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The Controller Improves Voltage Quality In Microgrids

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ABSTRACT

The inverters in the microgrid are connected in parallel to improve efficiency. When the Microgrid is operating in standalone mode, the inverters must be controlled to share their power to stabilize the frequency and voltage. The droop control method is one of the most popular power-sharing methods today, some studies have presented traditional and improved droop control methods. However, the purpose of the studies is power-sharing for the inverters that no purpose of reducing the voltage and frequency deviation to improve power quality. This paper presents a voltage and frequency adjustment method based on fuzzy logic to minimize voltage and frequency deviation to improve power quality in microgrids. This controller includes a Droop controller combined with fuzzy logic, the fuzzy logic block will control to change in the slope of the Droop characteristic curve when the load changes. The purpose of the proposed method is to improve the accuracy of power-sharing for inverters and at the same time minimize voltage and frequency deviations in microgrids. Simulation results will prove the effectiveness of the proposed method.

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1. Introduction

The microgrid includes a system of distributed generation (DG) sources, which uses renewable energy sources such as solar energy, wind energy and storage. However, in stand-alone mode, the microgrid must have power sh`aring between inverters connected in parallel to maintain voltage and frequency stability.

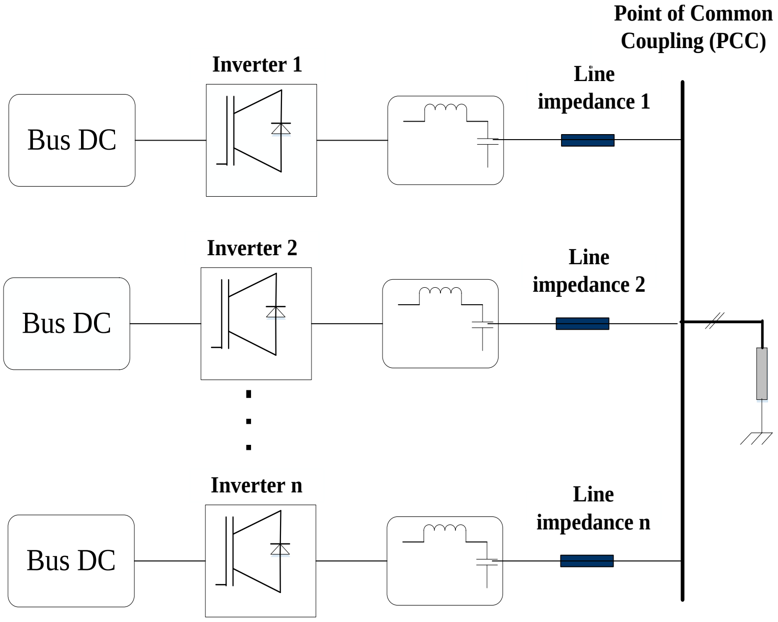


Fig. 1. *The microgrid consists of several inverters connected in parallel coupling (PCC)*

If there is no power sharing between inverters, there will be a balanced current flowing between the inverters, which can cause overload or even damage the inverter [1-3]. Based on the power characteristics of the source, previous studies have established a mathematical model for the droop controller to control the power-sharing between inverters operating in parallel. The droop controller controls active power according to frequency and controls reactive power according to voltage. Relationship between active power and frequency; Reactive power and voltage are expressed through slope coefficients [1-5]. Therefore, researchers relied on the slope factor to realize power sharing between parallel-connected inverters. Several studies have presented traditional droop control methods for power sharing. The purpose of this study is to share power among inverters without aiming to reduce voltage and frequency deviation to improve power quality. However, the traditional droop controller is affected by the line impedance parameter. Therefore, there have been several studies presenting improved droop control methods for power sharing [5-8]. However, the purpose of these studies is to improve the accuracy of power-sharing for inverters without aiming to reduce voltage and frequency deviations to improve power quality.

Therefore, this paper designs a droop controller combined with fuzzy logic to overcome the disadvantages of previous controllers. The purpose of these studies is to improve the accuracy of power-sharing for inverters without aiming to reduce voltage and frequency deviations to improve power quality. The droop-fuzzy logic controller automatically adjusts the slope of the droop characteristic curves when the load changes. Therefore, this controller will minimize the frequency and voltage deviation, it improves power quality in microgrid. In addition, the droop-fuzzy logic controller correctly power-sharing between the parallel-connected inverters in the Microgrid. Typically, the structure of an island microgrid consisting of inverters operating in parallel is shown in Figure 1. In standalone mode, the microgrid must be capable of self-stabilizing voltage and the frequency.

