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A Novel Accurate Power Sharing Method Versus Droop Control In Autonomous Microgrids With Critical Loads

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ABSTRACT In autonomous microgrids, the well-known frequency and voltage droop control are extensively used to share active and reactive powers among parallel inverters without using any communication infrastructure. However, power sharing is performed at the expense of altering the voltage and frequency of the system. To restore the voltage and frequency to their nominal amounts, a secondary control loop is often augmented to the system using communication links. To avoid using these complex hierarchical controls, this paper proposes a novel method for power sharing in parallel inverters providing constant frequency and nominal voltage operation for critical loads. The proposed method uses a simple structure based on communication links utilization. The simulation results show that the active and reactive powers are accurately shared with an acceptable transient response. Furthermore, the results are compared with the conventional droop control to show the superiority of the proposed method over the conventional one.

INDEX TERMS Autonomous microgrid, active and reactive power sharing, constant frequency operation, critical loads.

I. INTRODUCTION

In recent years, willingness to utilize Distributed Generation (DG) has gone up owing to 1) economic and ecosystem aspects, 2) development in DG technologies, 3) supporting the main grid during the peak load, and 4) reducing power losses of the main grid [1], [2]. Some of the DGs are connected to the grid through power electronic interfaces, called inverter-based DGs. A cluster of DGs and loads can constitute a Microgrid (MG) which can operate in 1) autonomous (islanded) mode and, 2) grid-connected mode [3], [4]. It should be noted that the concerns are different in these two operation modes. In grid-connected mode, the upstream grid is dominant, and inverter-based DGs are controlled to imitate the behavior of a Synchronous Generator (SG) [5], [6]. In autonomous mode, which is the subject of this paper, the major concern is power sharing among parallel DGs [7]. Several concepts have been introduced for this problem among which droop control methods are frequently seen in the literature. The most popular droop methods are power-frequency (P/f) [8], power-voltage (P/V) [9], [10] virtual flux [11], [12] and angle droop [13], [14]. The P/f droop method is appropriate for high and medium voltage lines which are purely inductive. On the contrary, P/V droop method is suitable for low voltage lines which are purely resistive. It is worth noticing that these droop methods do not depend on communication links and use local information; nevertheless, they suffer from the sluggish dynamic response, poor reactive power sharing, voltage and frequency deviations, unbalanced harmonic current sharing, circulating current among DGs, and highly dependent on the inverter output impedance [7]. Moreover, some modifications are made on the conventional P/f droop methods to achieve accurate power sharing and better dynamic performance in autonomous MGs. For instance, the improved transient response has been obtained by using derivative term combined with the droop method which is called adaptive droop controller [15], [16]. Also, virtual impedance and virtual power frame transformation have been

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introduced to ameliorate the power sharing accuracy [17]. The virtual flux droop proposes simple structure and benefits from low- frequency deviation; however, it suffers from voltage deviation similar to conventional P/f droop [11], [12]. It is to be noted that all the aforementioned droop methods suffer from voltage and frequency deviations as they are the inherent feature of these methods. These deviations increase during various load changes and lead to power quality reduction which is important for critical loads [12].

To overcome the problem of permanent frequency and voltage error, a secondary frequency and voltage control loop is used for restoring the frequency and voltage to the nominal values [18], [19]. As a result, communication infrastructure is needed to obtain satisfactory conditions. Recently, using communication links has attracted the attention of researchers to achieve power sharing enhancement and constant frequency operation.

The angle droop is one of the methods resulting in constant frequency operation; however, it suffers from poor power sharing and low stability margin [20]. To obtain accurate power sharing, a centralized control strategy using communication infrastructure has been introduced in [13] to regulate the load angle initial values. In [21], an optimal angle droop for power sharing enhancement has been proposed to achieve accurate power sharing using communication infrastructure. Nevertheless, this approach leads to changing the voltage magnitude of the load which is not desired for a critical load sensitive to voltage variations. Moreover, this method has limitation in terms of stability and it is not possible to meet any desired power sharing. It is logical when communication infrastructure like Global Positioning System (GPS) is used, each power sharing should be accurately carried out and appropriate condition should be provided for the loads. Furthermore, the control method should be simple as far as possible, taking precedence in practical applications.

The main idea of this paper is to introduce a straightforward analysis that finds out the required voltage vector of inverter-based DGs by the aid of communicating devices. Then, the controllers contribute to obtaining inverter voltages, which in turn, their switching pulses are finally modulated with a sinusoidal PWM scheme. It is noticeable that the procedure can be later extended for other power systems as well. Moreover, the proposed method meets nominal voltage for critical loads, and also the system frequency remains unchanged.

