

# IMPROVED POWER CONTROLLER FOR MICROGRID WITH NONLINEAR AND LINEAR LOADS

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## ABSTRACT

The main objective of this control is to maintain the stability of the microgrid frequency and voltage by forcing the inverters to operate at their rated power, while eliminating unwanted currents such as circulating currents and noise currents arising from output parameter inconsistencies. However, the presence of non-linear or unbalanced loads poses serious challenges, negatively affecting the effectiveness of this control mechanism. These harmonics will cause the power sharing control between inverters to become inaccurate, thereby creating circulating currents between inverters, causing overheating and potentially damaging the inverters. This paper proposes a control strategy that enhances the accuracy of power sharing between inverters and improves the voltage quality in the microgrid. The proposed method can accurately distribute power to the inverters in the microgrid by using a virtual impedance block, which can automatically adjust its value according to the load conditions, the ambient temperature conditions, and the structure changes of the microgrid. In addition, the power sharing accuracy of the proposed method is not affected by nonlinear or unbalanced loads, improving the voltage quality in the microgrid. The proposed controller overcomes the limitations of the conventional controller. The simulation and experimental results demonstrate the suitability of the proposed control method.

*Keywords:* Power sharing control, frequency control, voltage control, nonlinear load, *circulating current*.

## 1. INTRODUCTIONS

A microgrid is a system comprised of multiple components working together to supply electricity reliably and efficiently. The main components include: Distributed Generation (DG), renewable energy sources, and conventional power sources. However, DG sources cannot directly generate 3-phase AC voltage. Therefore, inverters are utilized to create 3-phase AC voltage from these renewable energy sources. Alternatively, inverters are connected in parallel for high-power electricity transmission or to link multiple generators to the grid. Fig.1 depicts a microgrid consisting of multiple inverters, interconnected via lines to a common AC Bus, also referred to as the Point of Common Coupling (PCC). Each inverter is powered by an individual DC source (which could be batteries, solar panels, or other DC sources). This microgrid is capable of operating in grid-connected mode via a Static Transfer Switch (STS) or in islanded mode [1],[2].

When the scale of a microgrid is expanded or to increase transmission capacity and provide reserve for the maintenance and repair of inverters, designing parallel operation for inverters is essential [1],[2]. When multiple inverters are connected in parallel, circulating current (CC) occurs due to differences in their output impedances. This leads to differences in terminal voltages among the inverters, causing circulating current to flow between them. The circulating current does not supply the load but only heats the inverters and can destabilize the system[3],[4],[5]. Currently, researchers worldwide are still investigating ways to eliminate circulating current in parallel-connected inverters in microgrids. On the other hand, microgrids often have nonlinear and unbalanced loads, which generate harmonics. These harmonics make the power sharing calculation of the inverters inaccurate.

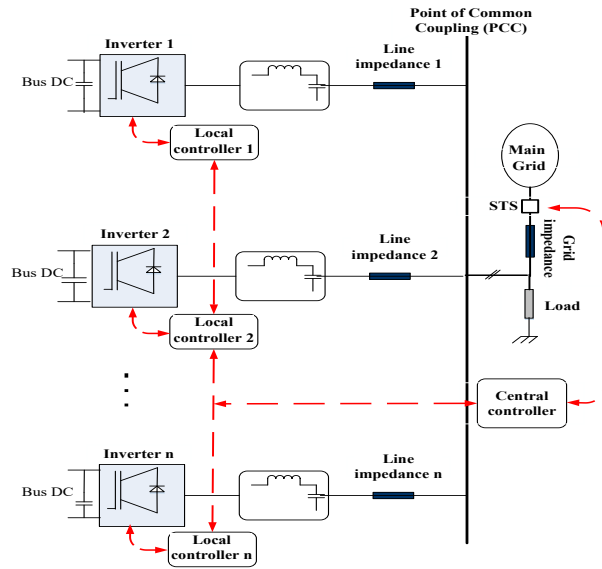


Fig. 1. Configuration of a microgrid consisting of parallel connected inverters

Fig. 2 shows that circulating current phenomena may appear in inverters if their power is not properly shared according to their rated power ratios.

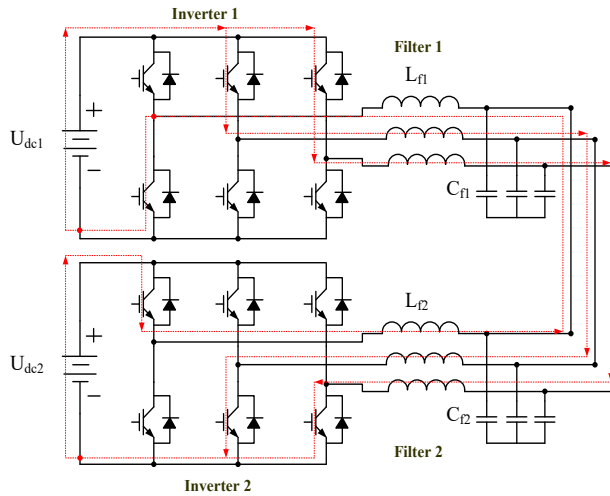


Fig. 2. Illustration of circulating current flowing between two inverters in a microgrid

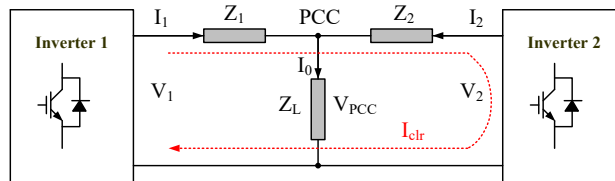


Fig. 3. Equivalent circuit of two parallel inverters

In Fig.3,  $Z_1$  is the output impedance of the first parallel inverter and  $Z_2$  is output impedance of second parallel inverter. The load's impedance  $Z_L$ ,  $V_1$  and  $V_2$  are the output voltages of the inverters,  $I_1$  and  $I_2$  are the output currents of the inverters,  $V_{PCC}$  is the load voltage, and  $I_0$  represents the current supplied to the load. In a practical system, two impedances ( $Z_1$  and  $Z_2$ ) will not be the same because filters have different parameters plus line impedances are also distinct. According to document[4] and Fig.3, the circulating current can be written in the form of the following expressions:

$$\dot{I}_{cir} = \frac{-\dot{I}_2 + \dot{I}_1}{2} \quad (1)$$

$$\dot{I}_1 = \frac{\dot{V}_1 - \dot{V}_{PCC}}{\dot{Z}_1} \quad (2)$$

$$\dot{I}_2 = \frac{\dot{V}_2 - \dot{V}_{PCC}}{\dot{Z}_2} \quad (3)$$

$$\dot{V}_{PCC} = \frac{\frac{\dot{V}_1}{\dot{Z}_1} + \frac{\dot{V}_2}{\dot{Z}_2}}{\frac{1}{\dot{Z}_1} + \frac{1}{\dot{Z}_2} + \frac{1}{\dot{Z}_L}} = \frac{\dot{Z}_L(\dot{V}_1\dot{Z}_2 + \dot{V}_2\dot{Z}_1)}{\dot{Z}_1\dot{Z}_2 + \dot{Z}_1\dot{Z}_L + \dot{Z}_2\dot{Z}_L} \quad (4)$$

If the terminal impedance of both inverters is the same,  $Z_1=Z_2=Z$ , then (1), (2) and (3) can be written:

$$\dot{I}_{cir} = \frac{\dot{V}_1 - \dot{V}_2}{2\dot{Z}} \quad (5)$$

In a practical system, maintaining absolute equality of parameters between different inverters is almost impossible. Recurrent current (CC) will always be present in microgrid if the inverters are not properly shared according to their rated power ratios.

