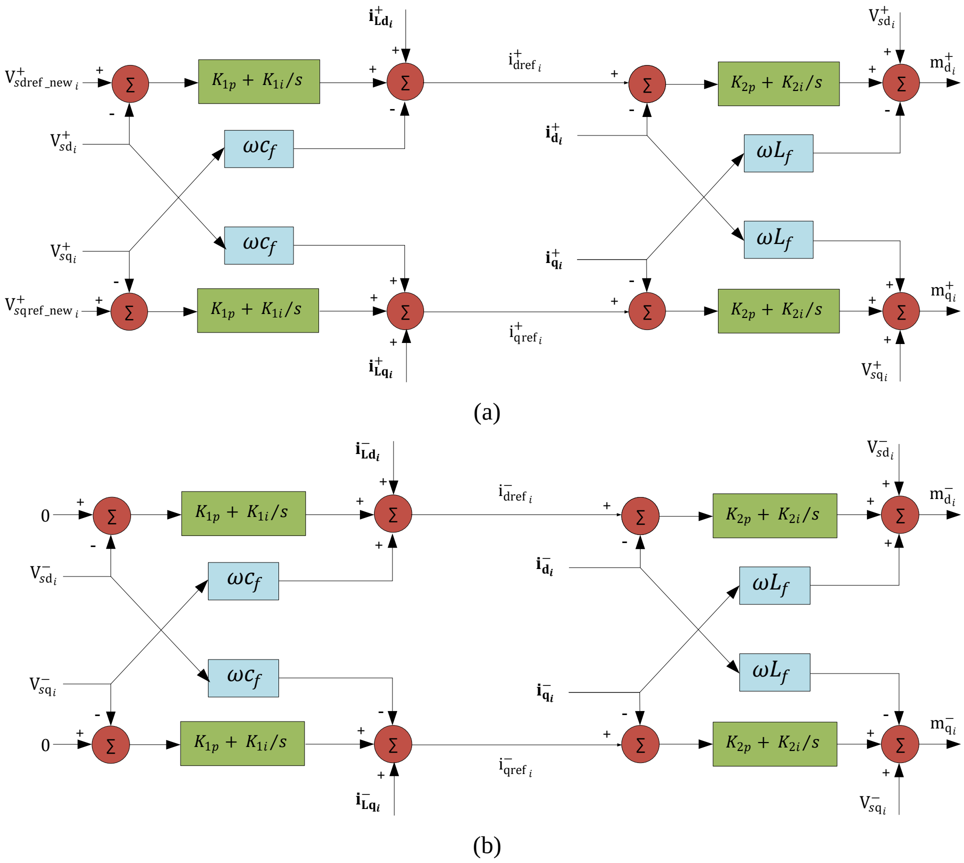


Fig. 8 Voltage-current control loops: a) for positive sequence and b) for negative sequence.

the inductance 2mH. The nominal capacity of the DG_1 and DG_2 are 300kVA and 200kVA, respectively. Thus, the capacity ratio of both DGs is equal to 1.5. Each DG is connected to the PCC via a line with the resistance of 0.161Ω and the inductance 0.605mH. Initially, the balanced load is connected to the studied system, then in 0.25 seconds, the unbalanced load is added to the system.

The frequency of the studied system is shown in Fig. 10. Fig. 10 depicts that the frequency is initially set to 50Hz, then in 0.25 seconds, the frequency changes and after a transient time about 0.3 seconds, it again returns to 50Hz.

Figs. 11(a) and 11(b) illustrate the ratio of the output active and reactive powers of two DGs, respectively. These figures show that, using the proposed control strategy, the active and reactive powers are appropriately shared among DGs, despite the unbalanced load connection.

Fig. 12 shows the PCC voltage. This figure illustrates that after unbalanced load connection, the proposed compensation method can effectively compensate the unbalanced voltage.

Fig. 13 presents the effective value of the PCC voltage in terms of p.u. This figure shows that there is no drop in the output voltage waveform despite using the virtual impedance. In other words, the proposed algorithm for compensating the voltage drop, can successfully compensate the voltage drop caused by the virtual impedance implementation.

Figs. 14 and 15 show the positive and negative sequence components of the PCC voltage, respectively. These figures depict that the positive sequence component in the q-axis and the negative sequence components desirably become zero after a short transient time of about 0.3 seconds.

Fig. 16 presents the %VUF at the PCC. This figure illustrates that the VUF reaches the permissible value of %2 at 0.401 seconds and remains less than %1 in the steady-state.

Fig. 17 shows the total harmonic distortion (THD) of the PCC voltage. The amount of THD is 0.56 %, which is within the allowable limit (<5% for low-voltage grids). In addition, the value of harmonic components is less than 0.2%.