The remainder of this paper is organized as follows. In Section II, a comprehensive investigation of conventional P/f droop is carried out. In Section III, the proposed method is presented. In Section IV, the closed-loop control strategy is introduced, and in Section V, the effectiveness of the proposed method and a comparison with conventional P/f droop control are investigated in MATLAB/SIMULINK environment.

II. DROOP CONTROL OF PARALLEL INVERTERS

Droop control is one of the well-known methods for power sharing among parallel inverters which was first introduced in [8]. The droop-based power sharing has gained significant attention among researchers, improving the state-of-the-art towards certain solutions. Conventional frequency droop control was the first method for acquiring power sharing without using any communication links. The main idea behind droop control of inverters is to imitate the behavior of an SG. There is, however, an important difference between droop control in parallel SGs and parallel inverters resulting from the absence of governor in the inverters. To clarify the difference, the performance of governor and load-frequency control in the power system should be reminded. In the power system, when there is an increase in the active load, the grid frequency drops automatically for sake of converting the kinetic energy of SG to electric energy. Afterward, the frequency variation triggers governor and consequently, the governor changes the mechanical input power to SG. In addition, power sharing among parallel SGs is carried out through governors according to reverse of droop coefficients [22]. It is worth mentioning that in parallel inverters, the frequency of inverters does not automatically change versus load variation. However, it can be implemented by a control loop leading to the same event in SGs. The main point in the inverters is that the active power can be controlled by phase angle and frequency. Likewise, the reactive power can be controlled by the voltage magnitude. Thus, by applying the droop control for inverters, the frequency of inverters changes in case of a load variation, so that the frequency variation results in active power sharing, and similarly, the voltage variation leads to reactive power sharing. Furthermore, in P/f droop control, the frequency is opted to regulate the active power instead of phase angle; because the inverter-based DGs do not sense and detect the initial phase angle of other units [23], [24]. In summary, the droop control equations are as follows:

$$\omega = \omega_0 - mP \tag{1}$$

$$E = E_0 - nQ \tag{2}$$

where ω and E are the angular frequency and voltage magnitude of the output voltage vector of inverter, respectively. ω_0 and E_0 are the nominal values of angular frequency and voltage magnitude at no load. P and Q are the output active and reactive power of the inverter. m and n are the droop coefficients, and they can be calculated for a maximum range of frequency and voltage magnitude as follows [8]:

$$m = \frac{\Delta\omega_{max}}{P^*} \tag{3}$$

$$n = \frac{\Delta E_{max}}{Q^*} \tag{4}$$

where P^* and Q^* are the rated active and reactive power. $\Delta\omega_{max}$ and ΔE_{max} are the maximum frequency and voltage deviation allowed.

It should be mentioned that larger droop coefficients lead to better power sharing. However, it suffers from unallowable voltage and frequency deviations leading to system instability. As a result, there is a trade-off between power sharing and system stability in the droop control method [7].

The stability of the droop control method has been comprehensively investigated in [25] based on eigenvalue analysis. It has been proven that larger droop coefficients can lead to system instability. It is necessary to keep in mind that reaching from one steady state to another gets the parallel inverters involved in transients due to the load variations. During the transient, the paralleled inverters step in different frequency variation regimes. This produces not only circulating currents within the devices but also imposes power losses to the whole system. The longer this transient duration, the more intense would be the mentioned impacts in practice. Fig. 1 shows the droop control strategy comprising power calculation, power sharing or droop setting, voltage and current controllers. It is worth recalling that a conventional approach for the output voltage control of an inverter is based on an external voltage loop and an internal current loop, which there are some reasons and advantages behind them [23], [26]. Moreover, the outer voltage and inner current control loops can be implemented for single-phase [27], [28] and three-phase system using rotating dq-frame [3], [29] and stationary $\alpha\beta$-frame [30].

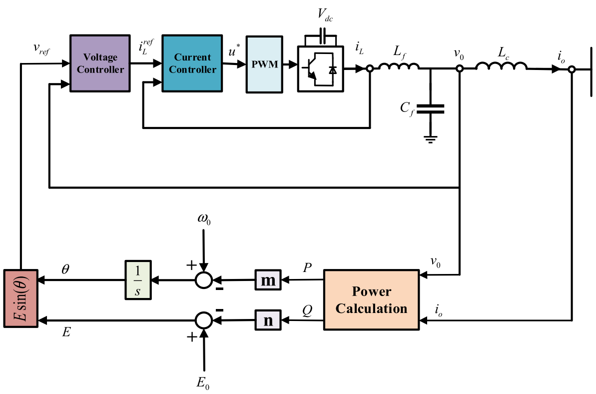

FIGURE 1. Droop control strategy.

