Droop Control for Parallel-Connected Three-Phase UPS Units with Different Ratings

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Abstract

The main objective of this paper is to achieve synchronization and power sharing between different ratings three-phase Uninterruptible power supply (UPS) units. A droop control scheme is presented in such a way that a discrete PI-controller is applied. The PI-controller produces a suitable control signal to sinusoidal pulse width modulation (SPWM) circuit. The SPWM produces suitable trigger pulses to the inverter gate. The validity of the proposed control scheme is illustrated through MATLAB simulation with two different ratings three-phase UPS units. The simulation results prove that it possible to share the total load among the different rating units in proportion with their rated values in the presence of load interruption.

Keywords— Uninterruptible Power Supply (UPS); Parallel Operation; Power Sharing; Droop Control; Discrete PI-Controller; Sinusoidal Pulse Width Modulation (SPWM).

1. Introduction

Parallel operation of UPS units has been used to increase reliability and power capacity of the system. UPSsare extensively used in the applications that require power quality and continuous electrical feedings such as some medical equipment, high-speed elevator, and database centers that cannot afford power losses, [1], [2].

During parallel operation, power sharing is sensitive to differences in components of each UPS unit such as amplitude/phase difference, output filters, and line impedance, [3]-[5]. To overcome these problems various control algorithms have been researched including concentrated method, master-slave method, distributed logic control method and voltage/frequency droop method, [6]-[9].In [10] a master and slave control algorithms for parallel operation is adequate. If the ratings of UPS systems are different, the value of passive LC filters will be different, and it will affect current sharing. In recent years, research on control strategies based on droop concept has become very popular. In [12] it was shown that the angle droop control gives constant frequency regulation but still suffers from the poor performance of power sharing. In [9] conventional droop characteristic presents some drawbacks such as frequency and voltage deviations and poor performance of power sharing. In [13] virtual impedance loop based droop method has excellent current sharing but the reactive power sharing is not presented.

However, these methods cannot be employed to UPS units with different ratings, [10], [11].In these methods, the output voltages of all the modules in parallel need to be synchronized exactly in frequency, phase and amplitude to guarantee proper equality of load sharing, [14].

Much researches on parallel operation of three-phase UPS units with the same ratings have been done. However, studies on parallel operation of different rating three-phase UPS units are still lacking.

This paper presents a droop control scheme for parallel-connected three-phase UPS units with different ratings using a discrete PI-controller. A discrete PI-controller is applied to give the suitable control signal to SPWM inverter. This method makes it possible to share the total load among the units in proportion with their rated values in the presence of load interruption. Simulation of two different ratings 3-phase UPS units (6 KW and 4 KW) are carried out using MATLAB/SIMULINK R2018a.

This paper is organized as follows. Section 2 introduces system description and droop characteristics.Section 3 presents the droop control scheme. Simulation results are introduced in Section 4.The conclusion is presented in Section 5 followed by the list of references.

2. System Description and Droop Characteristics

2.1 System Description

Fig. 1 shows the connection diagram of two different ratings three-phase UPS units connected in parallel and sharing power through a tie line. The main scope is to achieve synchronization and power sharing between this different rating UPS units. In our droop control schemes, each UPS unit has

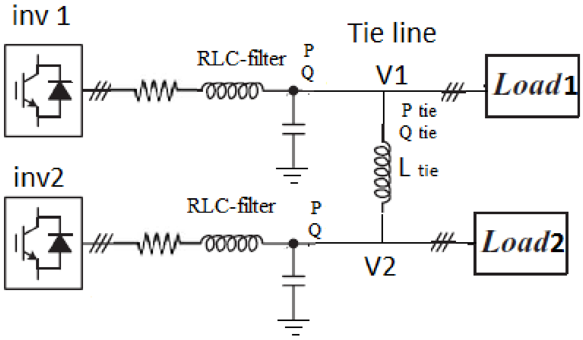


Fig.1. Simplified circuit of the system.

a power-calculating unit to detect output active power P, and reactive power Q.The equations that describe the active power and the reactive power can be expressed as,[13]-[16].