When the microgrid operates in stand-alone mode, the inverters have to share the load power according to their rated power ratio. This helps to avoid one inverter being overloaded while the others are not yet delivering their full power. Droop control is one of the most common and basic power control methods for parallel inverters in the microgrid, especially in stand-alone mode[1],[2],[4],[5]. However, the traditional P/f and Q/V droop methods yield inaccurate reactive power sharing results when the line impedance and output parameters of the inverters are inconsistent, which reduces the stability and voltage quality in the microgrid. Next, there have also been some studies on improving droop to share power to the inverters such as: The study[6] presents an adaptive power-sharing controller that aids the system in rapidly discovering fresh established states when there are alterations in load, for stabilization purposes. Recently, certain investigators have suggested an adaptive power sharing control technique which relies on voltage compensation concept; this implies that line impedance difference would be responsible for voltage deviation at output of the inverter[7],[8],[9]. The study is about an adaptive control method, based on common voltage to enhance power-sharing, the method proposed in this study is based on integration to recover voltage. In study[10], an improved Droop method is proposed, with this approach, the error in reactive power sharing becomes less but not completely eliminated and does not take into account the presence of local loads connected at the output of each inverter. A study presents a control strategy using a communication bus to achieve accuracy in reactive power sharing[11]. However, the case of communication bus interruption and its impact on power sharing is not taken into account. In addition, there are proposals for control strategies based on hierarchical control algorithms in studies[12],[13]. Because communication delays are always present in hierarchical control setups, it will affect the accuracy of power sharing, which these studies have not yet taken into account. On the other hand, studies[14],[15] used virtual impedance to adjust the output impedance of parallel inverters that can balance the parameter differences of parallel inverters and eliminate cyclic current. The virtual impedance can be pure resistance or pure inductance, or a combination of both based on the parameter differences between parallel inverters. However, the virtual impedance in these studies is a fixed value, so the suitability of virtual impedance for voltage drop compensation will be limited, because in practice the load parameters change continuously, fixing the virtual impedance value can cause large voltage drops, this causes the voltage in the microgrid to deteriorate. In study [16],[17],[18],[19] were presented which gave summary on different strategies for controlling reactive power-sharing among inverters. In this study, the advantages and disadvantages of classical and modern methods were presented to evaluate their strengths and weaknesses. The results from this comparison analysis suggest that each of these methods improve the classical technique, but they do so in different ways. There have been studies using communication, which have also given good results but the main drawbacks are the reliability of the communication and the complexity of the proposed algorithms. The simulation results in these studies show that the line impedance parameters and output parameters of the inverters need to be known in advance. Furthermore, the system is greatly influenced by the controller parameters.

This paper proposes a tunable virtual impedance method, which will improve the efficiency of power control in microgrids, this method improves the power sharing accuracy. The proposed method is presented in section 2.

The proposed controller will share the power precisely depending on the ratio of the rated power of the parallel connected inverters. This method will not be affected by line impedance or local loads present in the microgrid, delays or interruptions in communication.

- In this proposed method, the line impedance parameter does not need to be known exactly as in previous studies.
- The total harmonic distortion (THD) of voltage generated by the non-linear load is also minimized.
- The proposed method will give better results than conventional virtual impedance methods.
- The controller can operate in both standalone and grid-connected modes.

## 2. PROPOSED CONTROLLER

### 2.1. Islanded mode control

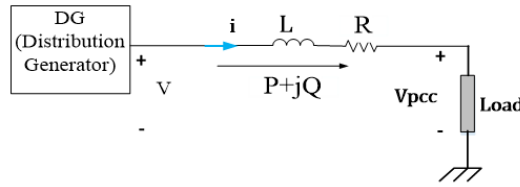


Fig. 4. Equivalent diagram of the inverter connected to a load

Where:  $R(\Omega)$  is the resistor;  $L(H)$  is the reactance,  $V(\text{voltage})$  is the terminal voltage,  $P(W)$  and  $Q(\text{Var})$  are the power at output of the inverter,  $V_{pcc}(\text{voltage})$  is the voltage at the load,  $I(A)$  is the current flowing on the line. According to research[2],[4],[5], the power running on the line can be defined as:

$$P = \frac{V}{R^2 + X^2} [X V_{PCC} \sin\delta + R (V - V_{PCC} \cos\delta)] \quad (6)$$

$$Q = \frac{V}{R^2 + X^2} [X (V - V_{PCC} \cos\delta) - R V_{PCC} \sin\delta] \quad (7)$$

Combine expressions (6) and (7):

$$\sin\delta = \frac{XP - RQ}{V V_{PCC}} \quad (8)$$

$$V - V_{PCC} \cos\delta = \frac{RP + XQ}{V} \quad (9)$$

For distribution and low voltage power networks, the line impedance has both resistance  $R$  and reactance  $X$ . To consider the droop characteristics in this case, we use the virtual coordinate system to convert the powers  $P$ ,  $Q$  to  $P'$ ,  $Q'$  through the conversion matrix  $T$ :

$$\begin{bmatrix} P' \\ Q' \end{bmatrix} = [T] \begin{bmatrix} P \\ Q \end{bmatrix} = \begin{bmatrix} \sin\theta & -\cos\theta \\ \cos\theta & \sin\theta \end{bmatrix} \begin{bmatrix} P \\ Q \end{bmatrix} = \begin{bmatrix} \frac{X}{Z} P - \frac{R}{Z} Q \\ \frac{R}{Z} P + \frac{X}{Z} Q \end{bmatrix} \quad (10)$$

Where:  $\dot{Z} = R + jX = Z \angle \theta$ ;  $\delta$  be the angle between voltage  $V$  and  $V_{pcc}$ , Usually angle  $\delta$  is small.

In the distribution network, the deviation angle  $\delta$  is usually very small. Formulas (8), (9) and (10) can be rewritten:

$$\delta \cong \frac{Z P'}{V V_{PCC}} \quad (11)$$

$$V - V_{PCC} \cong \frac{Z Q'}{V} \quad (12)$$

Expressions (11) and (12) show that the active power  $P'$  can be controlled through frequency, the reactive power  $Q'$  can be controlled through voltage. Therefore, we have the characteristics of the droop  $P'/f$  and  $Q'/V$  expressed by the formula:

$$\omega = -m_p P' + \omega_0 \quad (13)$$

$$V = -m_q Q' + V_0 \quad (14)$$

The droop controller consists of expressions (13) and (14) which are straight line equations with slopes  $m_p$  and  $m_q$ , expression (13) is droop  $P'/f$ , expression (14) is droop  $Q'/V$ , the slopes  $m_p$  and  $m_q$  are called slip coefficients. Each inverter will have a droop controller, the inverters connected in parallel will share power according to the slip coefficients  $m_p$  and  $m_q$ , the slip coefficients are determined according to expression (15).

$$m_p = \frac{\omega_{maximum} - \omega_{minimum}}{P_{maximum}}; m_q = \frac{V_{maximum} - V_{minimum}}{Q_{maximum}} \quad (15)$$

Equations (13) and (14) show that the frequency and voltage regulation depend on the power  $P'$  and  $Q'$ . On the other hand, according to formula (10),  $P'$  and  $Q'$  depend on  $R$  and  $X$ ,  $R$  and  $X$  are the actual impedance of the line. According to formula (14), the accuracy of power sharing  $Q$  depends on the voltage  $V$ , and the voltage  $V$  depends on the voltage drop created by  $R$  and  $X$ . Therefore,  $R$  and  $X$  greatly affect the power sharing  $Q$ . This has been demonstrated in [4],[19],[20],[21].