As can be seen from Fig. 1, the power calculation is carried out by measuring voltage and current after the LC filter. Subsequently, the reference voltage vector is constructed by droop equations. Finally, the reference voltage vector is produced by outer and inner control loops of the inverter which are voltage and current controllers. The voltage controller generates reference current for inductor of the LC filter and this signal is the input of the current controller responsible to generate the final signal for PWM of the inverter. In other words, the current controller regulates the current supplied by the inverter resulting in charging the capacitor of the LC filter to keep the output voltage close to its reference.

III. PROPOSED METHOD

In this section, a novel method for power sharing is proposed, power sharing is accurately accomplished without any frequency variations. This novel method focuses on power sharing with constant frequency operation, only for microgrids not having any SG-based DGs. Moreover, this method is suitable for critical loads sensitive to frequency and voltage deviations.

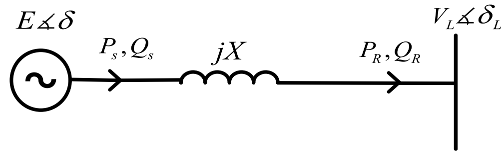

FIGURE 2. Equivalent circuit of an inverter-based DG connected to a bus.

Fig. 2 shows the equivalent circuit of an inverter connected to a load bus. In this figure, line impedance is considered to be purely inductive, but the proposed method can be generally implemented for both resistive and inductive-resistive lines. The sending and receiving end powers are as follows [31]:

$$P_s = P_R = \frac{EV_L}{X}\sin(\delta - \delta_L) \tag{5}$$

$$Q_s = \frac{E(E - V_L\cos(\delta - \delta_L))}{X} \tag{6}$$

$$Q_R = \frac{V_L(E\cos(\delta - \delta_L) - V_L)}{X} \tag{7}$$

where P_s and Q_s are the sending end active and reactive powers, respectively. P_R and Q_R are the active and reactive powers drawn by the load bus. X is the line reactance. E and δ are the terminal voltage vector. V_L and δ_L are the voltage vector of the load bus.

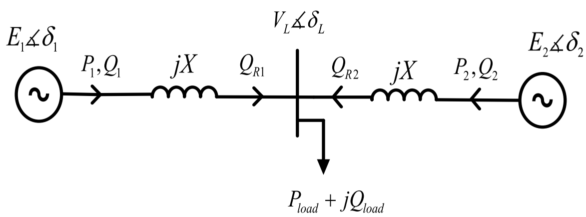

FIGURE 3. Parallel operation of two inverter-based DG.

Fig. 3 shows the model of two parallel inverter-based DGs and a load point, considered a benchmark problem in the literature [25], [30]. Also, the dynamic of DGs is generally neglected in this kind of study and DGs are considered as an ideal voltage source. By applying a KCL at the load bus, we have:

$$P_1 + P_2 = P_{load} \tag{8}$$

$$Q_{R1} + Q_{R2} = Q_{load} \tag{9}$$

substituting (5) and (7) in the above equations results in the following equations:

$$\frac{E_1V_L}{X}\sin(\delta_1 - \delta_L) + \frac{E_2V_L}{X}\sin(\delta_2 - \delta_L) = P_{load} \tag{10}$$

$$\frac{V_LE_1\cos(\delta_L - \delta_1) - V_L^2}{X} + \frac{V_LE_2\cos(\delta_L - \delta_2) - V_L^2}{X} = Q_{load} \tag{11}$$

where E_1 and E_2 are the terminal voltage magnitude and δ_1 and δ_2 the terminal power angle of inverter-based DGs, V_L and δ_L are the magnitude and phase angle of the load bus, respectively. In order to set the load voltage at nominal amount (1 per unit), the voltage vector of the load is considered as follows:

$$V_L \measuredangle \delta_L = 1^{pu} \measuredangle 0 \tag{12}$$

Consequently, (10) and (11) can be rewritten as follows:

$$\frac{E_1}{X}\sin\delta_1 + \frac{E_2}{X}\sin\delta_2 = P_{load} \tag{13}$$

$$\frac{E_1\cos\delta_1 - 1}{X} + \frac{E_2\cos\delta_2 - 1}{X} = Q_{load} \tag{14}$$