2. Proposed controller

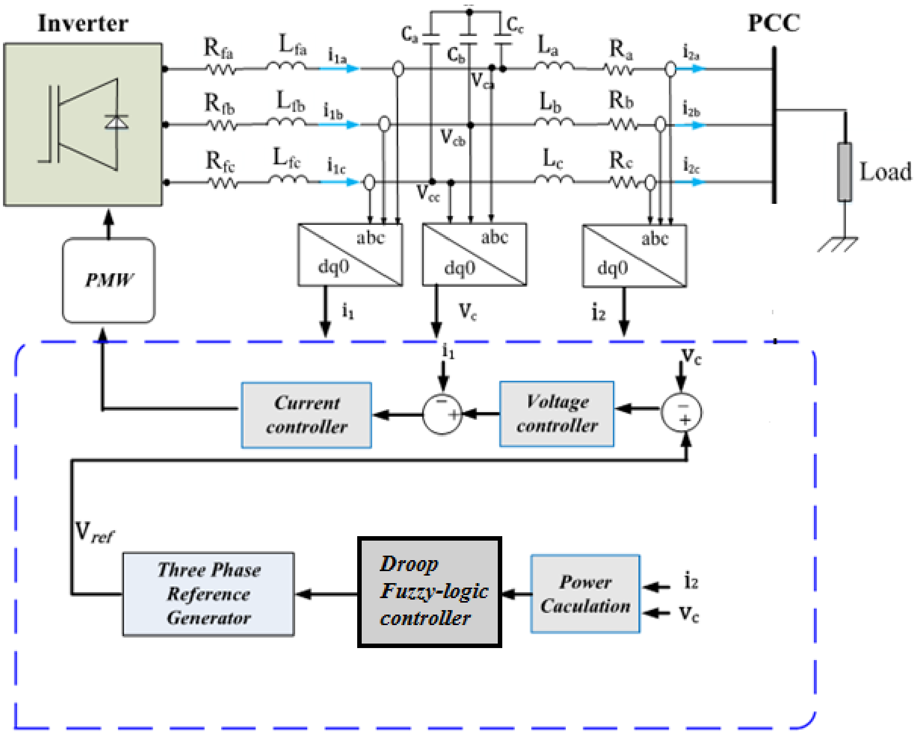


Fig. 2. *Block diagram of the proposed controller for an inverter in islanded microgrid*

The model of the proposed controller is shown in Figure 2. The proposed control system includes the following blocks: the external controller is the Droop- fuzzy logic power controller to control the power-sharing for the inverters, and the inside controllers are current and voltage controllers to control the current and voltage at the output of the inverter.

2.1. Design of the droop controller

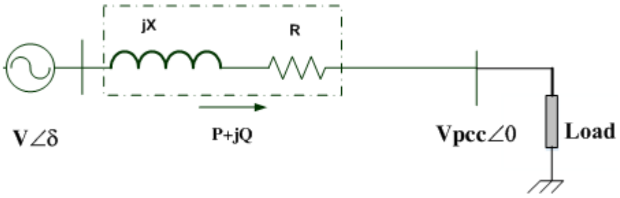


Fig. 3. *Equivalent schematic of inverters connected to a load*

According to Fig 3, the active and reactive power supplied by the inverter are calculated as follows [9-12]:

$$P=\frac{V}{R^2+X^2}[R(V-V_{PCC}\cos\delta)+XV_{PCC}\sin\delta] \tag{1}$$

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

When the angle δ is small and X>>R, equations (1) and (2) are rewritten as shown as formula (3), (4):

$$\delta\cong\frac{XP}{VV_{PCC}} \tag{3}$$

$$V-V_{PCC}\cong\frac{XQ}{V} \tag{4}$$

Expressions (3) and (4) show that the frequency depends on the active power (P), and the voltage deviation depends on the reactive power (Q). From the expressions (3) and (4), we can conclude that the voltage is controlled by Q, and the frequency is controlled by P. Therefore, the droop characteristics P/f and Q/V are used according to expressions (5) and (6), presented as shown in Figure 4:

$$f=f_0-m_p(P-P_0) \tag{5}$$

$$V=V_0-m_q\left(Q-Q_0\right) \tag{6}$$

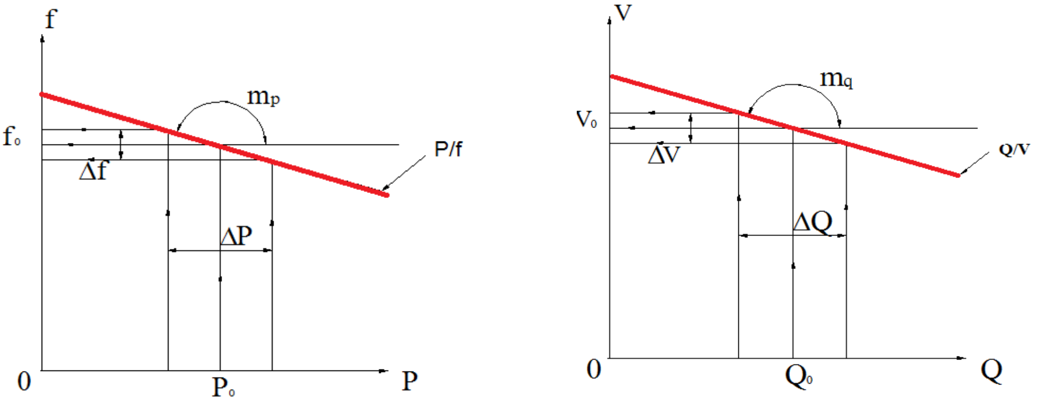
Where: V_0 and f_0 are the nominal amplitude voltage and the nominal frequency of the inverter; V and ω are the measured amplitude voltage and the measured frequency of the inverter; P and Q are the active power and reactive power at output of the inverter; m_p and m_q are the slope coefficients, which are calculated as follows formula (7):