$$P_{tie} = \frac{3}{2}\frac{V_1 V_2}{\omega L_{tie}} \sin\theta \qquad (1)$$

$$Qtie = \frac{3}{2}\frac{V_1(V_1 - V_2\cos\theta)}{\omega L_{tie}} \qquad (2)$$

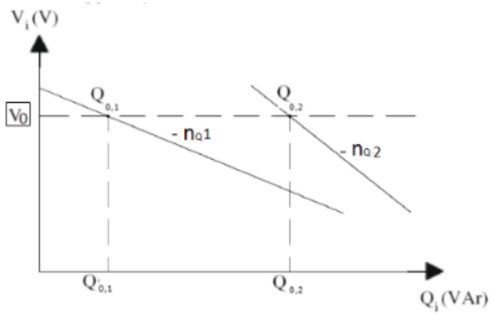
where V_1 and V_2 are the output voltage of the UPS_1 and UPS_2respectively, θ is the phase angle between V_1 and V_2, $\omega$the angular frequency,L_{tie} is the tie inductance.
Low pass filters (RLC) is introduced at the output terminals of each inverter to smooth out the waveform and makes it as close as possible to the required sine wave, [17].

2.2 P – ω Droop and Q - V Droop Characteristic

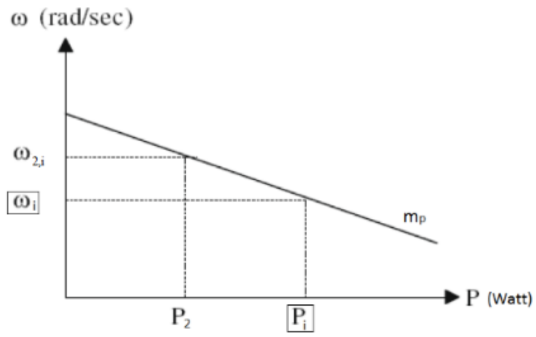
P–ω droop and Q–V droop controllers have been successfully adopted in the UPS systems, [18].Fig. 2-a represents the active power-frequency (P-ω) droop characteristics. The basic idea of this control is to mimic the behavior of synchronousgenerator; when the frequency reduces as the active power increases, [9], [15], [19]. Fig. 2-b represents the reactive power-voltage (Q-V) droop characteristics. As the reactive power drawn from the inverter increases, the voltage decreases, [19]-[21].The UPS units have different ratings so the slope must differ. Fig. 2 represents a straight-line relation so,

$$\omega_i = \omega_{2,i} - m_P\,(p_2 - p_i) \qquad (3)$$

$$V_i = V_{2,i} - n_Q\,(Q_2 - Q_i) \qquad (4)$$



(a)



(b)

Fig. 2. Droop characteristics. (a) Active power – frequency droop characteristics (b) Reactive power - voltage droop characteristics of two different rating UPS units.

where m_P is the slope of the P–ω characteristics, n_Q is the slope of the Q – V characteristics; i the index representing each UPS, ω is the angular frequency of the UPS unit at the rated output active power P.V is the voltage of the UPS unit at the rated output reactive power Q.

3. Droop Control Scheme

This method makes it possible to share the total load among the different rating units in proportion with their rated values in the presence of load interruption. Fig. 3shows the droop control scheme of one UPS unit. The instantaneous values of the active power (P) and a reactive component (Q) are calculated from the measured voltage and current on the load. These values are used as feedback signals to the restoration droop control circuits. The P- ω droop control address the active power sharing and frequency restoration while Q-V droop circuit controls the sharing of reactive power and load voltage restoration.
The output of the restoration control is introduced to the voltage controller in which a discrete PI-control algorithm is applied in order to give suitable control signal to SPWM circuit which produces suitable trigger pulses to the inverter gate. This is necessary to obtain the desired voltage and frequency which satisfy synchronization between different UPS units. Low pass filter is introduced at the output of the inverter to smooth out the waveform and makes it as close as possible to the required sine wave.

3.1 Discrete PI-Controller

The voltage controller employs a discrete proportional integral (PI) controller, which generates a voltage vector signal to the PWM circuit. Fig. 4 shows the discrete PI-controller block diagram. The discrete PI- controller block calculates the output control signal $u_c(k)$:

$$U_c(k) = \left[K_p + \left(K_i * \frac{k_g\,T_S}{z^{-1}}\right)\right] * E_V\,(k) + U_c\,(k-1) \qquad (5)$$