It is obvious that the voltage vectors of the inverters are the unknown parameters, whereas the active and reactive powers of the load and equivalent reactance are considered as known parameters of the system. As a result, the unknown parameters are more than existing equations so that a unique answer does not exist. In order to cope with this issue, two more equations are needed which can be the desired power sharing. If the power sharing is carried out according to the desired output powers of inverters, two more equations will be added as follows:

$$P_1 = \alpha P_2 \tag{15}$$

$$Q_1 = \beta Q_2 \tag{16}$$

where α and β are the power sharing coefficients, leading to the desirable power sharing. It is notable that Q_1 and Q_2 are the sending end reactive powers that are different from Q_{R1} and Q_{R2}. By substituting the output power flow equations into (15) and (16) and considering (12), the following equations can be written:

$$\frac{E_1}{X}\sin\delta_1 = \alpha\frac{E_2}{X}\sin\delta_2 \tag{17}$$

$$\frac{E_1(E_1 - \cos\delta_1)}{X} = \beta\frac{E_2(E_2 - \cos\delta_2)}{X} \tag{18}$$

Accordingly, by considering (13), (14), (17) and (18), the unknown parameters of the system which are the terminal voltage vectors ($E_1\measuredangle\delta_1, E_2\measuredangle\delta_2$) will be obtained considering the desirable power sharing. Thereby, some characteristics arise from the outcomes of solved equations for the first inverter shown in Fig. 4 and 5. As can be seen in these figures, the active power of the load and power angle depend on each other via an ascending function. The same behavior can be seen between the reactive power of the load and voltage magnitude. Moreover, the active power and voltage magnitude, reactive power and power angle are not independent completely.

IV. CLOSED-LOOP CONTROL STRATEGY

Given the fact that the derived equations are nonlinear, they cannot be analytically solved. Hence, repetitive numerical methods like Gauss-Seidel or Newton-Raphson are needed. The derived equations are therefore solved for a wide range of load variations using numerical methods and subsequently, a lookup table or Neural Network (NN) can be implemented to make a closed-loop system. But the lookup table does not

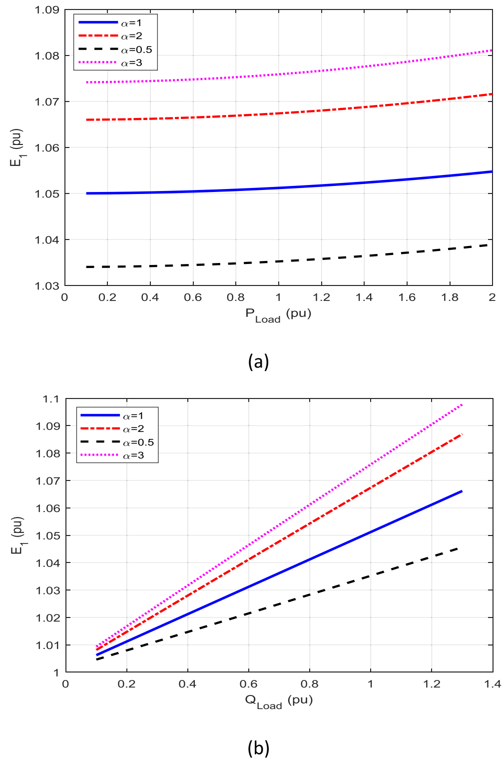

FIGURE 4. Variation characteristic of E1 versus load power changes a) variation of E1 versus P_{load} b) variation of E1 versus Q_{load}.

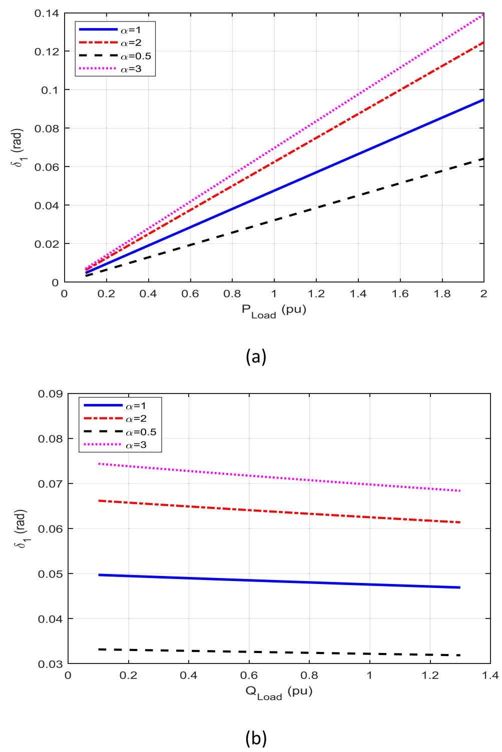

FIGURE 5. Variation characteristic of δ1 versus load power changes a) variation of δ1 versus P_{load} b) variation of δ1 versus Q_{load}.