$$m_p=\frac{f_0-f_{min}}{P_{max}-P_0}\ ;\qquad m_q=\frac{V_0-V_{min}}{Q_{max}-Q_0} \tag{7}$$

2.2. Design of the fuzzy logic controller

Equations (5) and (6) show that: $V=V_0$ and $f=f_0$ can only be obtained when $Q=Q_0$ and $P=P_0$.

When the active power of the load increases then the frequency decreases and when the active power of the load decreases then the frequency increases. When the reactive power of the load increases, then the voltage decreases and when the reactive power of the load decreases, then the voltage increases. That means, when the reactive power of the load changes by an amount ΔQ, it will cause a corresponding voltage deviation ΔV; When the active power of the load changes by an amount ΔP, it will cause a corresponding frequency deviation Δf.



(a) (b)

Fig. 4. *(a) The droop P/f characteristic; (b) The droop Q/V characteristic*

The equations (5) and (6) show that the power-sharing for inverters depends on the slope coefficients determined in equation (7). Figure 4 shows that the frequency at the output of the inverter changes according to the active power of the load and the voltage at the output of the inverter changes according to the reactive power of the load; The graph of droop P/f and Q/V in (5) and (6) have slopes that depend on (7). When the slopes (7) change, the power sharing will change accordingly.

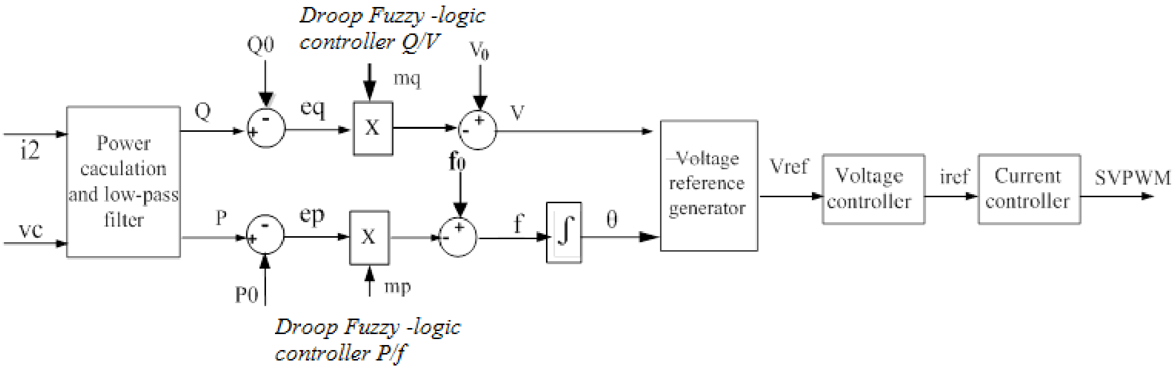


Fig. 5. *The proposed Droop-fuzzy logic controller*

Therefore, this paper proposes a method to shift the slope coefficients mp and mq according to changes in the load instead of fixing them according to the equation (7). In the conventional droop method, the slope coefficients mp and mq are fixed according to equation (7). When the load increases or decreases sharply, the frequency and voltage at the output of the inverter will deviate much from the value of its norm. The block diagram for the proposed droop-fuzzy logic controller is shown in Figure 5. Figure 5 is combined from equations (5), (6) and fuzzy-logic block to adjust the slope coefficients mp and mq.

a. The input signal of fuzzy logic controller:

- *The input signal of fuzzy logic controller Q/V:*

The first input signal is $e_q = Q - Q_0$ (8)

The second input signal is the rate of change of Q over time as $\frac{dQ}{dt}$ (9)

- The input signal of fuzzy logic controller P/f:

The first input signal is $e_p = P - P_0$ (10)

The second input signal is the rate of change of P over time as $\frac{dP}{dt}$ (11)

b. The output signal of fuzzy logic controller:

- *The output signal of fuzzy logic controller Q/V:*

The output signal of fuzzy logic controller Q/V is the slope m_q

- *The output signal of fuzzy logic controller P/f:*

The output signal of fuzzy logic controller P/f is the slope m_p

c. Define language variables for input and output:

