CHAPTER 5

A MODULAR THREE-PHASE PFC SCHEME USING p-q THEORY FOR BALANCED AND UNBALANCED SUPPLY CONDITIONS

5.1 INTRODUCTION

In this chapter, it is proposed to develop a three-phase PFC Ćuk converter for power factor improvement and output voltage regulation. It is proposed to study the performance of the converter under balanced and unbalanced supply conditions. p-q theory is used for reference current generation for both balanced and unbalanced supply conditions. Hysteresis and PI controllers are used for source current shaping and output voltage regulation respectively. The advantages of the proposed system are

- It uses a single stage for both PFC and voltage regulation.
- It guarantees the continuous operation of the system even in case of module failure.
- Simple control implementation.

5.2 THREE-PHASE PFC ĆUK CONVERTER

The circuit diagram of three-phase PFC Ćuk converter is shown in Figure 5.1. A single capacitor $C_o$ is connected at the output terminals for filtering the output voltage ripple. $L_{ia}$, $L_{ib}$, $L_{ic}$ represent the input inductors and $L_{oa}$, $L_{ob}$, $L_{oc}$ are the output inductors for the respective three-phases. $C_{ta}$, $C_{tb}$,
C_{ic} represent the transfer capacitors for the three-phases. S_a, S_b, S_c, D_{Fa}, D_{Fb}, D_{Fc} are active switches and freewheeling diodes for the three-phases and \( R_L \) is the load resistance. \( v_{sa}, v_{sb}, v_{sc} \) and \( V_o \) represent supply voltages for the three-phases and output voltage respectively.

![Figure 5.1 Circuit of the three-phase PFC Ćuk converter](image)

### 5.3 GENERATION OF REFERENCE CURRENTS USING p-q UNDER BALANCED SUPPLY CONDITIONS

The p-q theory is an effective tool to analyze and detect problems related to harmonics, reactive power and unbalance in three-phase systems. This theory is based on time domain and hence it is valid both for steady-state and transient operations. Since only algebraic operations are required to derive reference current, the calculations involved are straightforward. Following section discusses the generation of reference current using p-q theory under balanced supply voltage conditions.

The three-phase instantaneous source voltages and currents in a-b-c coordinates are transformed into \( \alpha-\beta \) coordinates using Clarke transformation. The power components are then calculated from voltages and currents in the
$\alpha-\beta$ coordinates. From the power components, the average real power $P_{\text{avg}}$ is extracted using low pass filter. Reference currents in $\alpha-\beta$ coordinates are then calculated and transformed to a-b-c components using inverse Clarke transformation. Here, the term $P_{\text{Loss}}$ represents the switching losses and ohmic losses in the converter. Due to losses in converter, the output capacitor voltage will decrease. When the capacitor voltage falls below the reference voltage, the compensator may not be able to track the reference current faithfully. So, a suitable PI controller is used which regulates the capacitor voltage to the reference value. $P_{\text{Loss}}$ is thus given by

$$P_{\text{Loss}} = K_p e + K_i \int e dt$$  \hspace{1cm} (5.1)$$

Figure 5.2 depicts the implementation of p-q theory.

![Schematic diagram of p-q theory](image-url)
5.4 CLOSED LOOP CONTROL OF THREE-PHASE PFC ĆUK CONVERTER USING HC

The closed loop system is comprised of an inner current loop which uses hysteresis controller for shaping the input current and an outer voltage control loop using PI controller to regulate the output voltage as shown in Figure 5.3. The PI controller parameters, $K_p$ and $K_i$ are found by Ziegler-Nichols tuning method. The proposed system provides sustained oscillations with ultimate gain ($K_u=4$) and ultimate period ($P_u=0.055s$). By this method the values of $K_p(=K_u/2)$ and $K_i$ are found to be 2 and 18.45 ($T_i=P_u/1.2$, $K_i=1/T_i$) respectively. The output voltage is compared with the reference voltage and the error is fed to the PI controller, which generates the $P_{Loss}$ component.