fit well for this problem because it needs a huge amount of data in order to respond accurately. Thus, the NN is chosen which can be easily implemented and trained once using derived characteristics of the solved equations. By measuring the load voltage and current, the active and reactive powers of the load are calculated. These powers are the input of the NN and the output is the reference voltage vectors of inverters terminal, which will be sent by communication links to be produced by the voltage and current controllers. As a consequence, a closed-loop system is formed as shown in Fig. 6.

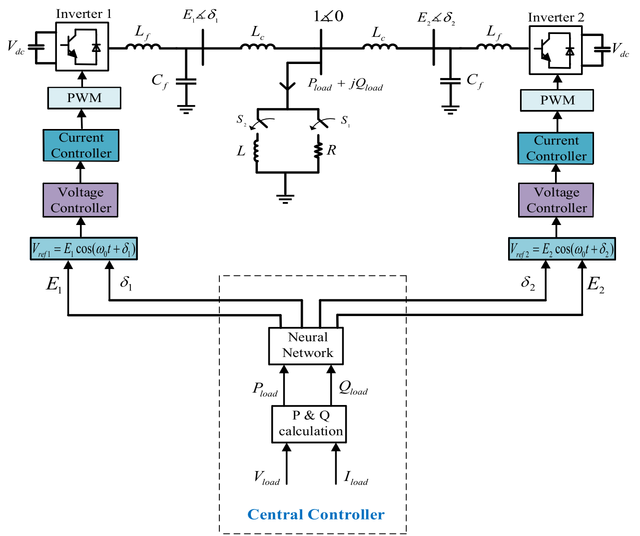

FIGURE 6. Proposed control system.

V. SIMULATION RESULTS

In order to assess the performance of the proposed method, it is simulated in 3 different scenarios in MATLAB/ SIMULINK environment. "nftool" toolbox and Levenberg-Marquardt algorithm are used for training the NN containing 10 hidden layers, one input and an output layer. The scenario I is done with equal droop coefficients for both inverters in order to achieve equal power sharing. The scenario II is carried out with different droop coefficients in order to obtain unequal power sharing and eventually, the scenario III is performed with large droop coefficients resulting in system instability. The proposed method is compared with the droop control method in all the scenarios. The system parameters used in simulations are given in TABLE 1.

A. SCENARIO I: EQUAL DROOP COEFFICIENTS

In this scenario, droop coefficients are small and equal to each other. Therefore, power sharing would be equal between two inverters and the small coefficients would ensure system stability. At $t = 0.05$ sec a resistive load is connected to the system through switch S_1 and at $t = 0.15$ sec an inductive load is connected to the system through switch S_2. The variations of load powers, load voltage and system frequency are shown in Fig. 7. Note that the frequency variation of both inverters is equal because of having the same droop coefficient. As shown in Fig. 7, the active and reactive powers of the load are different in the droop control method and proposed method when the inductive load is connected to the system. The main reason is that in the droop control method, the voltage of inverters decreases when there is an increase in inductive load and consequently, the load voltage reduces. Moreover, this load voltage decrement results in load powers reduction. The remarkable point is that the load voltage restores to the nominal value after a short period in the proposed method. This is due to the voltage magnitude of inverters having been regulated so that the load voltage is kept at 1 pu. Another difference is the system frequency, which is completely constant during the load variation because power control is carried out only through the power angle. It is worth noting that at $t = 0.06$ sec, a transient can be observed turning to the performance of the switch S_1 acting as a capacitor. The variations of the output active and reactive powers of the inverter 1 are shown in Fig. 8. The output powers of both inverters are identical in order to have equal droop coefficients. It should be noted that the output reactive power of inverters includes the reactive power of the load and the reactive losses of the transmission line which is assumed to be inductive.

TABLE 1. The parameters used in simulation.