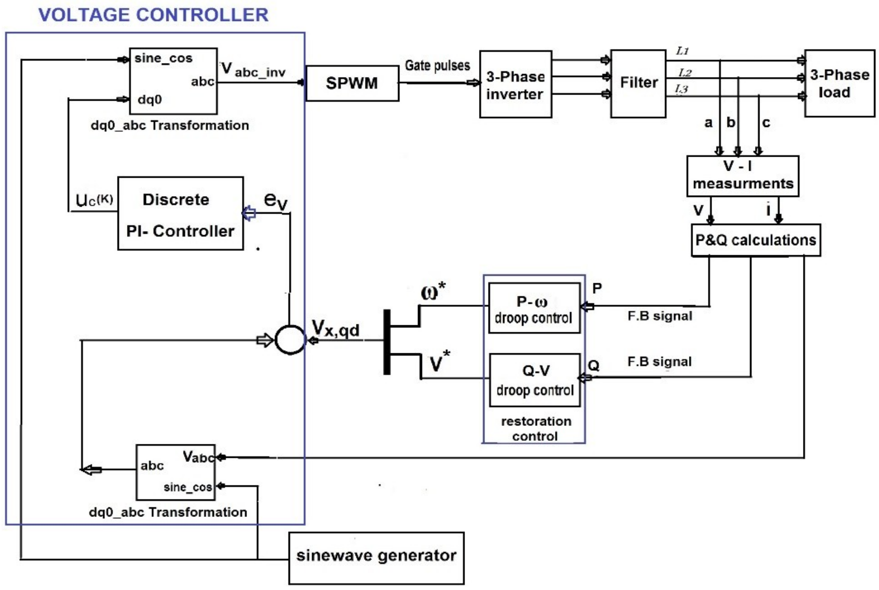


Fig. 3. The droop control scheme of one UPS unit.

where U_c is the output control signal, K_p is the proportional gain coefficient, K_i is the integral gain coefficient, K_g gain coefficient, T_s is the sampling period. E_v is the error signal.

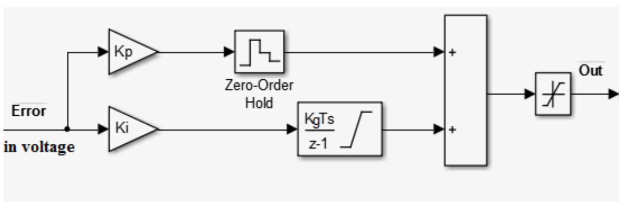


Fig. 4. The discrete PI-controller block diagram.

3.2 Droop Restoration Control

A restoration mechanism is proposed to bring frequency ω and voltage V to its rated values in order to satisfy synchronization between UPS units, [16]. Fig. 5. shows the voltage restoration by shifting the reactive power-voltage droop characteristics. Initially, the UPS unit operates with nominal voltage (V_0) at the reactive power level of Q_0 on the line L_1. If the load power increased to Q_1, the voltage of the unit shifts to a new value (V_0^*). In order to restore the voltage back to the rated value, the droop line should also be shifted up. The new line L_2 has the same slope as the original one.

The output of each inverter must have the same voltage after controlled and from equation (4).

$$V_0 = n_{Q1}Q_1 = n_{Q2}Q_2 \tag{6}$$

The reactive power shared between inverters are changed due to the change of the load reactive power ΔQ_L.

$$\Delta V_i = n_{Qi}\Delta Q_i \tag{7}$$

where, ΔQ_i is the change in reactive power, and ΔV_i is the change in the voltage of the i^{th} inverter unit.In equation (4), $Q_{2,i}$is changed for each unit to restore the voltage during load sharing.

$$\Delta Q_{2,i} = (Y_{res} * Q_{Ri}) * \Delta V_i \tag{8}$$

$$Q_{2,i} = (Y_{res} * Q_{Ri}) * \int \Delta V_i \tag{9}$$

The ‘‘$Y_{res}\, Q_{Ri}$” coefficients in these equations determine the Voltage restoration ratio (gain).Fig. 6 shows the voltage restoration control.