Assuming the microgrid has two inverters connected in parallel as Fig. 5, the condition to divide the power exactly between the two inverters is:

$$\Delta V_1 = \Delta V_2 = \Delta V \Rightarrow \begin{cases} V_1 = V_{pcc} + \Delta V \\ V_2 = V_{pcc} + \Delta V \end{cases} \quad (16)$$

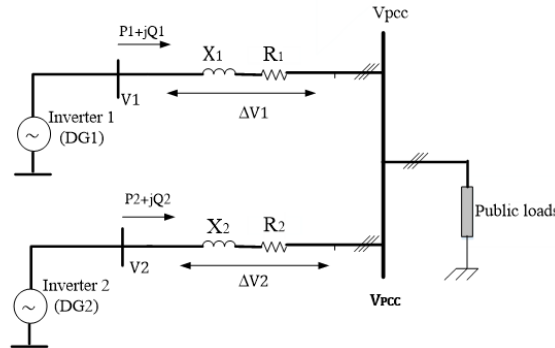


Fig. 5. Microgrid with 2 inverters connected in parallel

In practice, the voltage drops  $\Delta V_1$  and  $\Delta V_2$  are always different, so expression (15) occurs when the voltage drop is compensated, so  $\Delta V_1 = \Delta V_2$  and therefore  $V_1 = V_2$ . Normally, the voltage drop is compensated by using a virtual impedance  $Z_v$ . For accurate voltage drop compensation, the line impedance and output impedance parameters of the inverters must be known accurately, which in practice can vary depending on the temperature and structure of the microgrid, this will make it difficult to choose the virtual impedance  $Z_v$ , and if  $Z_v$  is not accurate, the power division between the two inverters will also be inaccurate.

Therefore, in order to improve the accuracy in selecting virtual impedance values, this paper proposed an adaptive adjustment method for virtual impedance values, the general control diagram is shown in Fig. 6, the detailed adjustment diagram of the virtual impedance block is shown in Fig. 7.

The general controller in Fig. 6 includes the following blocks:

- DSOGI-QSG block to get the amplitude and phase angle of the line current and the voltage to create the PCC point.

- The output signal of the DSOGI-QSG block is passed through the power calculation block and then passed through a low-pass filter to get the average power value P and Q.
- The power P, Q is fed into the droop block to perform power sharing for the inverters.
- The output of the droop block will be combined with the output of the adjustable virtual impedance block (the adjustable virtual impedance block is shown in detail in Fig. 7) to generate the reference voltage ( $V_{ref}$ ) for the inverter.

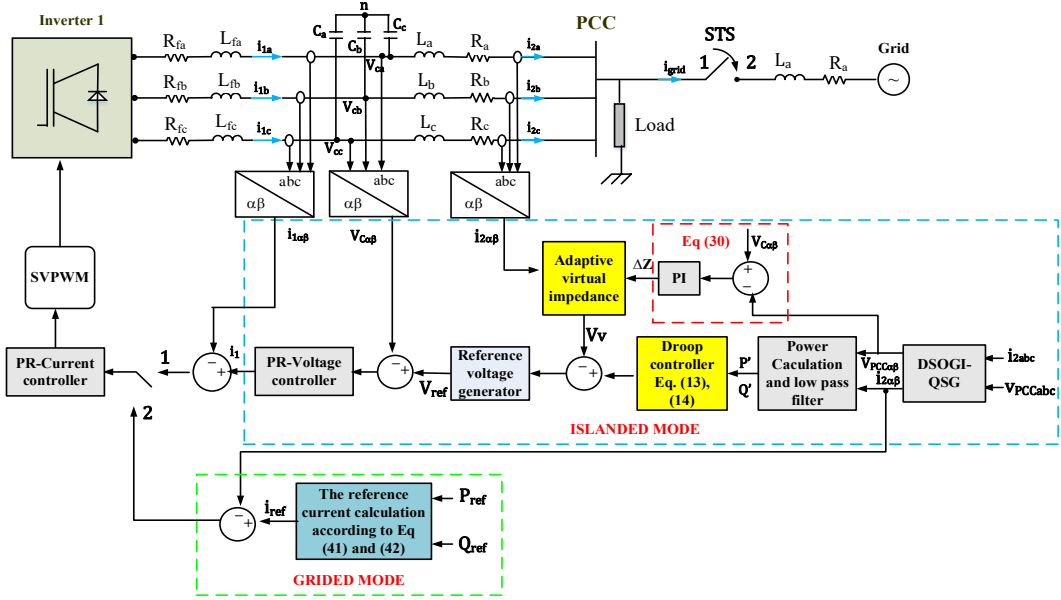


Fig. 6. The general control diagram for a microgrid

The adjustable virtual impedance block in Fig. 7. is set up as follows:

The first, based on factors such as rated power of inverter, load capacity, transmission distance, conductor material, etc. to select initial values for virtual impedance  $R_v$  and  $X_v$ .

According to the control diagram in Fig. 6, we can write the formula for virtual impedance as follows:

$$v_v = Z_v i_2 = R_v i_2 + L_v \frac{di_2}{dt} \quad (17)$$

$$v_{dv} = i_{2d} R_v + L_v \frac{di_{2d}}{dt} - i_{2q} \omega L_v \quad (18)$$

$$v_{qv} = i_{2q} R_v + L_v \frac{di_{2q}}{dt} + i_{2d} \omega L_v \quad (19)$$

In expressions (18) and (19), we can ignore the components  $L_v \frac{di_{2d}}{dt}$  and  $L_v \frac{di_{2q}}{dt}$  since  $L_v$  is small.

$$v_{dv} = i_{2d} R_v - i_{2q} \omega L_v = i_{2d} R_v - i_{2q} X_v \quad (20)$$

$$v_{qv} = i_{2q} R_v + i_{2d} \omega L_v = i_{2q} R_v + i_{2d} X_v \quad (21)$$

Where:  $R_v$ : This represents the virtual resistance ( $\Omega$ );  $X_v = \omega L_v$ : This represents the virtual reactance ( $\Omega$ )