System parameters	Symbol	Value
Base voltage	V_{base}	220 V
Base apparent power	S_{base}	1000 W
Input DC voltage	V_{DC}	400 V
Microgrid frequency	f	60 Hz
Line inductance	L_c	12.8 mH
Filter inductance	L_f	1.8 mH
Filter capacitance	C_f	25 µF
Resistive load	R	48.4 Ω
Inductive load	L	128 mH
Power sharing coefficients of proposed method in scenario I	α β	1 1
Power sharing coefficients of proposed method in scenario II	α β	1.2 1.2
Power sharing coefficients of proposed method in scenario III	α β	5 5
Droop coefficients in scenario I	m_1, n_1 m_2, n_2	10^{-4} (rad/s)/W, 10^{-4} V/var 10^{-4} (rad/s)/W, 10^{-4} V/var
Droop coefficients in scenario II	m_1, n_1 m_2, n_2	10^{-4} (rad/s)/W, 10^{-4} V/var 1.2×10^{-4} (rad/s)/W, 1.2×10^{-4} V/var
Droop coefficients in scenario III	m_1, n_1 m_2, n_2	10^{-4} (rad/s)/W, 10^{-4} V/var 5×10^{-4} (rad/s)/W, 5×10^{-4} V/var

B. SCENARIO II: UNEQUAL DROOP COEFFICIENTS

This scenario aims to show the unequal power sharing by the droop control method and the proposed method. To this end, different coefficients related to power sharing in both

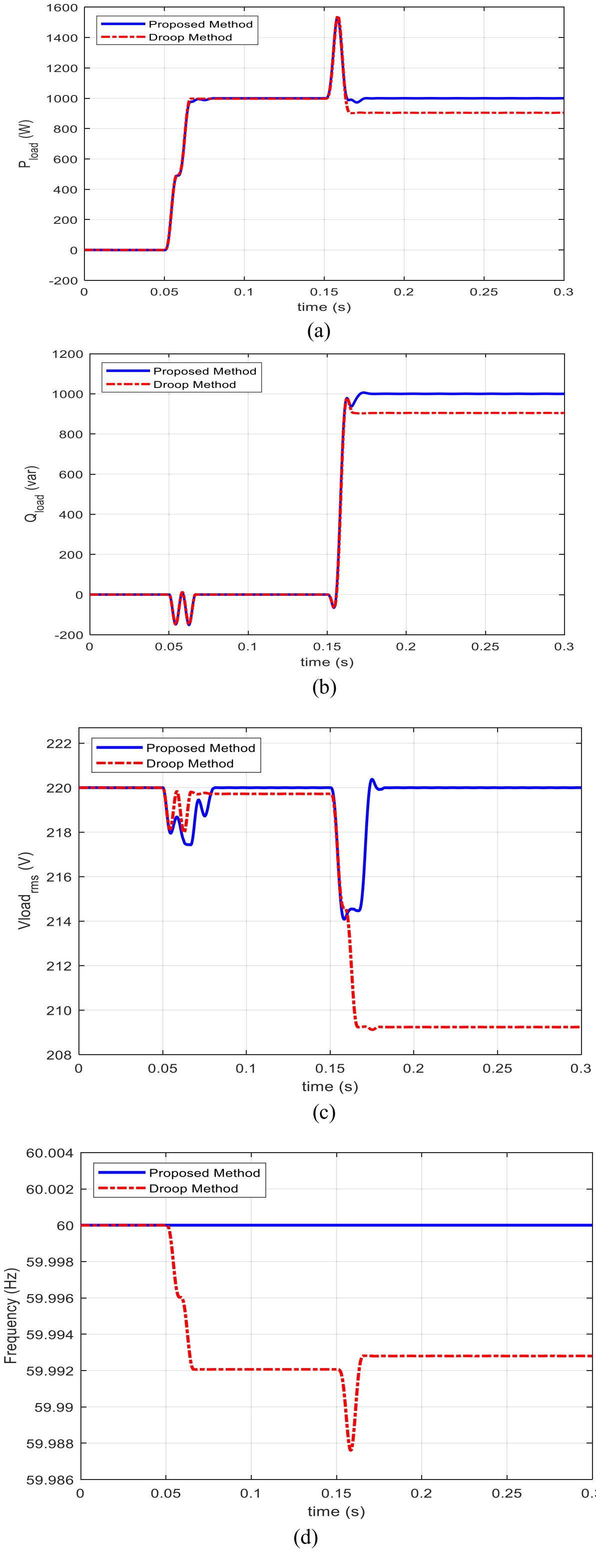

FIGURE 7. Load powers and voltage in scenario I. a) active power of load b) reactive power of load c) load voltage and d) system frequency.