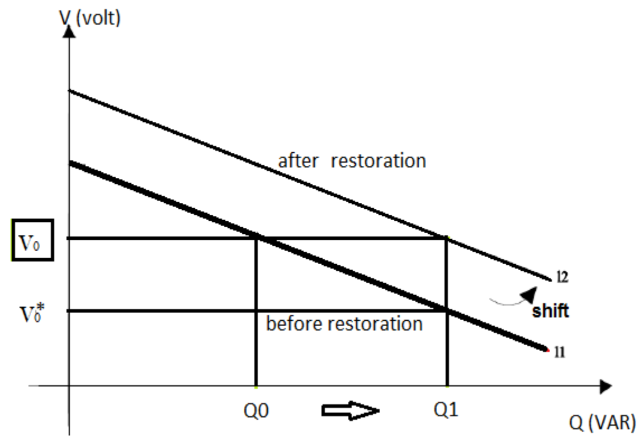


Fig. 5 Voltage restoration by shifting the reactive power-voltage. droop characteristics.

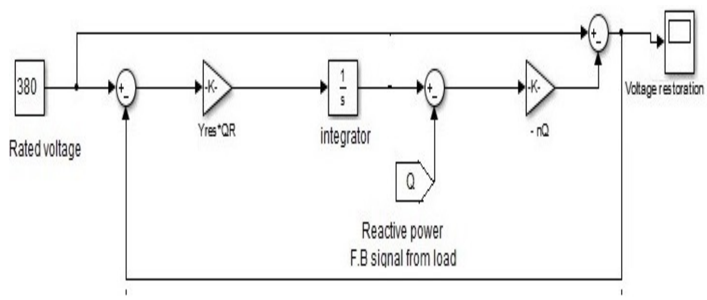


Fig. 6 Voltage restoration block diagram used in the simulation.

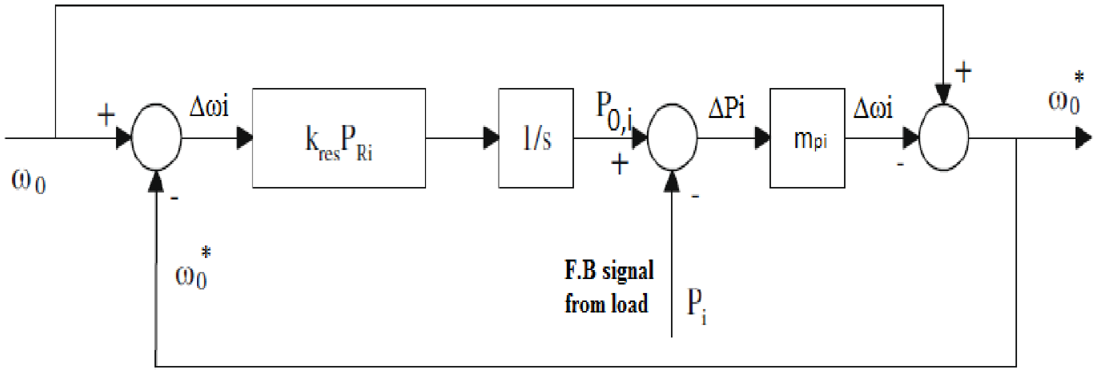


Fig. 7. Frequency restoration block diagram.

Table1 Simulation parameters of two different ratings UPS units.

Rated Frequency (ω_0)	*50 Hz*	*Rated Voltage* (V_0)	*380 Volt*
K_{res1}* P_{Ri1} *Frequency restoration gain1*	*900*	Y_{res1}* Q_{Ri1} *Voltage restoration gain1*	*600*
K_{res2}* P_{Ri2} *Frequency restoration gain2*	*1000*	Y_{res2}* Q_{Ri2} *Voltage restoration gain2*	*700*
m_{P1}	*-0.03*	n_{Q1}	*-0.02*
m_{P2}	*-0.02*	n_{Q2}	*-0.01*
PWM_switching freq.	*1000 Hz*	z_1=50Ω+13 mH	$S_{UPS1}>S_{UPS2}$
Tie line inductance	*100mH*	z_2=70Ω+0.01mH	z_{tr}=80Ω+1Mh
Filter	*R=1 Ω*	*L=3mH*	*C=1000 µF*
Discrete_PI controller	T_s=0.0001	K_p=0.6	K_i=0.01

Similar to the voltage restoration algorithm, frequency restoration is required upon the change of the active power of the load. In equation (3),$P_{2,i}$is changed for each unit to restore the frequency during load sharing.