![Figure 5.3 Control circuit of three-phase PFC Ćuk converter](image-url)
Reference currents are generated using $P_{\text{Loss}}$, three-phase source voltages $v_{sa}$, $v_{sb}$, $v_{sc}$, source currents $i_{sa}$, $i_{sb}$, $i_{sc}$ by p-q theory and extended versions of p-q theory under balanced and unbalanced supply voltage conditions respectively. The actual currents and reference currents are compared using hysteresis controller. The result of comparison is the PWM signals, which are used for driving the converter switches $S_a$, $S_b$, $S_c$. Thus the converter switches force the input current to follow the desired reference within hysteresis band. Here, the value of hysteresis band is chosen as $\pm 0.0005$. Hysteresis current control technique is simple, accurate, and robust and hence it is more advantageous (M. Castilla et al 2008, Luca Corradini et al 2009, Kisun Lee et al 2009, D. Williams et al 2010).

5.5 SIMULATION AND EXPERIMENTAL RESULTS FOR BALANCED SUPPLY CONDITIONS

In this section, a three-phase PFC Ćuk converter based on HC for UPF operation and dynamic response of load voltage is discussed. The configuration of the proposed system is simulated in MATLAB/SIMULINK environment. The simulation results of the proposed scheme under balanced supply conditions are shown in Figures 5.4(a) - 5.4(f). It is evident from Figures 5.4(a) - 5.4(b) that source currents become sinusoidal and almost UPF operation is achieved. The proposed system also provides regulated output voltage.

The response of the system for module loss conditions is shown in Figure 5.4(d). All the modules are in operation between (0.29–0.34)s, one module loss occurs in phase a between (0.34–0.41)s, module loss occurs in phases a and b between (0.41–0.51)s. It is inferred from Figure 5.4(d) that the converter is operating continuously irrespective of module loss in one or two phases. The transient response of the output voltage and load current waveforms for 10% step increase in load is shown in Figure 5.4 (e). The
output voltage follows the reference voltage with a settling time of 0.019s. The % THD of the source current under balanced supply condition is 1.98%.

Figure 5.4  Simulated waveforms for balanced supply conditions using p-q theory

Figure 5.5 shows the simulation results of individual input phase currents, inductor currents, output voltage, load current and output power for symmetric supply conditions, module loss in phase a, module loss in phases a and b under balanced supply conditions. It is inferred from the results that the steady state error in the output voltage is 8.25%, 16.5% of the reference voltage for one module loss and two module loss conditions respectively. Table 5.1 presents the variation of performance parameters of three-phase PFC Ćuk converter as a function of load under balanced supply conditions.
Figure 5.5  Simulation results for symmetric mains condition, module loss in phase a, module loss in phases a and b under balanced supply conditions using p-q theory

Table 5.1 Performance parameters for load variation under balanced supply conditions using p-q theory

<table>
<thead>
<tr>
<th>Load Current (A)</th>
<th>2.4</th>
<th>2.2</th>
<th>2.0</th>
<th>1.85</th>
<th>1.7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency (%)</td>
<td>86.13</td>
<td>85.7</td>
<td>85.31</td>
<td>85.0</td>
<td>84.3</td>
</tr>
<tr>
<td>PF</td>
<td>0.9967</td>
<td>0.9961</td>
<td>0.996</td>
<td>0.9948</td>
<td>0.9945</td>
</tr>
<tr>
<td>THD (%)</td>
<td>1.981</td>
<td>2.712</td>
<td>3.313</td>
<td>3.754</td>
<td>3.993</td>
</tr>
<tr>
<td>Voltage regulation (%)</td>
<td>-0.167</td>
<td>-0.208</td>
<td>-0.167</td>
<td>-0.208</td>
<td>-0.25</td>
</tr>
</tbody>
</table>
The graphical representation of data in Table 5.1 under balanced supply conditions using p-q theory is presented in Figure 5.6. It is observed that the % efficiency is maintained above 80% for all the loads and the maximum efficiency at rated load is found to be 86.13 %.

A prototype model for three-phase PFC Ćuk converter is constructed in order to experimentally test the proposed control method using the following specifications $f_s = 50$ kHz, $V_s = 24$ Vrms, $L_{ia}$, $L_{ib}$, $L_{ic} = 2$ mH, $L_{oa}$, $L_{ob}$, $L_{oc} = 1$ mH, $C_{ta}$, $C_{tb}$, $C_{tc} = 25$ µF, $C_o = 2000$ µF, $R_L = 10$ Ω using dSPACE 1104 signal processor. The input and output inductors are of ferrite core type and the capacitors are of plain polyester type. Power MOSFET IRF540N is used as a switch and IN 4007 is used as a diode. Figure 5.7 shows the...
implementation of proposed control strategy. The dS1104 controller board of dSPACE specifically designed for the development of high-speed multivariable digital controllers is plugged into a PCI slot of the PC. The board also includes a slave-subsystem based on the TMS320F2407 DSP processor.