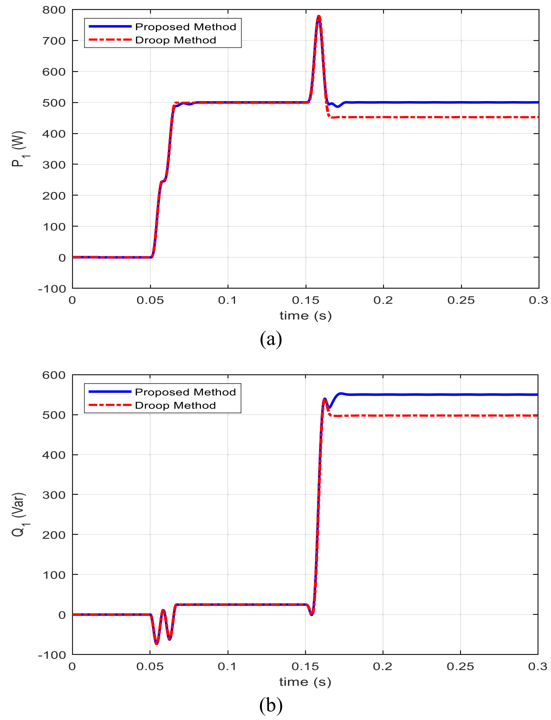

FIGURE 8. Output powers of inverter 1 in scenario I. a) Output active power and b) Output reactive output power.

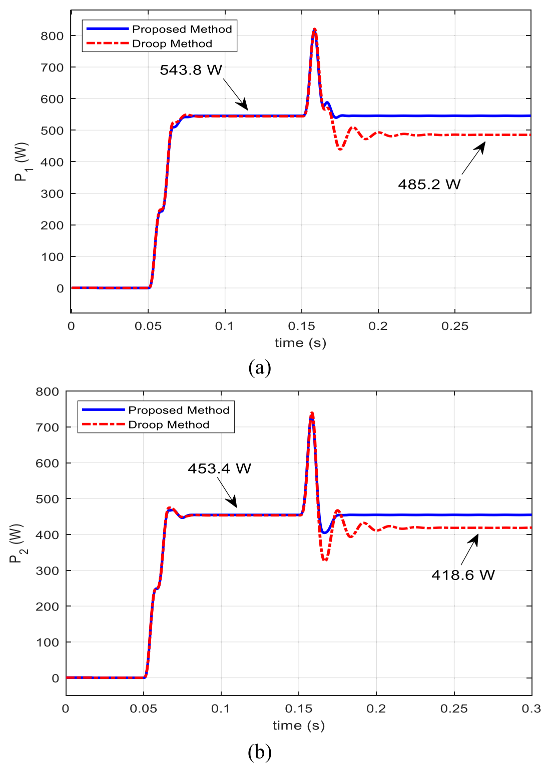

FIGURE 9. Output active powers variations of inverters in scenario II a) output active power of inverter 1 and b) output active power of inverter 2.

methods are considered. Based on the droop control method of parallel inverters, the active power can be shared proportionally to the inverse of droop coefficients similar to the droop control and power sharing for parallel SGs. Although, this is not true for reactive power sharing where one of the disadvantages of P/f droop control is poor reactive power

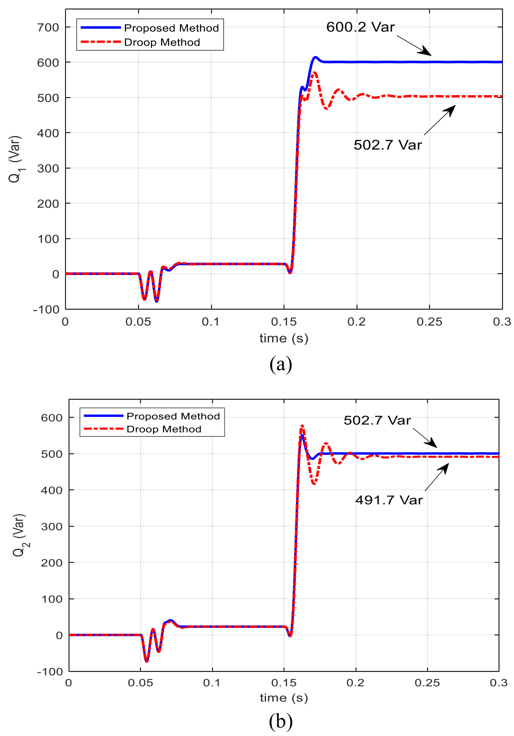

FIGURE 10. Output reactive powers variations of inverters in scenario II a) output reactive power of inverter 1 and b) output reactive power of inverter 2.