$$\Delta P_{2,i} = (K_{res} * P_{Ri}) * \Delta\omega_i \quad (10)$$

$$P_{2,i} = (K_{res} * P_{Ri}) * \int \Delta\omega_i \quad (11)$$

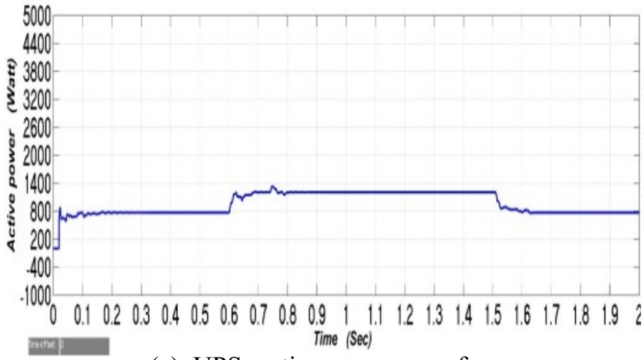
The ''$K_{res}P_{Ri}$'' coefficients in these equations determine the frequency restoration ratio. Fig. 7 shows the frequency restoration control.

4. *Simulation Results*

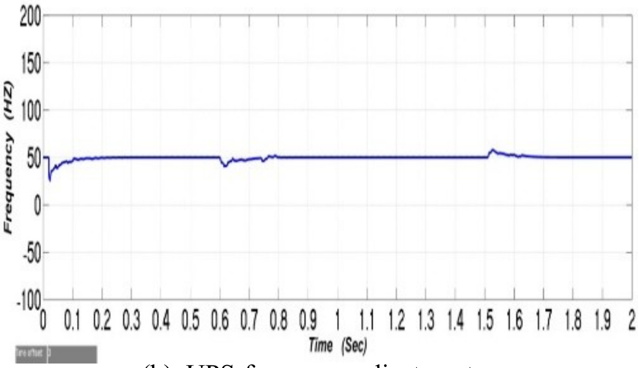
In order to validate the performance of the proposed system in the presence of load interruption, MATLAB/SIMULINK is used for the simulation of two parallel-connected 3-phase UPS units with different ratings. The power rating of UPS_1 is 6 KW and the power rating of $UPS_2$is 4 KW. The simulation is made for 2 seconds. Initially, the loads z_1 and z_2 are connected in parallel on the tie line and the UPS units worked in the normal case. When the time reaches 0.6 Sec, an interruption is introduced by adding additional load z_{tr} connected on the tie line in parallel with the loads z_1 and z_2.

When the time reaches 1.5 Sec the load z_{tr} is disconnected from the tie line and the units returned to work in the normal case.

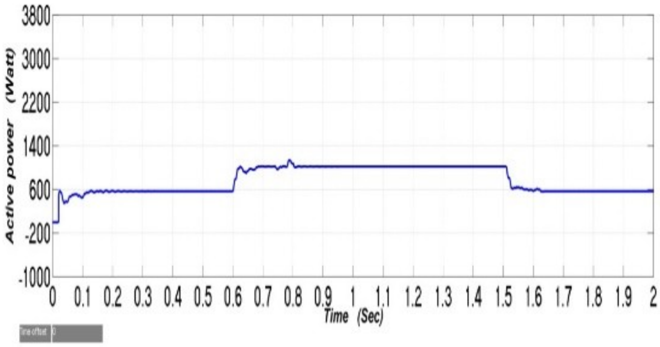
Table 1 shows the parameters of the proposed control system used in the verification simulation. The values of m_P and n_Q of each UPS units are different because they represent different power rating units. The $K_{res}P_{Ri}$ and $Y_{res}Q_{Ri}$ represents the frequency gains and voltage restoration gains, respectively. The z_i represents the UPS loads while Z_{tr} represents the interruption loads.
Fig. 8 shows the effect of load interruption on active power and frequency. The change in the active power of UPS1 and UPS2 occurred at T= 0.6 Sec and T=1.5 Sec as shown in Fig. 8-a and Fig. 8-c. The two UPS have different ratings (power rating of UPS_1 greater than UPS_2) and they share the total active power proportionally with their rated values. The UPS_1 supplies 0.8 KW while UPS_2 supplies 0.6 KW active power. As shown in Fig. 8-b and Fig. 8-d the frequency is instantaneously interrupted at T= 0.6 Sec and T=1.5 Sec then returned back to its initial value 50 Hz.
Fig. 9 shows the output voltage and current of the UPS_1 and UPS_2units when adding/removing loads. The phase voltage of UPS_1 and UPS_2 is maintained constant however interrupted loads are connected/disconnected as shown in Fig. 9-a and Fig. 9-c. The 3-phase voltage is maintained at its rated value 380 Volt as shown in Fig. 9-e and Fig. 9-g. As shown in Fig. 9-b,Fig. 9-d,Fig. 9-f and Fig. 9-h, when the load z_{tr} is connected on the tie line in parallel with z_1 and z_2 at T=0.6 Sec the total impedance, decreased so the current is increased. At T=1.5 Sec the load z_{tr} is disconnected so the current is returned back to the first value. Because the power rating of UPS_1 greater than UPS_2, the current of UPS_1 is kept higher than the current of UPS_2 as expected.