Select 5 language variables for first input signal as shown in formula (12)

$$e_p = e_q = \{NB, NS, ZE, PS, PB\} \qquad (12)$$

NB: more negative; NS: less negative; ZE: equal zero; PS: less positive; PB: much positive

Select 3 language variables for second input signal: $\frac{dQ}{dt} = \frac{dP}{dt} = \{N, Z, P\}$ (13)

N: negative; Z: zero; P: positive

Select 9 language variables for output signal as shown in formula (14)

$$m_p = m_q = \{A1, A2, A3; B1, B2, B3; C1, C2, C3\} \qquad (14)$$

A1, A2, A3: small; B1, B2, B3: medium; C1, C2, C3: big

d. Select value domain for input and output:

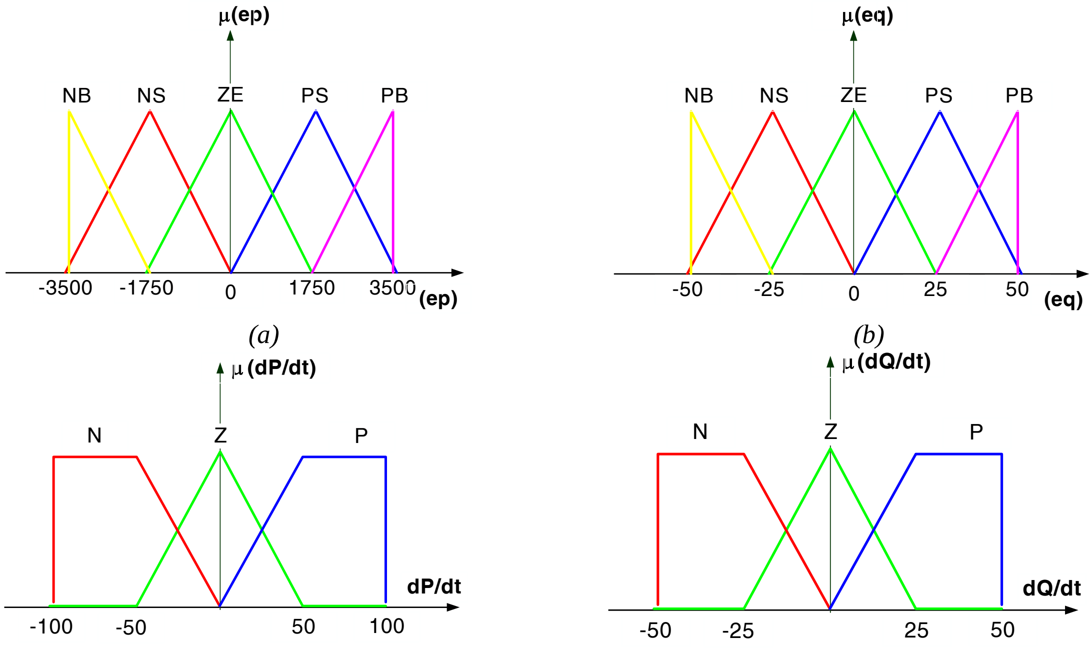
Based on equations (10), (11), (14) and values P, Q, P_0, Q_0, we choose the range of values for the inputs and outputs:

The value domain for the first input: $e_p = [-3500; 3500]$, $e_q = [-500; 500]$

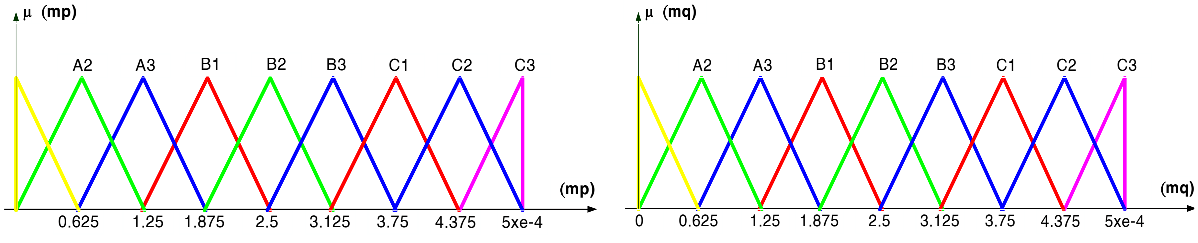
The value domain for the second input: $\frac{dP}{dt} = [-100;\ 100]$, $\frac{dQ}{dt} = [-50;\ 50]$

The value domain for the output: $m_p = m_q = [0;5.\ e\text{-}4]$

e. Define membership functions for input and output:



(c) *(d)*



(e) *(f)*

Fig.6. *The membership functions for inputs and output; (a) Membership function of input e_p; (b) Membership function of input e_q; (c) Membership function of input dP/dt; (d) Membership function of input dQ/dt; (f) Membership function of output m_q*

f. Define control rules:

Equations (5), (6), (7) and Figure 4 show them:

If $Q>Q_0$ then $V<V_0$, In order for V to get close to V_0, we have to control to decrease the slope mq.