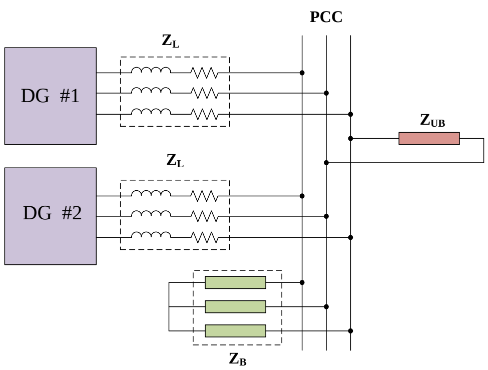


Fig. 9 Studied autonomous microgrid.

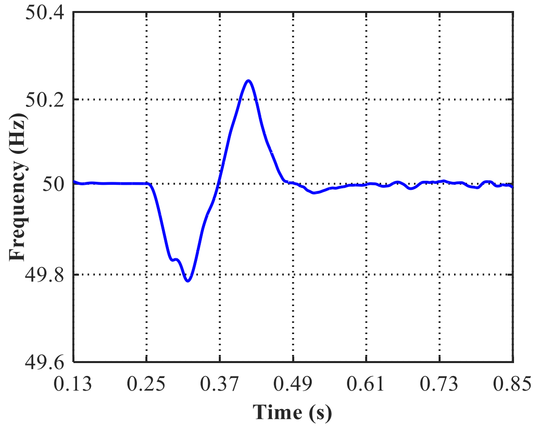
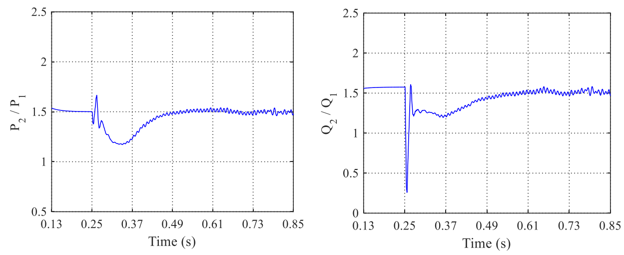


Fig. 10 Frequency of the studied system.



(a) (b)

Fig. 11 Active and reactive power sharing.

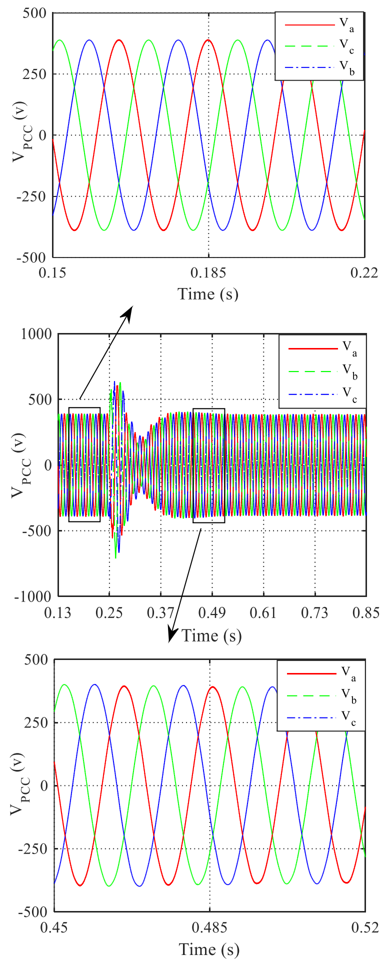


Fig. 12 Voltage at PCC.

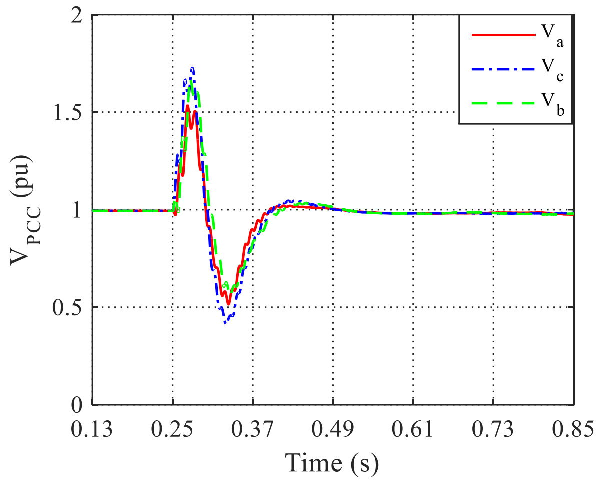
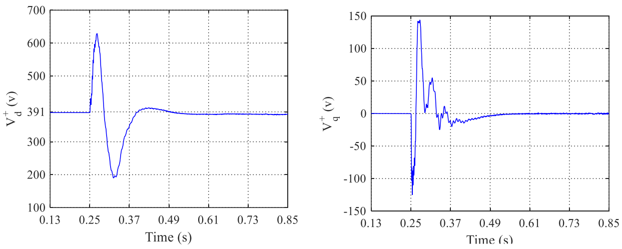
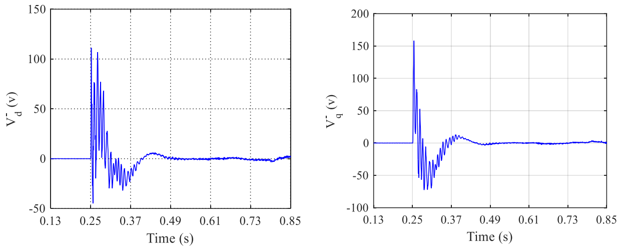