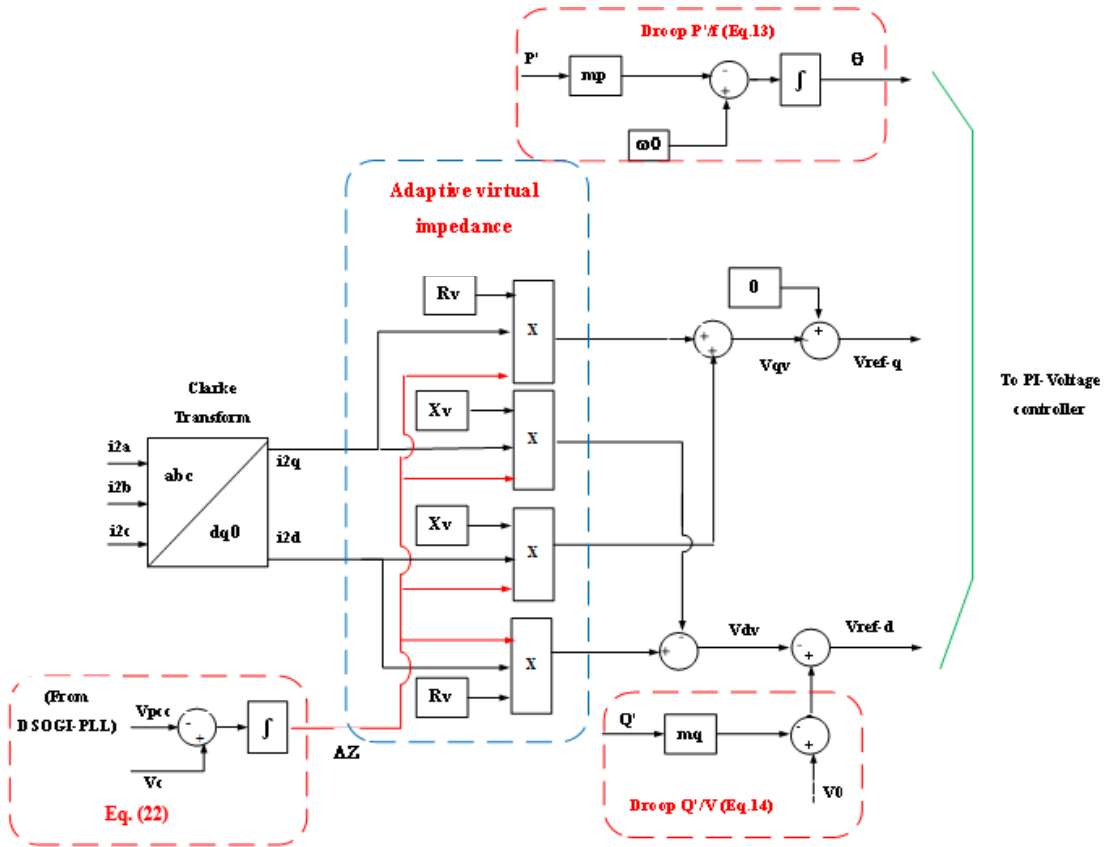


Fig. 7. The droop controller and Adaptive virtual impedance proposed

The virtual impedance values in expressions (20) and (21) are constant, so if we determine this virtual impedance incorrectly, it will affect the accuracy of power sharing. In fact, voltage drop compensation depends a lot on actual conditions such as environment, load changes, microgrid structure, etc. If the virtual impedance is chosen too large, the voltage drop in the microgrid will be large, affecting the voltage quality. If the virtual impedance is chosen too small, the power sharing will be inaccurate.

Therefore, the virtual impedance values chosen above must be adjusted through a variable set as  $\Delta Z$ , the variable  $\Delta Z$  is adjusted to achieve accurate voltage compensation and line voltage drop compensation. Because for accurate power sharing, condition (16) must be satisfied, therefore  $\Delta Z$  is set as in equation (22).

$$\Delta Z = k_{pZ} \int (V_C - V_{PCC}) dt \quad (22)$$

Where:  $k_{pZ}$  is the integral constant

$V_C$  is the voltage at the output of the inverter and  $V_{PCC}$  is the voltage at the PCC.

The variable  $\Delta Z$  is adjusted to change the virtual impedance value as proposed in this paper.

Equation (22) shows that  $\Delta Z$  is adjusted through the PI stage, the input signal of the PI stage is the difference between the output voltage of each inverter ( $V_C$ ) and the reference voltage ( $V_{PCC}$ ). For each inverter, this difference is the voltage drop on the line of that inverter. Corresponding to a certain value of  $V_C$  and  $V_{PCC}$ , there will be a corresponding “ $\Delta Z$ ” value given to adjust the virtual impedance block selected above, with the aim of accurately compensating for the voltage drop on the line. This controller works on the principle of virtual impedance parameter control to achieve the desired reactive power sharing goal, instead of directly controlling the reactive power quantity,  $\Delta Z$  is a variable, this variable changes according to  $V_C$  and  $V_{PCC}$  voltage, it represents the deviation of line impedance. Because the  $V_C$  output voltage of each inverter depends on the line impedance that connects the inverter to the PCC point.

Suppose we perform power sharing control for 2 parallel connected inverters with line impedances  $Z_1 \neq Z_2$ :

Then according to formula (22): The voltage at output ( $V_{C1}$ ) of inverter 1 will be adjusted respectively by a variable  $\Delta Z_1$ .

Then the formula (20) and (21) can be adjusted by  $\Delta Z_1$  as follows:

$$\Delta Z_1 \cdot i_{2d} R_v - \Delta Z_1 \cdot i_{2q} X_v = v_{dv} \quad (23)$$

$$\Delta Z_1 \cdot i_{2q} R_v + \Delta Z_1 \cdot i_{2d} X_v = v_{qv} \quad (24)$$

The voltage at output ( $V_{C2}$ ) of inverter 2 will be adjusted respectively by a variable  $\Delta Z_2$ .

Then the formula (20) and (21) can be adjusted by  $\Delta Z_2$  as follows:

$$\Delta Z_2 \cdot i_{2d} R_v - \Delta Z_2 \cdot i_{2q} X_v = v_{dv} \quad (25)$$

$$\Delta Z_2 \cdot i_{2q} R_v + \Delta Z_2 \cdot i_{2d} X_v = v_{qv} \quad (26)$$

Equations (22); (23) and (24) or (25) and (26) are presented in Fig. 7.

- **Power calculation and filtering:**

To improve the accuracy of the power sharing controller, here we use a double second order generalized integrator - quadrature signal generation (DSOGI-QSG) to calculate the power [8]- [10].

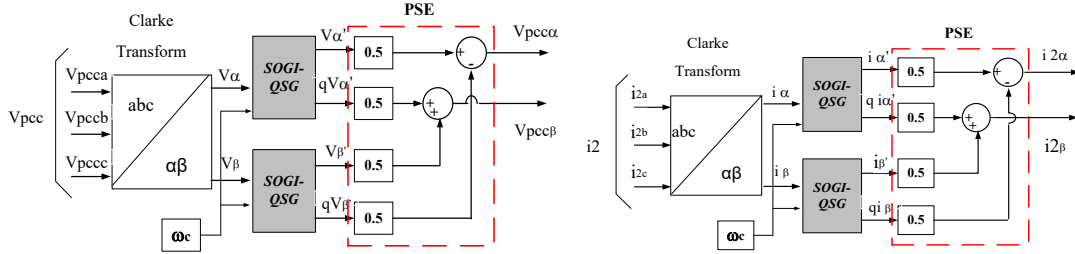


Fig. 8. Power calculation and filtering use a DSOGI-QSG

$$p = \frac{3}{2} (i_{2\alpha} V_{PCC\alpha} + i_{2\beta} V_{PCC\beta}) \quad (27)$$

$$q = \frac{3}{2} (i_{2\alpha} V_{PCC\beta} - i_{2\beta} V_{PCC\alpha}) \quad (28)$$

The instantaneous active and reactive power in expressions (27) and (28) are passed through a low-pass filter (LPF):

$$P = \frac{\omega_c}{S + \omega_c} p \quad (29)$$

$$Q = \frac{\omega_c}{S + \omega_c} q \quad (30)$$

Where: p and q are instantaneous power; P(W) and Q(Var) are the average values power.