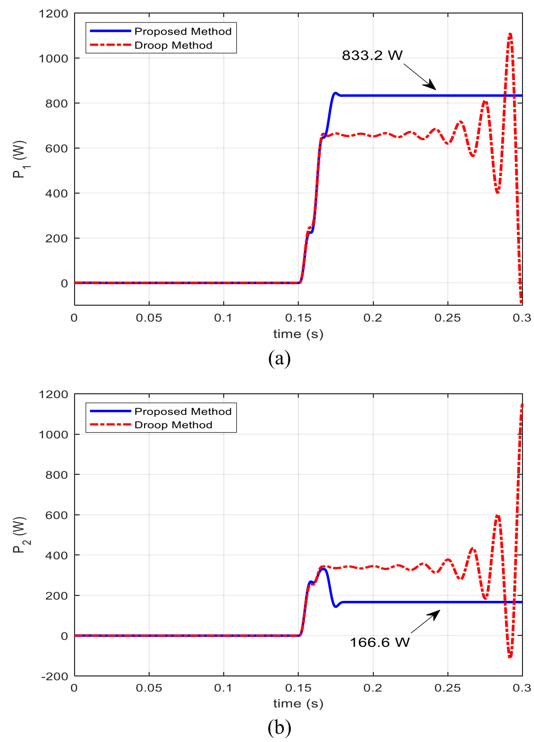

FIGURE 11. Output active powers variations of two inverters in scenario III, a) output active power of inverter 1 and b) output active power of inverter 2.

sharing. Therefore, the inverter 2 is assumed to produce %20 power more than the inverter 1. The inverse proportion of droop coefficients is considered to be 1.2 according to TABLE 1. As a result, the inverter 1 that has smaller droop coefficient, produces more active power rather than the inverter 2. The load switching is analogous to the scenario I leading to similar power and voltage variations of the load. Fig. 9 and 10 show the variations of the output active and reactive powers of inverters, respectively.

As can be seen in Fig. 9, the active load is shared between two inverters proportional to the inverse of droop coefficients. This power sharing, however, cannot be seen in reactive powers with the droop control method (Fig. 10). Unlike the droop control method, which suffers from poor reactive power sharing, the reactive powers are accurately shared in the proposed method.

C. SCENARIO III: LARGE DROOP COEFFICIENTS

In order to achieve a fast-dynamic response and improved power sharing in the droop control method, large droop coefficients are required. However, the large droop coefficients can lead to system instability, so that it is not possible to obtain desired dynamic response and power sharing. In this scenario, at $t = 0.15$ sec a purely resistive load is connected to the system. Fig. 11 shows the output active powers variations of two inverters in both droop control and proposed method. As shown in Fig. 11, the proposed method can share the active power with high proportion, while the droop control method could not share the power due to instability.

VI. CONCLUSION

In this paper, a novel approach has been proposed for accurate power sharing in islanded microgrids, which benefits from constant frequency operation. The proposed method has been compared with the conventional P/f droop control. The simulations have been carried out for two parallel inverter system under three different scenarios. The simulation results have shown that the droop method suffers from voltage and frequency deviations which are not suitable for a critical load. Moreover, it has been demonstrated that the P/f droop control method suffers from poor reactive power sharing while the proposed method is capable to perform accurate reactive power sharing. It has been shown that the proposed method is strongly appropriate for critical loads sensitive to voltage and frequency variation. Furthermore, it has been shown that in some cases, the droop control fails in power sharing due to instability whereas the proposed method is able to perform desired power sharing of each inverter-based DG. Although the stability of the proposed method relies heavily on the performance of communication links, it is worth applying this control method for systems equipped with a reliable communication link.

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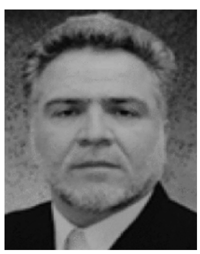

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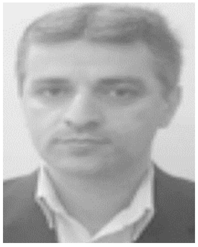

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