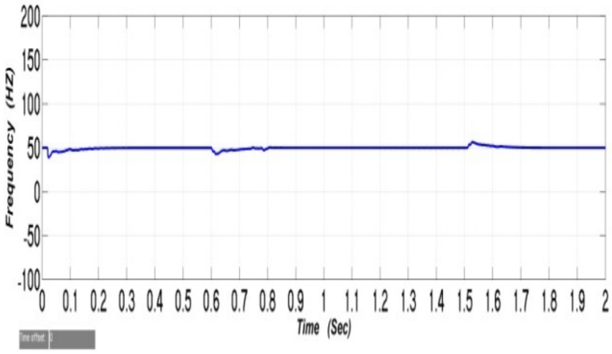
(a) UPS$_1$ active power waveform



(b) UPS$_1$frequency adjustment.

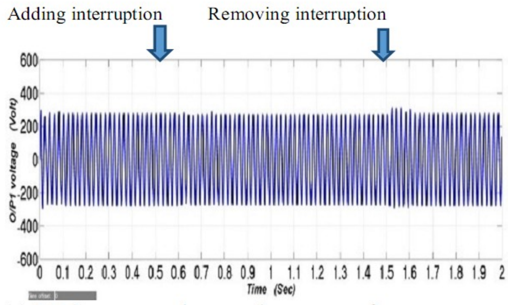


(c) UPS$_2$ active power waveform

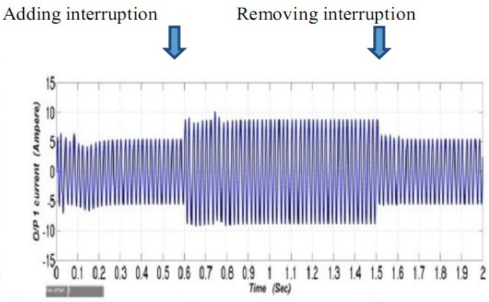


(d) UPS$_2$frequency adjustment.

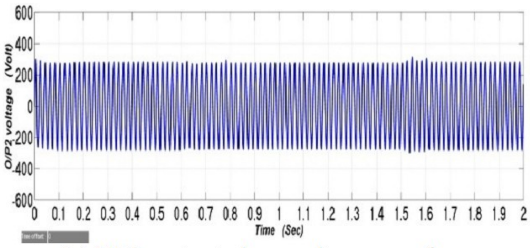
Fig. 8.Effect offload interruption on the active power and frequency.



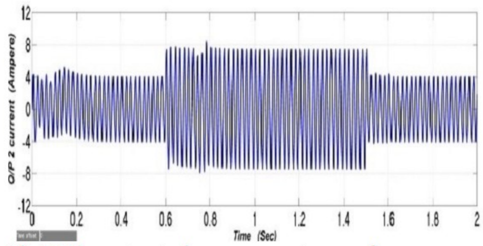
(a) UPS$_1$ output phase voltage waveform.



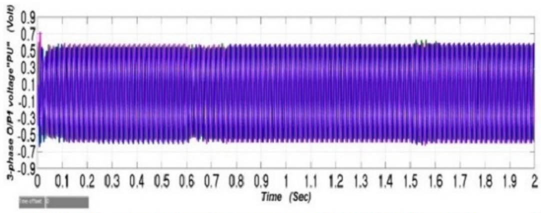
(b) UPS$_1$ output phase current waveform.



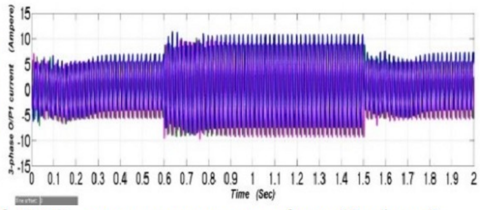
(c) UPS$_2$ output phase voltage waveform.