- **Voltage controller and current controller:**

Nonlinear load and unbalance load cause the three-phase load voltage to not balance; they produce current harmonics that could lead to instability in voltage and frequency within Microgrid. In this paper, the PR (Proportional-Resonant) controllers are used for improving the stability of both frequency control and voltage control, decreasing stability errors as well as reducing distortion in voltage due to nonlinear load or unbalance loads. The PR controllers can be expressed like this [17]- [18]:

*PR-Voltage controller:*

$$G_V(S) = k_{pv} + \frac{k_{rv} S}{S^2 + \omega_c S + \omega_0^2} + \sum_{h=3,5,7} \frac{k_{hv} S}{S^2 + h\omega_c S + (h\omega_0)^2} \quad (31)$$

*PR-Current controller:*

$$G_i(S) = k_{pi} + \frac{k_{ri}S}{s^2 + \omega_c S + \omega_0^2} + \sum_{h=3,5,7} \frac{k_{hi}S}{s^2 + h\omega_c S + (h\omega_0)^2} \quad (32)$$

Where  $k_{pv}$ ,  $k_{pi}$ ,  $k_{rv}$ ,  $k_{ri}$ ,  $k_{hv}$  and  $k_{hi}$  are the resonant gains at the fundamental frequency and harmonic frequencies.

## 2.2. Grid-connected mode control

In grid-connected mode, the microgrid is controlled to generate active and reactive power flows into the grid by controlling the current according to the reference power value. Equations (27) and (28) are rewritten as expressions (33) and (34):

$$i_{2\alpha} = \frac{2(p \cdot v_{PCC\alpha} + q \cdot v_{PCC\beta})}{3(v_{PCC\alpha}^2 + v_{PCC\beta}^2)} \quad (33)$$

$$i_{2\beta} = \frac{2(p \cdot v_{PCC\beta} - q \cdot v_{PCC\alpha})}{3(v_{PCC\alpha}^2 + v_{PCC\beta}^2)} \quad (34)$$

According to equations (33) and (34), for a given reference power value, we will have a reference current value. In other words, power is controlled through current control.

## 3. SIMULATIONS RESULTS

The controller proposed is simulated using Matlab/Simulink, the simulation analysis calculations of these controllers are implemented for 2 inverters 4kVA, rectified nonlinear loads, the controller parameters are presented as shown in Table 1.

Table 1. The parameters for the controller

Parameters	Values	Parameters	Values
Rate frequency $f_0$ (Hz)	50	Input source voltage $V_{cd}$ (V)	600
Rate power (kVA)	4	Filter inductance $L_f$ (mH)	4.2
Nominal voltage $V_{AC,p}$ (V)	310	Filter resistance $R_f$ ( $\Omega$ )	0.1
Droop coefficient $m_q$ (V/Var)	1.25e-3	Filter capacitance $C$ ( $\mu$ F)	2.2
Droop coefficient $m_p$ (rad/s /W)	1.25e-4	Switching frequency $f_s$ (kHz)	10
		$k_{pz}$	0.006
<i>Line impedances</i>			
$L_1$ (mH)	2	$R_1$ ( $\Omega$ )	1.2
$L_2$ (mH)	4	$R_2$ ( $\Omega$ )	0.8
PR controller			
$k_{pi}=0.2; k_{ri}=200; k_{3i}=30; k_{5i}=100; k_{7i}=60; \omega_{ci}=0.0015$			
$k_{pv}=0.2; k_{rv}=200; k_{3v}=25; k_{5v}=22; k_{7v}=60; \omega_{cv}=0.0015$			
<i>A nonlinear rectified load</i>			
R	200 $\Omega$		
L	20mH		
C	85 $\mu$ F		

### 3.1. Case 1

Using the proposed controller to share power for 2 inverters with  $P_{dm1}:P_{dm2}=1:1$ .

During the time period from 0s to 4s, the microgrid operates in islanded mode (switches in position 1). During the time period from 4s to 8s, the microgrid operates in grid-connected mode (switches in position 2). The total load at the PCC has power:  $P=2000W$ ,  $Q=1500Var$ . The parameters of the rectified and nonlinear load is  $R=200\Omega$ ;  $L=20mH$ ;  $C=85\mu F$ .