Fig. 13 Effective value of the PCC voltage.



(a) (b)

Fig. 14 The positive sequence components in dq axis.



(a) (b)

Fig. 15 The negative sequence components in dq axis.

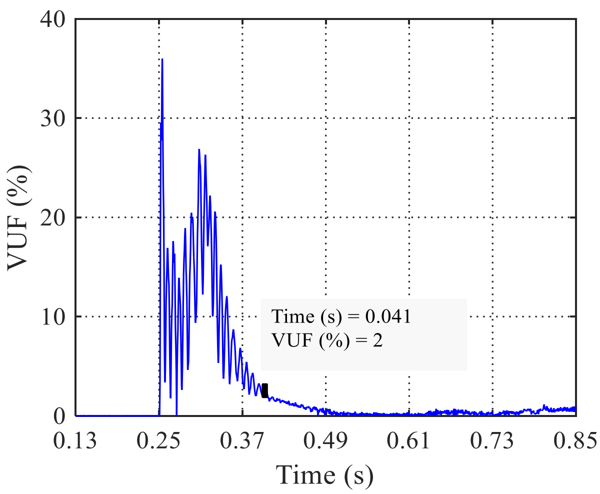


Fig. 16 VUF at the PCC.

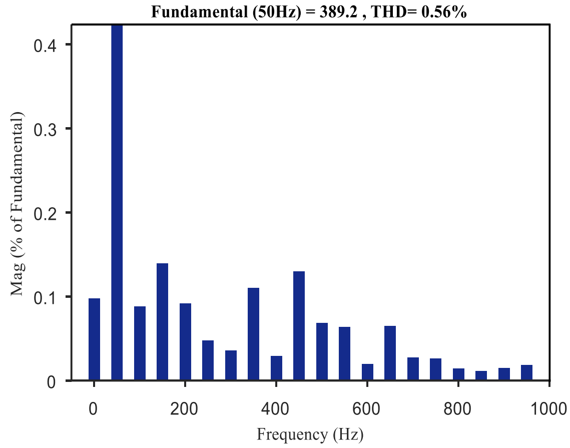


Fig. 17 THD of the PCC voltage.

Table 1 System parameters.

Parameters	Value	Parameters	Value
R_f [Ω]	0.01	m_1	5×10^{-7}
L_f [H]	1×10^{-4}	n_1	5×10^{-7}
C_f [F]	2.5×10^{-5}	m_2	3.3×10^{-6}
V_{dc} [V]	700	n_2	3.3×10^{-6}
f_s [Hz]	5000	K_{1p}	0.2
V_{sdref} [V]	391	K_{1i}	0.414
f [Hz]	50	K_{2p}	0.2
P_2/P_1	1.5	K_{2i}	0.414

6 Conclusion

The main purpose of this paper is that in the autonomous microgrids simultaneously compensates the unbalanced voltage in the d-q reference frame and performs appropriate power sharing among DG units without a communication link. In this paper, a new control strategy based on the modified DDSRF is proposed for voltage balancing and power sharing in the autonomous microgrids. The principles of the suggested DDSRF and control strategy were discussed in detail. In order to evaluate the effectiveness of the proposed control strategy, an autonomous microgrid with two DGs was considered. The simulation results show that using the proposed strategy, VUF and THD of the PCC voltage are less than 2% and 5%, respectively. Also, it has been shown that the proposed approach can appropriately share the active and reactive power among two DGs. In addition, the obtained results depict that the proposed method compensates the voltage drop in the output impedance of the DGs despite using the virtual impedance and keeps the PCC voltage near the nominal voltage.

The following studies are suggested for future research in this field:

- One can consider the DC link dynamics and evaluate its effect on the power sharing and the unbalanced voltage compensation.
- The effect of non-linear load connection on the power sharing and the unbalanced voltage compensation can be analyzed.

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