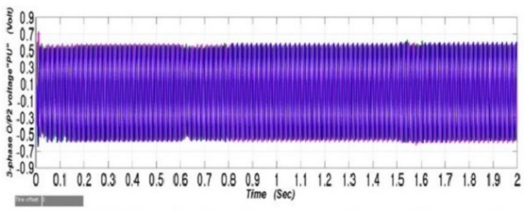
(d) UPS$_2$ output phase current waveform.



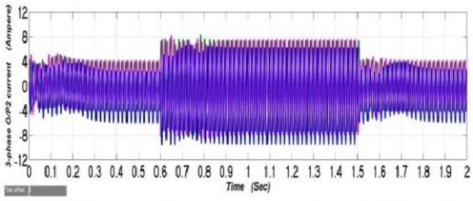
(e) UPS$_1$ output voltage waveform "3-phase".



(f) UPS$_1$ output current waveform "3-phase".

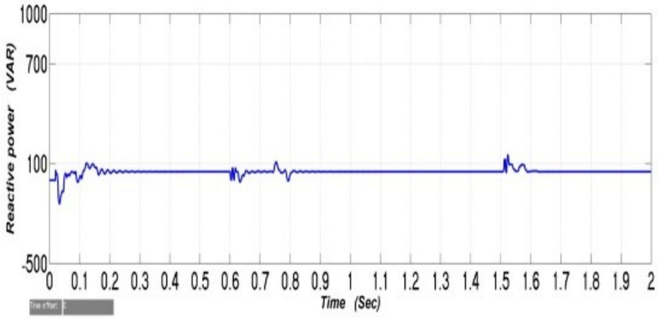


(g) UPS2 output voltage waveform "3-phase".

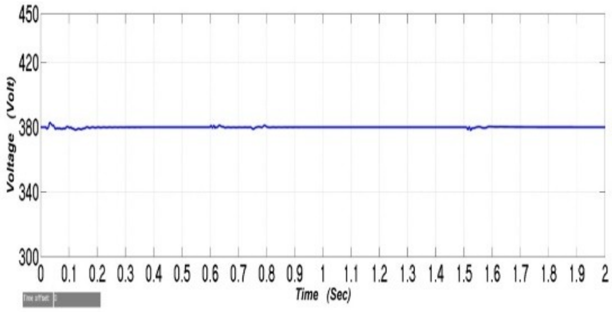


(h) UPS2 output current waveform "3phase".

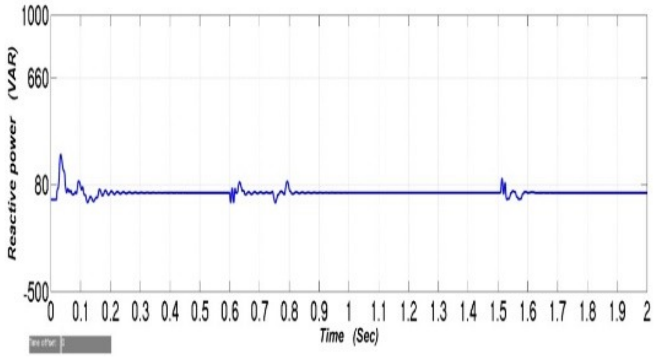
Fig. 9 Variation of the output voltage and current of the UPS system.



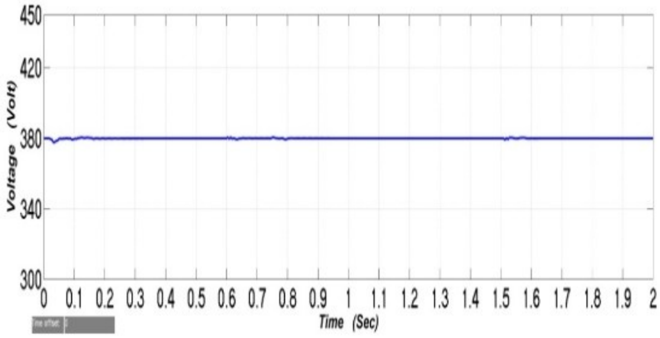
(a)UPS_1 reactive power waveform.



(b) UPS_1voltage adjustment.