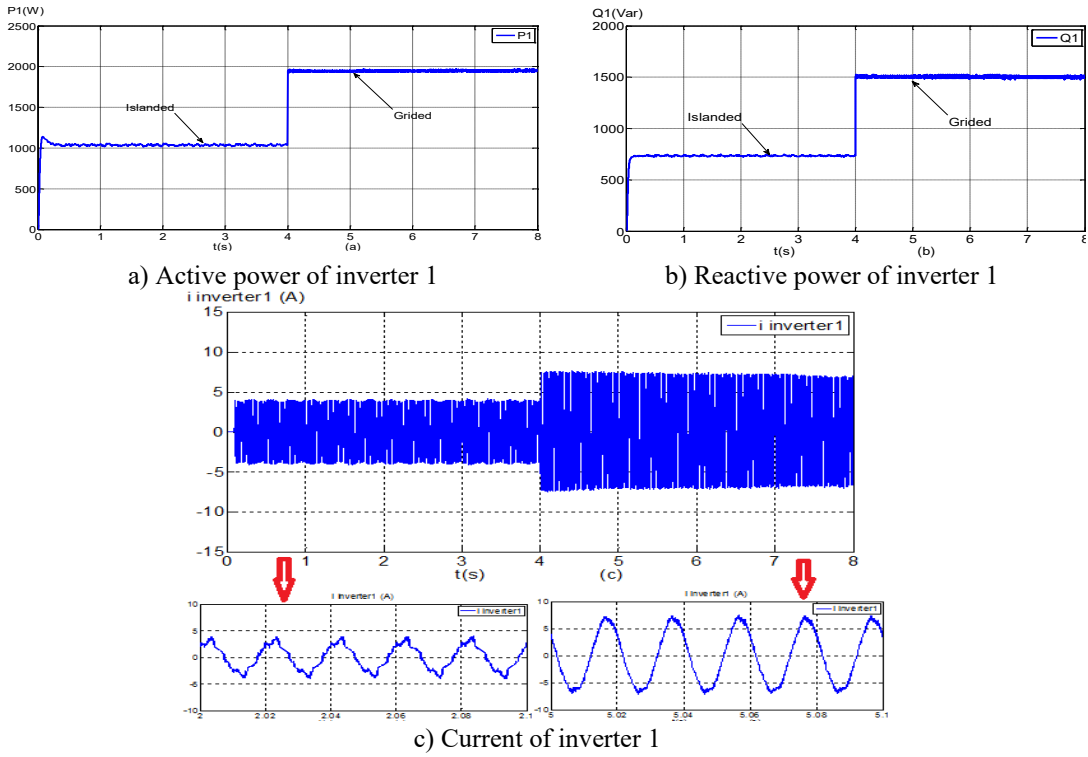


Fig. 9. Power and output current of inverter 1

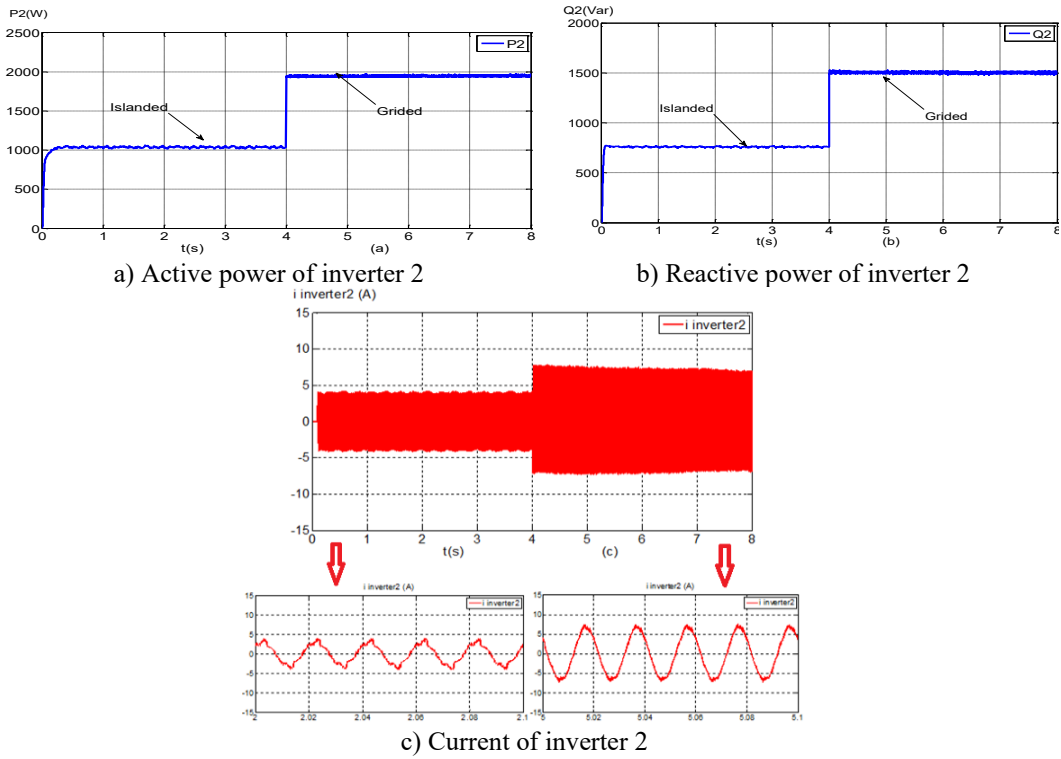
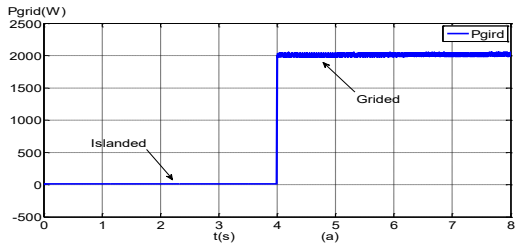
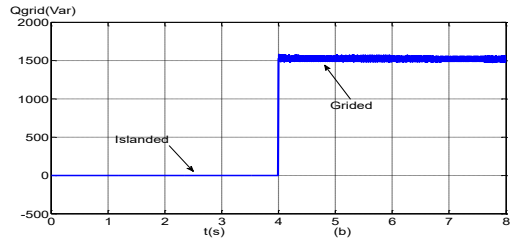


Fig. 10. Power and output current of inverter 2

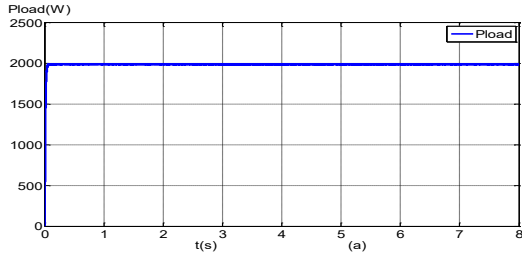


a) Active power transmitted to the grid

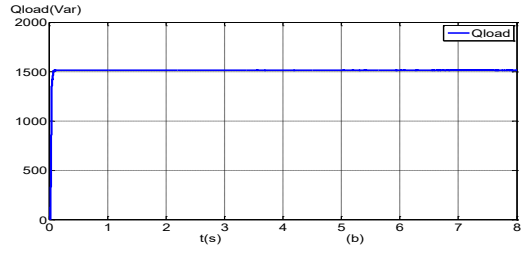


b) Reactive power transmitted to the grid

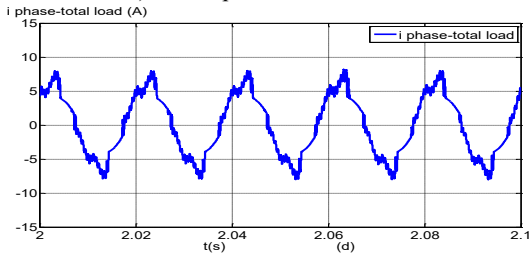
Fig. 11. The active power and reactive power transmitted to the grid



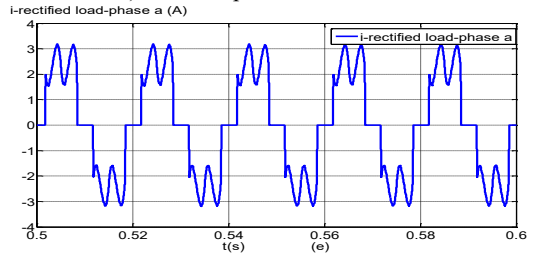
a) Active power of total load



b) Reactive power of total load

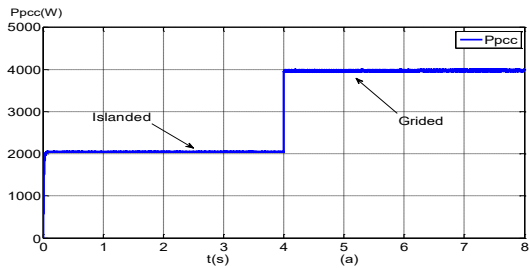


d) Current of the total load

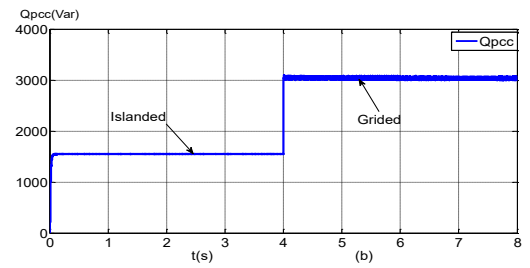


e) Current of the rectified load

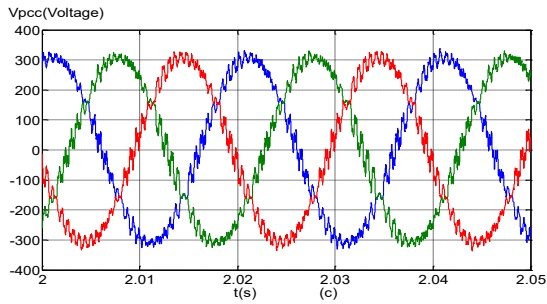
Fig. 12. The powers and current of the load



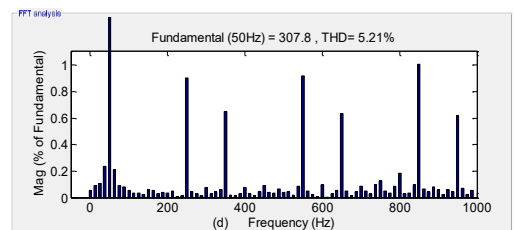
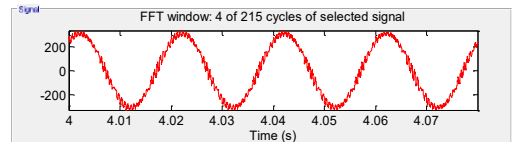
a) Active power at the PCC



b) Reactive power at the PCC



c) PCC voltage



d) THD of PCC voltage

Fig. 13. The powers and voltage at the PCC

During the period from 0s to 4s, the STS is in position 1, the microgrid operates in islanded mode; During the period from 4s to 8s, STS locks in position 2, the microgrid operates in grid-connected mode.