Figure 5.7 Hardware implementation using HC

During closed loop operation, the three-phase source voltages, source currents and output voltage are sensed by hall effect voltage and current sensors and scaled down to less than ±10V using the signal conditioning circuit, fed-back to the controller through the ADC channels of the DSP. The reference current generation using p-q theory and HC are then
designed in SIMULINK and downloaded to the DSP which provides the necessary switching signals to the driver circuit. Figure 5.8 shows the experimental circuit of the three-phase PFC Čuk converter.

Figure 5.8 Hardware setup of three-phase PFC Čuk converter

Figure 5.9 depicts the experimental results of the proposed converter module under balanced supply conditions using p-q theory. Figure 5.9(a) illustrates that the source currents are sinusoidal and balanced. From the Figure 5.9(b), it is also observed that the source current is in phase with the source voltage. It is evident from Figure 5.9(c) that the proposed system provides constant output voltage. Figure 5.9(d) illustrates that system continues to operate despite of module loss in any one or two phases. Figure 5.9(e) shows that the converter recovers its reference voltage for 10% step increase in load after 0.019s. Figure 5.9(f) represents the harmonic spectrum of source current for the three-phases and the %THD is 3.8%.
5.6 GENERATION OF REFERENCE CURRENTS USING EXTENDED VERSIONS OF p-q THEORY UNDER UNBALANCED SUPPLY CONDITIONS

The p-q theory used for reference current generation under unbalanced supply conditions should satisfy one of the following characteristics.
- Draw a constant instantaneous active power from the source.
- Draw a sinusoidal current from the source.
- Draw the source currents proportional to the source voltages.

The above mentioned three characteristics are satisfied simultaneously under balanced supply conditions. However, under unbalanced system voltages, only one optimal compensation characteristic can be obtained. And, hence the following methods are applied for reference current generation under unbalanced supply conditions. In the following section, extended p-q methods such as constant instantaneous power control strategy, sinusoidal current control strategy, Fryze current control strategy are discussed.

### 5.6.1 Constant Instantaneous Power Control Strategy

This method of reference current generation guarantees that only real power being drawn from the source. The implementation of this strategy is same as shown in Figure 5.2. According to constant instantaneous control strategy theory, to draw constant instantaneous active power from the source means that the compensator must compensate for the oscillating real power. Additionally, the rms value of the reference current is minimized by the compensation of the total imaginary power. If the system voltage contains unbalance at the fundamental frequency, the compensated current cannot be sinusoidal to guarantee constant real power to be drawn from the source.

### 5.6.2 Sinusoidal Current Control Strategy

This strategy provides balanced, sinusoidal compensated currents, even when the system voltage is unbalanced. Execution of this strategy is shown in Figure 5.10. Although it requires some calculation effort, this
control strategy is versatile and robust (Mahesh K. Mishra et al 2001). Positive sequence extractor extracts continuously and accurately the amplitude, phase angle of the fundamental positive sequence voltages from the unbalanced source voltages and gives in the form of instantaneous values $v_{sa}'$, $v_{sb}'$, $v_{sc}'$.

![Schematic diagram of sinusoidal current control strategy](image)

**Figure 5.10 Schematic diagram of sinusoidal current control strategy**

Then $v_{sa}'$, $v_{sb}'$, $v_{sc}'$ and $i_{sa}$, $i_{sb}$, $i_{sc}$ are transformed to $\alpha$-$\beta$ coordinates using Clarke transformation. The power components are then calculated from voltages and currents in the $\alpha$-$\beta$ coordinates. From the power components, the average real power $P_{Lavg}$ is extracted using low pass filter. Reference currents in $\alpha$-$\beta$ coordinates are then calculated and transformed to a-b-c components using inverse Clarke transformation.

### 5.6.3 Generalized Fryze Current Control Strategy

This control strategy makes the source current to be proportional to the corresponding source phase voltages. An advantage of the generalized
Fryze current control strategy is the reduced calculation effort, since it handles directly with the instantaneous phase voltages and line currents. The elimination of the Clarke transformation makes this control strategy very simple. Figure 5.11 shows the schematic diagram of Fryze current control strategy.