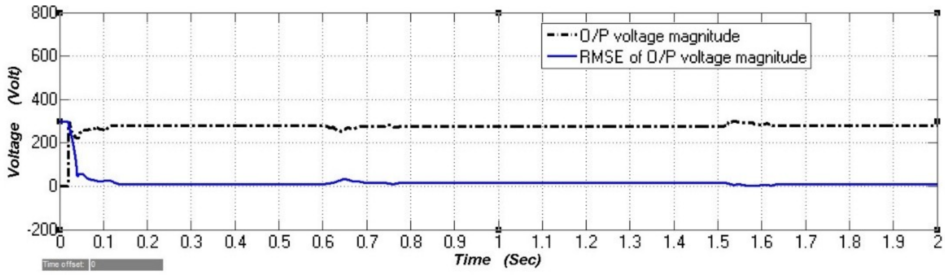


(c) UPS_2 reactive power waveform.

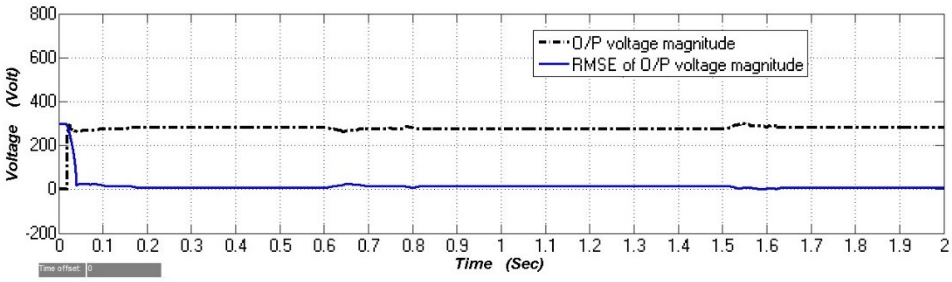


(d) UPS_2 voltage adjustment.

Fig. 10. Effect of load interruption on the reactive power and voltage.



(a)



(b)

Fig.11.RMSE of output voltage magnitude variation
(a) UPS_1units. (b) UPS_2 unit.

Fig. 10 shows the effect of load interruption on the reactive power and voltage. The two UPS units share the total reactive power proportionally with their rated values. The UPS_1 supplies 50 VAR while UPS_2 supplies 35 VAR. The change in the reactive power of UPS1 and UPS2 occurred at T= 0.6 Sec and T=1.5 Sec as shown in Fig. 10-a and Fig. 10-c. The voltage is instantaneously interrupted at T= 0.6 Sec and T=1.5 Sec then returned back to its initial value 380 Volt as shown in Fig. 10-b and Fig. 10-d.
This behavior is due to the droop restoration control. Thus, the restoration droop circuits regulate the system frequency and voltage (which satisfy synchronization) in the presence of load interruption and the UPS units are sharing load correctly.
Fig.11 shows the root mean square error (RMSE) of the output voltage magnitude variation of UPS_1 and UPS_2 units when load change occurred at 0.6 Sec and 1.5 Sec. The desired value of voltage magnitude = 380 Volt. The RMSE of the output voltage variation of the UPS unit reaches zero within a short period. This means that the system response goes to the desired value. Thus, the droop-controlled method succeeded in improving thepower sharing capability in the presence of load interruption.

The results that obtained from the simulation show that the restoration droop circuits regulate the system frequency and voltage (which satisfy synchronization) in the presence of load interruption.UPS_1 and UPS_2 share the total active power proportionally with their rated values. In addition, they succeeded in sharing the total reactive power proportionally with their rated values. As a result, the droop scheme makes it possible to share the total load among the different rating units in proportion with their rated values in the presence of load interruption.

5. Conclusion

A droop control scheme for different ratings three-phase UPS units using a discrete PI-controller is introduced. The instantaneous values of the active power and reactive power are measured. Then used as a feedback signals to the restoration droop control. The output of the restoration control is introduced to the voltage controller. A discrete PI-controller algorithm is applied in order to give suitable control signal to SPWM inverter. Simulations of two parallel-connected 3-phase UPS units with different ratings (6 KW and 4 KW) are carried out using MATLAB. The results that obtained from the simulation show that it possible to share the total load among the different rating units in proportion with their rated values in the presence of load interruption. The RMSE of voltage magnitude of the UPS unit reaches zero within a short period. Thus, the droop-controlled scheme succeeded in improving synchronization and the power sharing capability in the presence of load interruption.

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