In islanded mode, microgrid immediately performs power-sharing to stabilize frequency and voltage. The Fig. 9a, 9b, 9a and 9b show that the proposed controller has given the correct power-sharing results with the ratio of 1:1 ( $P_1 \approx P_2 \approx 1000W$ ,  $Q_1 \approx Q_2 \approx 750Var$ ). The active power at the PCC is  $2000W$  ( $P_{PCC} = P_{load}$ ), and the reactive power at the PCC is  $1500Var$  ( $Q_{PCC} = Q_{load}$ ). So, during this time, the power of the microgrid transmitted to the grid is 0 (Fig. 11a and 11b). Its transient response and steady-state response are also very good, and the time steady-state set up early.

In grid-connected mode, microgrid is controlled to generate power according to the setting reference value for each inverter is  $P_{ref1} = P_{ref2} = 2000W$  and  $Q_{ref1} = Q_{ref2} = 1500Var$ . Fig. 9a, 9b, 10a and 10b show that the proposed controller has delivered according to the set reference value ( $P_1 = P_2 = 2000W$ ,  $Q_1 = Q_2 = 1500Var$ ). Fig. 13a and 13b show that the proposed controller has delivered according to the set reference value ( $P_{PCC} = P_1 + P_2 = 4000W$ ,  $Q_{PCC} = Q_1 + Q_2 = 3000Var$ ). Fig. 11i and 11j show that the proposed controller has been delivered into the grid ( $P_{Grid} = P_{PCC} - P_{load} = 4000 - 2000 = 2000W$ ,  $Q_{Grid} = Q_{PCC} - Q_{load} = 3000 - 1500 = 1500Var$ ).

The Fig. 13c and 13d show that the system is working well in terms of voltage (Standard EN50160:  $THD_{max} \leq \pm 8\%$ ).

The Fig. 9a, 10a, 9b and 10b show that  $P_1 : P_2 = 1:1$  in stand-alone mode ( $P_1 \approx P_2 \approx 1000W$ ,  $Q_1 \approx Q_2 \approx 750Var$ ). The active power at the PCC is  $2000W$  ( $P_{PCC} = P_{load}$ ), and the reactive power at the PCC is  $1500Var$  ( $Q_{PCC} = Q_{load}$ ).

Fig. 9b and 10b show that the accuracy for reactive power-sharing by the proposed controller is (-0.26%) for inverter 1 and 0.26% for inverter 2 (consider the time period from 0-4s):

$$e_{q1(0-4s)} \% = \frac{Q_1 - Q_1^*}{Q_1^*} \cdot 100\% = \frac{748 - 750}{750} \cdot 100\% = -0.26\%$$

$$e_{q2(0-4s)} \% = \frac{Q_2 - Q_2^*}{Q_2^*} \cdot 100\% = \frac{752 - 750}{750} \cdot 100\% = 0.26\%$$

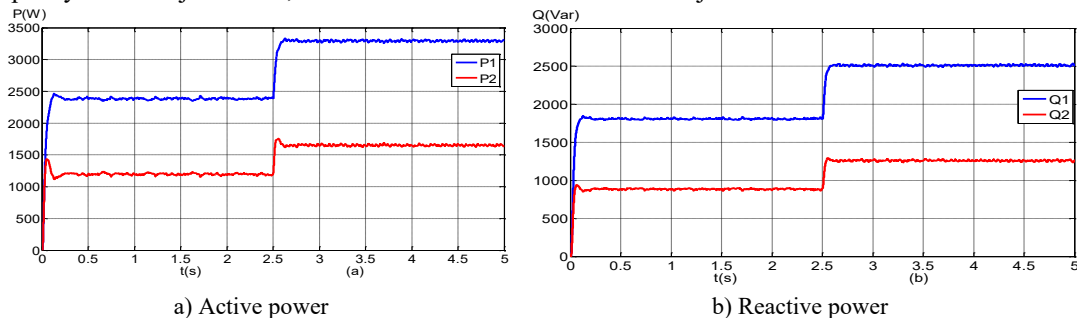
Table 2. Results of the methods in [17]

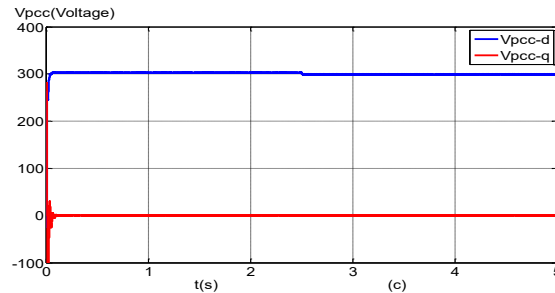
Control method	The accuracy of reactive power sharing between inverters
Virtual Capacitor Control provides the best performances	$Q_{err}\% = 2.4\%$
Q - V method	$Q_{err}\% = 4.3\%$
Conventional Droop	$Q_{err}\% = 5.1\%$
Adaptive Virtual Impedance Control	$Q_{err}\% = 5.2\%$

Table 2 shows that the power division method in this paper gives better results than the power division methods in the study [17].

### 3.2. Case 2

In this case, the power is shared between 2 inverters at a ratio of 2:1 using the proposed controller, the microgrid operates in independent mode, the load changes. In the period from 0-2.5s, the load has a capacity of  $2600 + j2600 VA$ , after 2.5s the load increases to  $5000 + j3750 VA$ .





c) Voltage at PCC- $v_{pcc}$

Fig. 14. The powers and voltage at the PCC ( $P_1: P_2 = 2:1$ )

Fig. 14a and 14b show that the proposed controller gives accurate power division results even when the load changes. (0s-2.5s:  $P_1=2400W$ ,  $P_2=1200W$ ;  $Q_1=1735Var$ ,  $Q_2=865Var$ ); (2.5s-5s:  $P_1=3335W$ ,  $P_2=1665W$ ;  $Q_1=2500Var$ ,  $Q_2=1250Var$ ). Fig.s 16c shows that the system is working well in terms of voltage.

#### 4. EXPERIMENTAL RESULTS

To test the suitability of the proposed method, this paper presents an experimental model consisting of two 3-phase inverters as shown in Fig. 15. The experimental results on power sharing for the two inverters are presented in Fig. 16, 17, 18 and 19.