![Schematic diagram of Fryze current control strategy](image)

**Figure 5.11 Schematic diagram of Fryze current control strategy**

The instantaneous equivalent conductance $G_e$ is calculated from the instantaneous active three-phase power and the squared value of instantaneous aggregate voltages. Then, the instantaneous active currents are calculated directly from the instantaneous conductance. This method does not guarantee sinusoidal reference current or constant instantaneous active power drawn from the source.
5.7 SIMULATION AND EXPERIMENTAL RESULTS UNDER UNBALANCED SUPPLY CONDITIONS

The simulation results of the proposed system under unbalanced supply conditions using constant instantaneous power control strategy is presented in Figures 5.12(a) - 5.12(h).

Figure 5.12 Simulated waveforms for constant instantaneous power control strategy

From Figure 5.12(a), it is observed that the source currents are sinusoidal and unbalanced after employing constant instantaneous power control strategy.
control strategy. Figure 5.12(b) depicts source current is in phase with the source voltage. It is evident from Figure 5.12(c) that the proposed system provides constant output voltage. Figure 5.12(d) depicts that the system can continuously operate in spite of module loss in any one or two phases. Figure 5.12(e) shows that the closed loop system attains the reference voltage for 10% step increase in load after 0.06s. Figures 5.12(f) - 5.12(h) represent the harmonic spectrum of source current for the three-phases and it is observed that % THD of the source current is not the same for all three-phases due to the existence of unbalance in the magnitude of the compensated current. For constant instantaneous power control strategy, %THD of supply currents are 3.64%, 4.58%, 5.23% for the phases a, b and c respectively.

Figure 5.13 shows the simulation results of constant instantaneous power control strategy under unbalanced supply conditions for the individual input source currents, inductor currents, output voltage, load current and output power for symmetric mains condition, module loss in phase a, module loss in phases a and b. It is inferred from the results that for one module loss, the steady state error in the output voltage is 6.5% of the reference voltage and for two module losses, the steady state error in the output voltage is 14.5% of the reference voltage. Table 5.2 presents the variation of performance parameters of three-phase PFC Ćuk converter as a function of load for constant instantaneous power control strategy.

Table 5.2 Performance parameters for load variation using constant instantaneous power control strategy

<table>
<thead>
<tr>
<th>Load Current (A)</th>
<th>2.4</th>
<th>2.2</th>
<th>2</th>
<th>1.85</th>
<th>1.7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency (%)</td>
<td>85.97</td>
<td>85.65</td>
<td>85.31</td>
<td>84.98</td>
<td>84.64</td>
</tr>
<tr>
<td>PF</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>0.997</td>
</tr>
<tr>
<td>THD (%)</td>
<td>3.643</td>
<td>4.007</td>
<td>4.75</td>
<td>5.565</td>
<td>5.781</td>
</tr>
<tr>
<td>Voltage regulation (%)</td>
<td>-0.125</td>
<td>-0.125</td>
<td>-0.167</td>
<td>-0.167</td>
<td>-0.167</td>
</tr>
</tbody>
</table>
Figure 5.13 Simulation results for symmetric mains condition, module loss in phase a, module loss in phases a and b for constant instantaneous power control strategy
Calculation of effective apparent power plays a vital role in obtaining the power factor under unbalanced supply conditions. The effective phase voltage under unbalanced supply condition is given by

\[ V_e = \sqrt{\frac{1}{18} \left[ 3(V_{sa}^2 + V_{sb}^2 + V_{sc}^2) + V_{sab}^2 + V_{sbc}^2 + V_{sca}^2 \right]} \]  

(5.1)

Effective current is calculated by the Equation (5.2)

\[ I_e = \sqrt{\frac{I_{sa}^2 + I_{sb}^2 + I_{sc}^2}{3}} \]  

(5.2)

Here, \( V_{sa}, V_{sb}, V_{sc}, I_{sa}, I_{sb}, I_{sc} \) represent the rms value of the phase voltages and currents. \( V_{sab}, V_{sbc}, V_{sca} \), are the rms value of the line voltages. Using the Equations (5.1) and (5.2), the effective apparent power is calculated as

\[ S_e = 3V_e I_e \]  

(5.3)

Power factor is calculated using the average power, \( P_{\text{avg}} \) and effective apparent power, \( S_e \) as

\[ \text{Power factor} = \frac{P_{\text{avg}}}{S_e} \]  

(5.4)

Graphical representation of data in Table 5.2 is shown in Figure 5.14. It is observed that the % efficiency is maintained nearly equal to 85% for all the loads and the maximum efficiency at rated load is found to be 85.97%.
Figure 5.14 System performance for load variation using constant instantaneous power control strategy