If $Q<Q_0$ then $V>V_0$, In order for V to get close to V_0, we have to control to decrease the slope mq.

If $P > P_0$ then $f < f_0$, In order for f to get close to f_0, we have to control to decrease the slope mp.

If $P < P_0$ then $f > f_0$, In order for f to get close to f_0, we have to control to decrease the slope mp.

On the other hand, we rely on the language variables, the range of values, the membership function of the input and the output, we can set up the control rules as shown in Table 1.

If e_p = NB ($P \ll P_0$) and $\frac{dP}{dt}$ = N (P is decreasing) then we choose m_p output as A1.

If e_p = NS ($P \ll P_0$) and $\frac{dP}{dt}$ = N (P is decreasing) then we choose m_p output as B1.

If e_p = ZE ($P = P_0$) and $\frac{dP}{dt}$ = N (P is decreasing) then we choose m_p output as C1.

Table 1. *The rules for fuzzy logic controller*

e_p , e_q / dP/dt, dQ/dt	NB	NS	ZE	PS	PB
N	A1	B1	C1	B3	A3
Z	A2	B2	C2	B2	A2
P	A3	B3	C3	B1	A1

Choose the composition rule according to the Sum-Prod principle. Defuzzification by the centroid method.

2.3. Block of power calculation and low-pass filter

The active and reactive power produced by converters are calculated in a stationary $\alpha\beta$ frame [12]:

$$p = \frac{3}{2}\left(i_{2\alpha}v_{c\alpha} + i_{2\beta}v_{c\beta}\right) \tag{15}$$

$$q = \frac{3}{2}\left(i_{2\alpha}v_{c\beta} - i_{2\beta}v_{c\alpha}\right) \tag{16}$$

The active P and reactive power Q at the output of low-pass filter (LPF)

2.4. The current controller and voltage controller

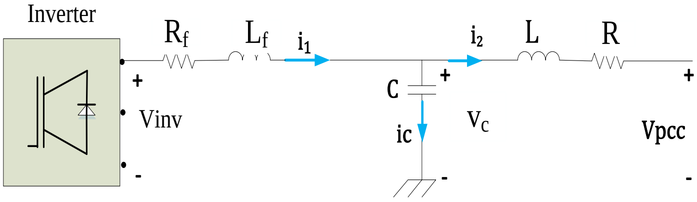


Fig. 8. *Equivalent schematic of an inverter connected to load*

Based on Figure 8, the following equations can be obtained:

$$i_1=i_2+C\frac{dv_c}{dt}+i' \tag{17}$$

$$v_{inv}=L_f\frac{di_1}{dt}+R_f i_1+v_c \tag{18}$$

Where: R and R_f are line resistor and the filter (Ω), L and L_f are line inductor and the filter (H)

According to [12], the equation (17) can be written:

$$i_{1d}=i_{2d}+C\frac{dv_{cd}}{dt}-\omega C v_{cq}+i'_d=\Delta i_d+i_{2d}-\omega C v_{cq}+i'_d \tag{19}$$

$$i_{1q}=i_{2q}+C\frac{dv_{cq}}{dt}+\omega C v_{cd}+i'_q=\Delta i_q+i_{2q}+\omega C v_{cd}+i'_q \tag{20}$$

Where:
$$\Delta i_d=k_{pv}\left(v^*_{cd}-v_{cd}\right)+k_{iv}\int\left(v^*_{cd}-v_{cd}\right)dt \tag{21}$$

$$\Delta i_q=k_{pv}\left(v^*_{cq}-v_{cq}\right)+k_{iv}\int\left(v^*_{cq}-v_{cq}\right)dt \tag{22}$$

Equations (19) to (20) are the voltage controller.

According to [12], the equation (18) can be written:

$$\text{``} \tag{23}$$

$$i_{1q}=i_{2q}+C\frac{dv_{cq}}{dt}+\omega C v_{cd}+i'_q=\Delta i_q+i_{2q}+\omega C v_{cd}+i'_q \tag{24}$$

Where:
$$\Delta v_d=k_{pi}\left(i^*_{1d}-i_{1d}\right)+k_{ii}\int\left(i^*_{1d}-i_{1d}\right)dt \tag{25}$$

$$\Delta v_q=k_{pi}\left(i^*_{1q}-i_{1q}\right)+k_{ii}\int\left(i^*_{1q}-i_{1q}\right)dt \tag{26}$$

Equations (32) to (33) are the current controller.