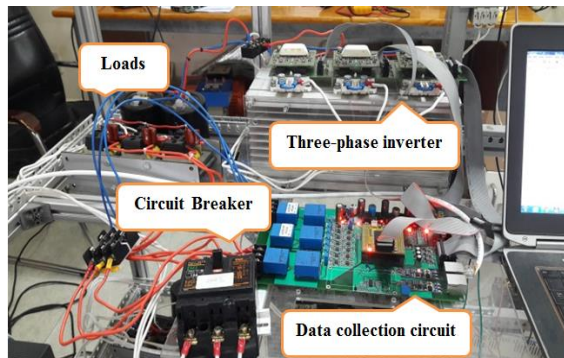


Fig. 15. Hardware setup for the experiment

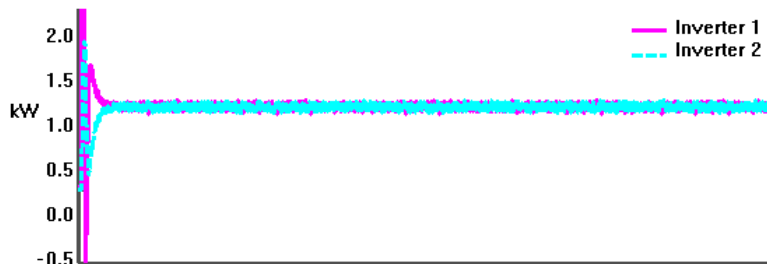


Fig. 16. Active power sharing

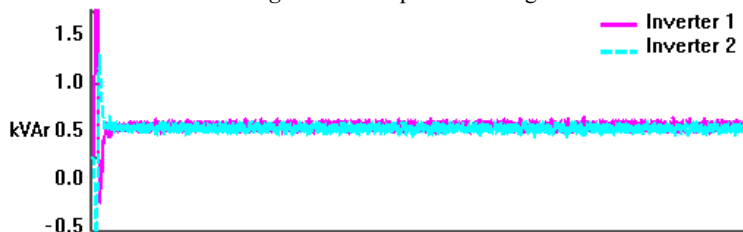


Fig. 17. Reactive power sharing

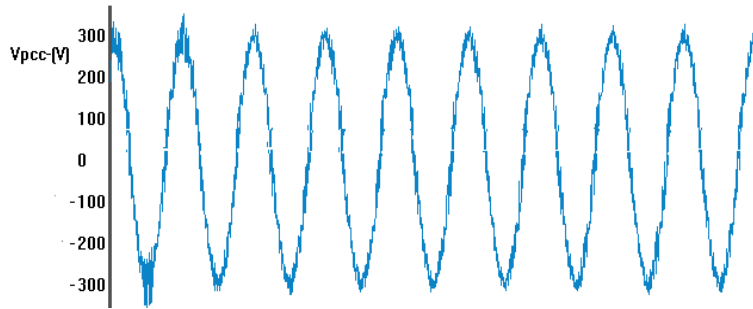


Fig. 18. Voltage at the PCC

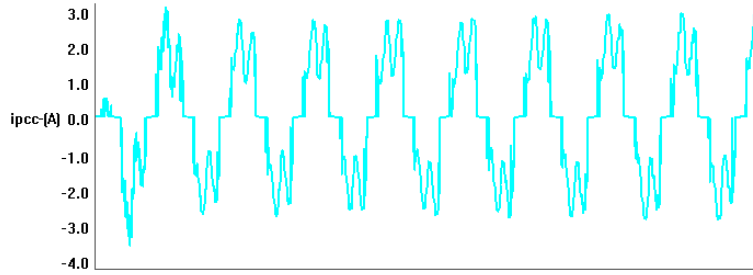


Fig. 19. Current supplied to the rectifier nonlinear load at PCC (phase a)- $i_{pcc-a}$

Fig. 16, 17, 18 and 19 show that the proposed controller gives accurate power division results even when the load changes. while the load is rectifier nonlinear ( $P_1=P_2=1.2\text{kW}$ ,  $Q_1=Q_2=0.5\text{kVar}$ ), the voltage quality in the microgrid is also very good, the voltage drop does not exceed the allowable limit.

#### 4. CONCLUSION

The proposed control method for the microgrid containing nonlinear loads, and the power sharing error was negligible (0.26%). The voltage at the load was very close to the allowable value, which showed that adjusting the impedance value would not cause a large voltage to drop compared to choosing a fixed virtual impedance value. In addition, the use of DSOGI-QSG improved the accuracy of the power calculation block, calculated the amplitude and phase angle of the voltage at the load, thereby making the power sharing more accurate. The current and voltage controller used PR to eliminate harmonics, so the power sharing was also more accurate. The THD of the voltage generated by the nonlinear load was also within the allowable range (5.21%). The simulation results show that the proposed controller provides accurate results in power sharing, eliminating circulating currents, enhancing stability characteristics and improving voltage quality. The proposed controller overcomes the disadvantages of conventional controllers. The proposed control method is easy and simple to apply and does not require knowledge of line impedance parameters.

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## TÓM TẮT

### BỘ ĐIỀU KHIỂN CÔNG SUẤT CẢI TIẾN CHO LƯỚI ĐIỆN SIÊU NHỎ VỚI TẢI PHI TUYẾN VÀ TUYẾN TÍNH

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Mục tiêu chính của bộ điều khiển này là duy trì sự ổn định của tần số và điện áp trong lưới điện siêu nhỏ (microgrid) bằng cách buộc các bộ nghịch lưu (inverter) hoạt động tại công suất định mức, đồng thời loại bỏ các dòng điện không mong muốn như dòng tuần hoàn và dòng nhiễu phát sinh từ sự không đồng nhất của các tham số đầu ra. Tuy nhiên, sự hiện diện của các phụ tải phi tuyến hoặc không cân bằng gây ra những thách thức nghiêm trọng, ảnh hưởng tiêu cực đến hiệu quả của việc điều khiển này. Các sóng hài này sẽ làm cho việc điều khiển chia sẻ công suất giữa các bộ nghịch lưu trở nên không chính xác, từ đó tạo ra dòng tuần hoàn giữa các bộ nghịch lưu, gây ra hiện tượng quá nhiệt và có khả năng làm hỏng thiết bị. Bài báo này đề xuất một chiến lược điều khiển giúp tăng cường độ chính xác của việc chia sẻ công suất giữa các bộ nghịch lưu và cải thiện chất lượng điện áp trong lưới điện siêu nhỏ. Phương pháp được đề xuất có thể phân phối công suất một cách chính xác cho các bộ nghịch lưu trong lưới điện bằng cách sử dụng một khối trở kháng ảo, khối này có thể tự động điều chỉnh giá trị theo điều kiện tải, điều kiện nhiệt độ môi trường và những thay đổi về cấu trúc của lưới điện siêu nhỏ. Ngoài ra, độ chính xác chia sẻ công suất của phương pháp đề xuất không bị ảnh hưởng bởi các phụ tải phi tuyến hoặc không cân bằng, giúp cải thiện chất lượng điện áp trong lưới điện. Bộ điều khiển được đề xuất khắc phục được những hạn chế của bộ điều khiển truyền thống. Các kết quả mô phỏng và thực nghiệm đã chứng minh tính phù hợp của phương pháp điều khiển được đề xuất.

*Từ khóa:* Điều khiển chia sẻ công suất, điều khiển tần số, điều khiển điện áp, tải phi tuyến, dòng điện tuần hoàn.