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 is 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. UPSs are 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

\[
P_{\text{tie}} = \frac{3}{2} \frac{V_1 V_2}{\omega_{\text{tie}}} \sin \theta \quad (1)
\]

\[
Q_{\text{tie}} = \frac{3}{2} \frac{V_1 (V_1 V_2 \cos \theta)}{\omega_{\text{tie}}} \quad (2)
\]

where \(V_1\) and \(V_2\) are the output voltage of the UPS\(_1\) and UPS\(_2\), respectively, \(\theta\) is the phase angle between \(V_1\) and \(V_2\), \(\omega\) the angular frequency, \(L_{\text{tie}}\) 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 – \(\omega\) Droop and Q - V Droop Characteristic**

P–\(\omega\) droop and Q-V droop controllers have been successfully adopted in the UPS systems, [18]. Fig. 2-a represents the active power-frequency (P-\(\omega\)) droop characteristics. The basic idea of this control is to mimic the behavior of a synchronous generator; 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,

\[
\omega_i = \omega_{2i} - m_p (p_2 - p_i) \quad (3)
\]

\[
V_i = V_{2i} - n_o (Q_2 - Q_i) \quad (4)
\]

where \(m_p\) is the slope of the P–\(\omega\) characteristics, \(n_o\) is the slope of the Q–V characteristics; \(i\) the index representing each UPS, \(\omega\) is the angular frequency of the UPS unit at the rated output active power \(P\), \(V\) 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. 3 shows the droop control scheme of one UPS unit. The instantaneous values of the active power (P) and a reactive component (Q) are calculated using discrete measurement and current on the load. These values are used as feedback signals to the restoration droop control circuits. The P-\(\omega\) 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 \(u_c(k)\):

\[
U_c(k) = K_p + \left( K_i \frac{K_p T_c}{Z - 1} \right) E_r(k) + U_c(k - 1) \quad (5)
\]
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 \( \omega \) 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).

\[
V_0 = nQ_1Q_1 = nQ_2Q_2
\]  

(6)

The reactive power shared between inverters are changed due to the change of the load reactive power \( \Delta Q_i \).

\[
\Delta Q_i = nQ_1 \Delta Q_i
\]  

(7)

where, \( \Delta Q_i \) is the change in reactive power, and \( \Delta V_i \) is the change in the voltage of the \( i \)th inverter unit. In equation (4), \( Q_2 \) is changed for each unit to restore the voltage during load sharing.

\[
\Delta Q_{2,i} = (Y_{res} * Q_{Ri}) \* \Delta V_i
\]  

(8)

\[
Q_{2,i} = (Y_{res} * Q_{Ri}) \* \Delta V_i
\]  

(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.
The simulation is made for 2 normal case from the tie line and the units returned to work in the parallel on the tie line interruption is introduced by adding additional load connected on the tie line.

When the time reaches 0.6 Sec, an interruption is introduced by adding additional load \( z_1 \) connected on the tie line in parallel with the loads \( z_1 \) and \( z_2 \).

When the time reaches 1.5 Sec the load \( z_2 \) is disconnected from the tie line and the units returned to work in the normal case.

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.

\[
\Delta P_{2,i} = (K_{res} \cdot P_{Ri}) \cdot \Delta \omega_i
\]  

\[
P_{2,i} = (K_{res} \cdot P_{Ri}) \cdot \int \Delta \omega_i
\]

The “\( K_{res} \cdot P_{Ri} \)” coefficients in these equations determine the frequency restoration ratio. Fig. 7 shows the frequency restoration control.