3. Simulations Results

The proposed controller is simulated by Matlab/Simulink, this controller performs power-sharing for 3 inverters 4kVA, parameters of the controller are presented in Table 2.

Table 2. *Parameters for the controllers*

Parameters	Values	Parameters	Values
Input source voltage V_{cd} (V)	600	Rate frequency f_0 (Hz)	50
Filter inductance L_f (mH)	4.2	Rate power (kVA)	4
Filter resistance R_f (Ω)	0.1	Ratevoltage $V_{AC,p}$ (V)	310

Filter capacitance *C* (μF)	2.2	Switching frequency f_z(kHz)	10
k_{pv}	0.1	k_{pi}	10
K_{iv}	0.05	k_{ii}	1

Case 1: Simulate power division between two inverters connected in parallel using the proposed method in the case that the two inverters have the same rated capacity and the load increases at time t=6s. The simulation results are shown in Figures 8, 9 and 10. Figures 8a and 8b show that for an erroneous value of active power (ep) at the input of the fuzzy logic block, there will be a corresponding slope coefficient mp at the output of the fuzzy logic block. On the other hand, when the ep deviation decreases, mp increases, and vice versa when the ep deviation increases the mp decreases. These results are completely consistent with the fuzzy control law established in Table 1. Figure 8c shows that when the slope coefficient mp changes, the frequency at the output of the Droop-fuzzy logic controller also changes accordingly, the curve of frequency shows as the load increases then the frequency decreases, which is also completely consistent with the equation (5) and power curve in the Figure 4a. The frequency deviation from the norm is calculated in Table 3. Same as above, Figures 8d and 8e show that for a deviation of reactive power eq, it will give a value of slope coefficient mq in the selected range of values, and we see that when the deviation eq decreases, the slope coefficient mq increases and vice versa, at t=6s, the eq deviation continues to decrease compared to the previous one, so the slope coefficient mq at continues to increase. This is completely consistent with the fuzzy control law established in Table 1. Figure 9f shows that when the slope coefficient mq changes, the voltage at the output of the Droop-fuzzy logic controller or the output voltage of the inverter also changes accordingly, which is also completely consistent with equation (6) and power curve in Figure 4b. The voltage value is also calculated according to mq and eq in formula (6), (7), voltage deviation from the norm is calculated in Table 3. Table 3 shows that the voltage difference is very small, to get this result is because we control the slope of the power characteristic curve when the load changes.

Figures 8, 9 and 10 show the Droop-fuzzy logic control method for a good dynamic response as soon as the load changes and the current and voltage stabilizes well right after the load changes. The output power of the inverters is divided exactly in a 1:1 ratio.