Figure 5.15 represents the experimental results of the proposed converter module for the constant instantaneous power control strategy. Figure 5.15(a) illustrates that the source currents are sinusoidal and unbalanced after employing constant instantaneous power control strategy. From the Figure 5.15(b), it is observed that the source current is in phase with the source voltage. It is evident from Figure 5.15(c) that the proposed system provides constant output voltage. Figure 5.15(d) proves that the system can continuously operate in spite of module loss in any one or two phases. Figure 5.15(e) shows that the converter attains a constant voltage for 10% step increase in load after 0.06s. Figures 5.15(f) - 5.15(h) represent the harmonic spectrum of source current for three-phases.
Figure 5.15 Experimental waveforms for constant instantaneous power control strategy

The simulation results of the proposed system under unbalanced supply condition using sinusoidal current control strategy are presented in Figures 5.16(a) – 5.16(f).
Figure 5.16 Simulated waveforms of for sinusoidal current control strategy

From Figures 5.16(a) and 5.16(b), it is observed that source currents are sinusoidal, balanced and source current is in phase with the source voltage after employing sinusoidal current control strategy. It is evident from Figure 5.16(c) that the proposed system provides constant output voltage. Results from Figure 5.16(d) reveal that the system continuously operates in spite of module loss in any one or two phases and the converter gets back the reference voltage for 10% step increase in load after 0.054s. From the harmonic spectrum of source current, the %THD is found to be 3.02% for all the three-phases.

Figure 5.17 shows the simulation results of the individual input phase currents, inductor currents, output voltage, load current and output power for symmetric mains condition, module loss in phase a, module loss in
phases a and b after applying sinusoidal current control strategy. It is inferred from the results that the steady state error in the output voltage is 6.5%, 14% of the reference voltage for one module loss and two module loss conditions respectively.

Figure 5.17 Simulation results for symmetric mains condition, module loss in phase a, module loss in phases a and b for sinusoidal current control strategy

Table 5.3 presents the variation of performance parameters of three-phase PFC Ćuk converter as a function of load for sinusoidal current control strategy.
Table 5.3 Performance parameters for load variation using sinusoidal current control strategy

<table>
<thead>
<tr>
<th>Load Current (A)</th>
<th>2.4</th>
<th>2.2</th>
<th>2</th>
<th>1.85</th>
<th>1.7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency (%)</td>
<td>86.06</td>
<td>85.7</td>
<td>85.31</td>
<td>85</td>
<td>84.43</td>
</tr>
<tr>
<td>PF</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>THD (%)</td>
<td>3.02</td>
<td>3.5</td>
<td>3.8</td>
<td>4</td>
<td>4.01</td>
</tr>
<tr>
<td>Voltage regulation (%)</td>
<td>-0.0417</td>
<td>0</td>
<td>0.083</td>
<td>0.25</td>
<td>0.25</td>
</tr>
</tbody>
</table>

The graphical representation of data in Table 5.3 under unbalanced supply conditions using sinusoidal current control strategy is presented in Figure 5.18. It is inferred that % efficiency is maintained nearly 85% for all the loads and the maximum efficiency at rated load is found to be 86.06 %.

Figure 5.18 System performance for load variation using sinusoidal current control strategy
The experimental results of the proposed system under unbalanced supply condition using sinusoidal current control strategy are presented in Figure 5.19. From Figures 5.19(a) and 5.19(b), it is observed that source currents are sinusoidal, balanced and the source current is in phase with the source voltage after employing sinusoidal current control strategy.

Figure 5.19 Experimental waveforms for sinusoidal current control Strategy

It is evident from Figure 5.19(c) that the proposed system provides constant output voltage. Results also reveal that the system continuously operates in spite of module loss in any one or two phases and the converter provides a constant voltage for step load variation after 0.054s. From the
harmonic spectrum of source current, the %THD is found to be 3.7% for all the three-phases.

Simulation results for Fryze current control strategy are presented in Figures 5.20(a) - 5.20(h).

**Figure 5.20 Simulated waveforms for Fryze current control strategy**

It is apparent from Figures 5.20(a) and 5.20(b) that the compensated source currents are sinusoidal but have magnitude unbalance. Results also depict that the UPF operation is possible in the proposed control strategy. It is also inferred from Figure 5.20(c) that the proposed control strategy provides an output voltage of -22V with a steady state error of 8%. It is understood from Figure 5.20(d) that the converter is operating continuously
irrespective of module loss in any of the phases. From the Figure 5.20(e), it is inferred that the converter gets back the voltage -22V (with the steady state error of 8%) after 0.03s for 10% step increase in load. Figure 5.20(f) - 5.20(h) depict the harmonic spectrum of source current for the three-phases and the %THD is found to be 4.51%, 5.12% and 6.04% respectively.