### Table 1: Simulation parameters of two different ratings UPS units.

<table>
<thead>
<tr>
<th>Rated Frequency (( \omega_0 ))</th>
<th>50 Hz</th>
<th>Rated Voltage (( V_0 ))</th>
<th>380 Volt</th>
</tr>
</thead>
<tbody>
<tr>
<td>( K_{res1} \cdot P_{Ri1} ) Frequency restoration gain1</td>
<td>900</td>
<td>( Y_{res1} \cdot Q_{Ri1} ) Voltage restoration gain1</td>
<td>600</td>
</tr>
<tr>
<td>( K_{res2} \cdot P_{Ri2} ) Frequency restoration gain2</td>
<td>1000</td>
<td>( Y_{res2} \cdot Q_{Ri2} ) Voltage restoration gain2</td>
<td>700</td>
</tr>
<tr>
<td>( m_{P1} )</td>
<td>-0.03</td>
<td>( m_{Q1} )</td>
<td>-0.02</td>
</tr>
<tr>
<td>( m_{P2} )</td>
<td>-0.02</td>
<td>( m_{Q2} )</td>
<td>-0.01</td>
</tr>
<tr>
<td>PWM switching freq.</td>
<td>1000 Hz</td>
<td>( z_1 = 50 \Omega + 13 \text{ mH} )</td>
<td>( S_{UPS1} &gt; S_{UPS2} )</td>
</tr>
<tr>
<td>Tie line inductance</td>
<td>100mH</td>
<td>( z_2 = 70 \Omega + 0.01 \text{ mH} )</td>
<td>( z_2 = 80 \Omega + 1 \text{ mH} )</td>
</tr>
<tr>
<td>Filter</td>
<td>( R = 1 \Omega )</td>
<td>( L = 3 \text{ mH} )</td>
<td>( C = 1000 \mu \text{F} )</td>
</tr>
<tr>
<td>Discrete_PI controller</td>
<td>( T_p = 0.0001 )</td>
<td>( K_p = 0.6 )</td>
<td>( K_i = 0.01 )</td>
</tr>
</tbody>
</table>

The values of \( m_P \) and \( n_Q \) of each UPS units are different because they represent different power rating units. The \( K_{res} \cdot P_{Ri} \) and \( Y_{res} \cdot Q_{Ri} \) represents the frequency gains and voltage restoration gains, respectively. The \( z_i \) represents the UPS loads while \( z_x \) 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 \( T = 0.6 \text{ Sec} \) and \( T = 1.5 \text{ Sec} \) as shown in Fig. 8-a and Fig. 8-c. The two UPS have different ratings (power rating of UPS1 greater than UPS2) and they share the total active power proportionally with their rated values. The UPS1 supplies 0.8 KW while UPS2 supplies 0.6 KW active power. As shown in Fig. 8-b and Fig. 8-d the frequency is instantaneously interrupted at \( T = 0.6 \text{ Sec} \) and \( T = 1.5 \text{ Sec} \) then returned back to its initial value 50 Hz.

Fig. 9 shows the output voltage and current of the UPS1 and UPS2 units when adding/removing loads. The phase voltage of UPS1 and UPS2 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 \( z_{10} \) is connected on the tie line in parallel with \( z_1 \) and \( z_2 \) at \( T = 0.6 \text{ Sec} \) the total impedance, decreased so the current is increased. At \( T = 1.5 \text{ Sec} \) the load \( z_{10} \) is disconnected so the current is returned back to the first value. Because the power rating of UPS1 greater than UPS2, the current of UPS1 is kept higher than the current of UPS2 as expected.
Fig. 8. Effect of load interruption on the active power and frequency.

(a) UPS$_1$ active power waveform
(b) UPS$_1$ frequency adjustment.

(c) UPS$_2$ active power waveform
(d) UPS$_2$ frequency adjustment.

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

(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) UPS$_2$ output voltage waveform "3-phase".
(h) UPS$_2$ output current waveform "3-phase".
Fig. 10. Effect of load interruption on the reactive power and voltage.

(a) UPS₁ reactive power waveform.  
(b) UPS₁ voltage adjustment.  
(c) UPS₂ reactive power waveform.  
(d) UPS₂ voltage adjustment.

Fig. 11. RMSE of output voltage magnitude variation
(a) UPS₁ units.  (b) UPS₂ 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 UPS1 supplies 50 VAR while UPS2 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 UPS1 and UPS2 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 the power 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. UPS1 and UPS2 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.

References