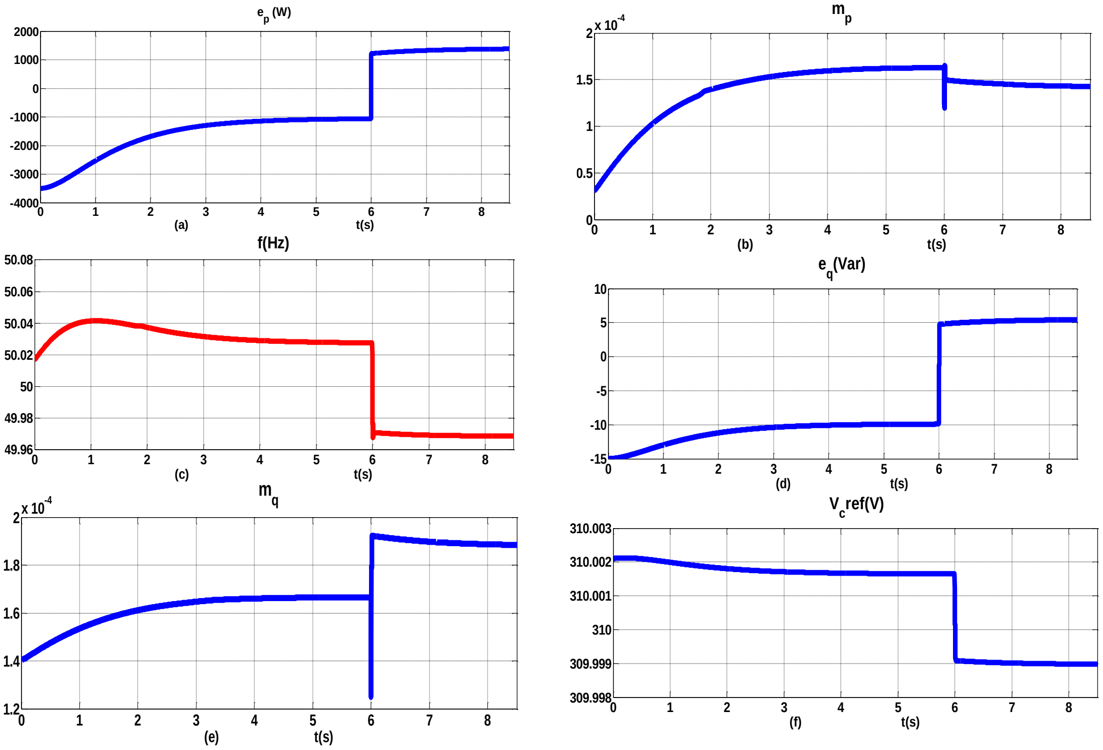
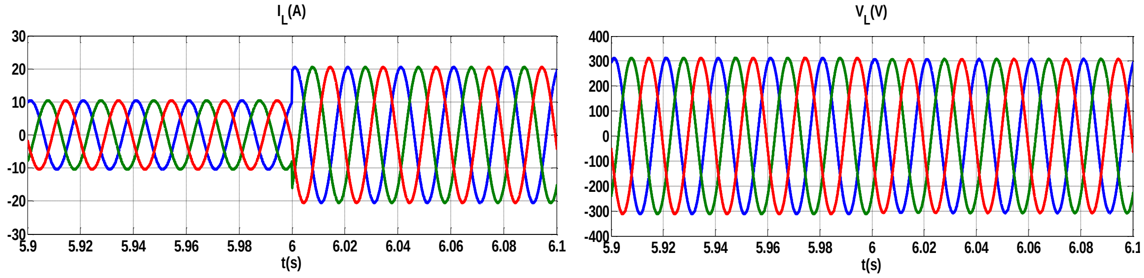
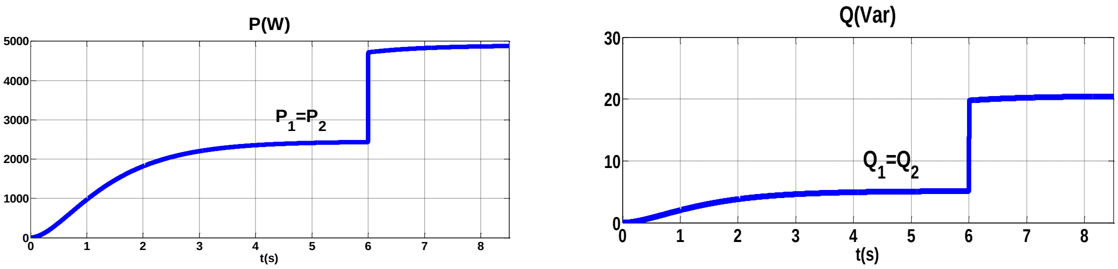


Fig. 8. *The graph showing the change of slip coefficients (m_p, m_q, e_p, e_q, f, v)*



(a) *(b)*

Fig. 9. *The waveform of voltage and current at the load; (a) the current; (b) the voltage*



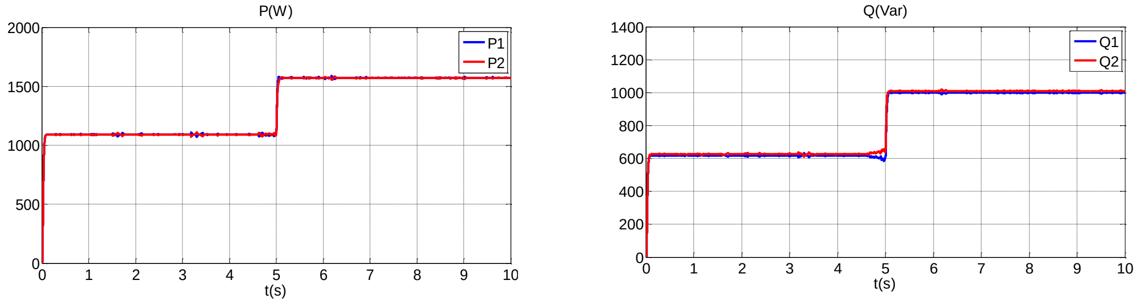
(a) *(b)*

Fig. 10. *Output power of two inverters; (a) the active power; (b) the reactive power*

Table 3. *Table of results for frequency and voltage deviation from rated value*

Load parameters	**($\Delta f=f_0-f$)**	**($\Delta V=V_0-V$)**
Z_1=30+j0.1256 (Ω) (From 0s to 6s	Δf=50-50.0276= -0.276(Hz)	ΔV=310-310.0016= -0.0016(V)
Z_2=15+j0.06283 (Ω) (From 6s onwards)	Δf=50-49.9686= 0.0314(Hz)	ΔV=310-309.98= 0.002 (V)

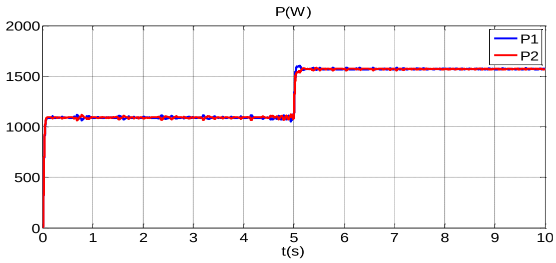
Case 2: Simulate power division between two inverters connected in parallel by 2 methods: the proposed method and the conventional method. Two inverters have the same rated power.