Figure 5.21 shows the simulation results of Fryze current control strategy for the individual input phase currents, inductor currents, output voltage, load current and output power for symmetric mains condition, module loss in phase a, module loss in phases a and b.

Figure 5.21 Simulation results for symmetric mains condition, module loss in phase a, module loss in phases a and b for Fryze current control strategy
It is inferred from the results that for symmetric mains condition, steady state error in the output voltage is 8%. For one module loss, the steady state error in the output voltage is 14.5% of the reference voltage and for two module loss, the steady state error in the output voltage is 25.5% of the reference voltage. Table 5.4 presents the different performance parameters of the converter for load variation using Fryze current control strategy.

**Table 5.4 Performance parameters for load variation using Fryze current control strategy**

<table>
<thead>
<tr>
<th>Load Current (A)</th>
<th>2.4</th>
<th>2.2</th>
<th>2</th>
<th>1.85</th>
<th>1.7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency (%)</td>
<td>86.6</td>
<td>86.59</td>
<td>86.35</td>
<td>86.19</td>
<td>86.06</td>
</tr>
<tr>
<td>PF</td>
<td>0.9819</td>
<td>0.9793</td>
<td>0.9764</td>
<td>0.9734</td>
<td>0.9695</td>
</tr>
<tr>
<td>THD (%)</td>
<td>4.51</td>
<td>6.42</td>
<td>7.577</td>
<td>8.69</td>
<td>9.64</td>
</tr>
<tr>
<td>Voltage regulation (%)</td>
<td>8.0</td>
<td>8.33</td>
<td>8.42</td>
<td>9.08</td>
<td>9.17</td>
</tr>
</tbody>
</table>

The graphical representation of data in Table 5.4 for unbalanced supply conditions using Fryze current control strategy is presented in Figure 5.22. It is observed that the % efficiency is maintained above 85% for all the loads and the maximum efficiency at rated load is found to be 86.6%. Figures 5.23(a) - 5.23(h) represent the experimental results of the proposed converter module for Fryze current control method.

It is apparent from Figures 5.23(a) and 5.23(b) that the compensated source currents are sinusoidal but have magnitude unbalance and it also depicts that the UPF operation is possible in the proposed control strategy. It is also inferred from Figure 5.23(c) that the proposed control strategy provides an output voltage of -22V with a steady state error of 8%. It is understood from Figure 5.23(d) that the converter is operating continuously irrespective of module loss in any of the phases. From Figure 5.23(e), it is inferred that the converter gets back the voltage -22V (with the steady state
error of 8%) after 0.03s for 10% increase in load. Figures 5.23(f) - 5.23(h) show the harmonic spectrum of source current for the three-phases.

Figure 5.22 System performance for load variation using Fryze current control strategy

Based on the results obtained from simulation and experimentation, the following analysis is made. Among the three types of extended p-q methods for unbalanced supply voltage conditions, it is inferred that sinusoidal current control strategy gives the best results for PFC as it provides less percentage of THD, the source currents are sinusoidal and balanced after compensation and it also gets back to its reference voltage after 0.054s for step load variation. It also maintains the output voltage almost equal to the reference voltage for one module and two module loss conditions.
Figure 5.23 Experimental waveforms for Fryze current control strategy

5.8 CONCLUSION

In this chapter, the analysis and design of a three-phase PFC Ćuk converter for UPF operation is presented. Reference currents are generated using p-q theory for balanced supply voltage conditions and for unbalanced supply voltage conditions extended versions of p-q theory such as sinusoidal
current control method, instantaneous constant power control method and Fryze current control method are used. The control strategy is based on outer voltage control loop and three inner hysteresis current controllers. The proposed controller guarantees the continuous operation of the system in case of module failure.

To support the proposed method, a prototype controlled by dSPACE signal processor is set up. From the results, it is found that the sinusoidal current control strategy offers excellent results for PFC when compared to constant instantaneous power control strategy and Fryze current control method under unbalanced supply voltage conditions. Simulation and experimental results reveal that the proposed system offers regulated output voltage for step load variations and also provides power factor close to unity.