(a) *(b)*

Fig.11. *The graph of sharing active power, reactive power, and voltage at load when simulated by the proposed droop-fuzzy controller; (a) the active power; (b) the reactive power*

Figure 11 shows that the proposed droop-fuzzy controller has high accuracy in sharing active and reactive power, the error is very small. The error of sharing the active power and reactive power are 0.45% and 0.32%

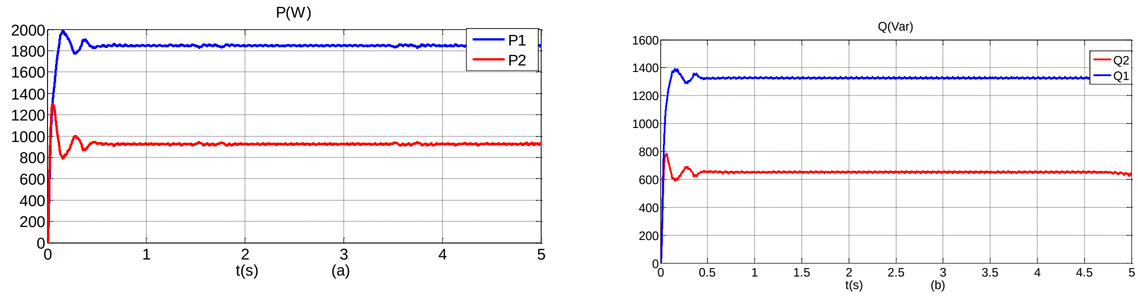


(a) *(b)*

Fig.12. *The graph of sharing active power, reactive power by the conventional droop; (a) the active power; (b) the reactive power*

Figure 12 shows that the error of sharing the reactive is 4%. The voltage graph in Figure 11 also shows that the voltage deviation given by the proposed drooping fuzzy controller is very small, especially as the load increases, the voltage drop is smaller than the voltage graph in Figure 12.

Case 3: Simulate power division between two inverters connected in parallel using the proposed method in the case two inverters have different rated power, $P_{\text{đm1}}=2P_{\text{đm2}}$



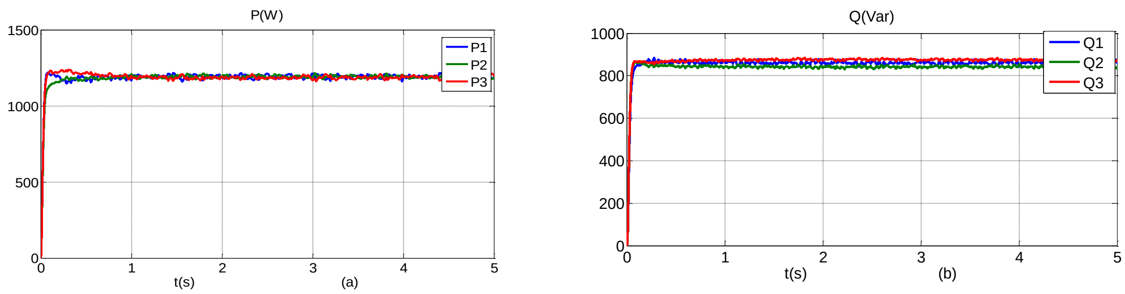
(a) (b)

Fig.13. *The graph of sharing active power, reactive power (a) the active power (b) the reactive power*

Figures 13 shows that the proposed controller has given the correct power-sharing results with the rated power ratio 2:1.

Case 4: Simulate power division between three inverters connected in parallel using the proposed method in the case three inverters have the same rated power, $P_{\text{đm1}}=P_{\text{đm2}}=P_{\text{đm3}}$.

Figures 14 shows that the proposed controller gave the correct power-sharing results with the rated power ratio 1:1:1.



(a) (b)

Fig.14. *The graph of sharing active power, reactive power, and voltage at load by the proposed droop-fuzzy controller; (a) the active power (b) the reactive power*

The above simulation results show that the proposed control method gives good results in the power-sharing for the load and ensuring the quality of the voltage supplied to the load.

4. Conclusions

The proposed control method has resulted in accurate power sharing for inverters and reduced voltage and frequency deviation when the load changes suddenly, improving the quality of the power supply for the load. The proposed method has overcome the disadvantages of the conventional or improved droop methods before, by adjusting the slope of the power curve. So when the load changes, it can adjust the voltage deviation and frequency to improve power quality. The proposed control method is simple and easy to implement.

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Conflicts of Interest

All of the authors there aren't conflicts of benefit and data in the research.

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