Chapter 4: Three Phase Modular Boost PFC Scheme using \( pq \) Theory and Extended \( pq \) Theory for Balanced and Unbalanced Supply Conditions

4.1 Introduction

In this chapter, the design and analysis of a three phase modular boost converter for output DC voltage regulation and input current wave shaping is presented. To achieve the objectives of power factor improvement and output voltage regulation, a nested control method is used with PI based voltage controller in outer voltage control loop for DC voltage regulation and current controllers like LQR and HC in the inner current control loop for current wave shaping under balanced and unbalanced supply voltage conditions respectively.

For current wave shaping, it requires an algorithm for sinusoidal reference current generation which is established by two current control schemes. In the first technique, \( pq \) theory is used for balanced supply voltage conditions. In the second technique, extended versions of \( pq \) theory such as Sinusoidal Current Control Strategy and Generalized Fryze Current Control Strategy are used for unbalanced supply voltage conditions. The controllers work successfully in tracking the reference voltage changes in order to vary the regulated DC output voltage and it also guarantees that the continuous DC output voltage is possible in case of non availability of one or two modules in the 3-phase arrangement, which is often referred to as module loss in literature [52, 53]. Extensive simulation results based on the models developed using MATLAB/SIMULINK reveal that the proposed system performs satisfactorily for step variations in load.

This chapter also covers the fabrication and experimental work carried out on a low power prototype developed and is controlled using a dSPACE 1104 digital signal
processor board. The hardware experimental results corroborate the simulation studies in achieving good output voltage regulation and power factor improvement under wide variations in load current. Figure 4.1 shows the sequential flow diagram, where the various blocks represent alternative control algorithms employed for reference current generation.

Figure 4.1: Sequential Flow Diagram - pq Theory and Extended pq Theory

4.2 Three Phase Modular Boost Converter

Figure 4.2 shows the schematic of a three phase modular boost converter which includes three individual full-wave diode rectifiers and DC boost converters. The input side inductors of the boost converter in each phase is represented as \( L_a, L_b, L_c \) and the active switches in each phase are represented as \( S_a, S_b, S_c \) and the diodes of the three phases of the modular boost converter are represented as \( D_a, D_b, D_c \). The source voltage...
and currents in the respective phases are represented as \( v_{sa}, v_{sb}, v_{sc} \) and \( i_{sa}, i_{sb}, i_{sc} \). All the three modules are connected to a common DC load resistor \( R_L \) with a filter capacitor \( C_0 \) in parallel with it. \( V_0 \) represents the output DC voltage.

![Three Phase Modular Boost Converter](image)

**Figure 4.2**: Three Phase Modular Boost Converter

### 4.3 Generation of Reference Currents under Balanced Supply Conditions

#### 4.3.1 \( pq \) Theory

The \( pq \) theory is based on a set of instantaneous powers defined in the time domain. It is valid for both steady state and transient state. This theory is very efficient and flexible in designing controllers for power conditioners based on power electronic devices. For the reference current generation, the instantaneous phase voltages \( v_{sa}, v_{sb}, v_{sc} \) and the instantaneous phase currents \( i_{sa}, i_{sb}, i_{sc} \) are sensed and made
available to the reference current calculator. In $pq$ theory, it is required to transform the sensed voltages and currents from $abc$ to $\alpha\beta\theta$ coordinates using Clarke transformation and then the instantaneous power are defined in these coordinates. The output of the PI controller is also required for the calculation. All the necessary calculations are carried out as shown in Figure 4.3 and the reference currents in $\alpha\beta\theta$ coordinates are generated [58, 59]. These are then transformed to $abc$ components using inverse Clarke transformation. The functional blocks required for reference current generation using $pq$ theory is shown in Figure 4.3.

**Figure 4.3**: Reference Current Generation using $pq$ Theory

The average load power derived from the instantaneous power ($\alpha$-$\beta$) components is added with the $P_{loss}$ component obtained from the output of PI controller. This $P_{loss}$ is
due to ohmic losses and switching losses in the power electronic converter which make the capacitor voltage to decrease. Hence the purpose of PI controller is to provide information about $P_{loss}$ that causes an additional flow of energy to the capacitor for maintaining the DC voltage equal to the reference value so that PFC rectifier is able to track the reference current exactly. Thus an expression for $P_{loss}$ is given by

$$P_{loss} = K_p(V_{\text{ref}} - V_0) + K_i \int (V_{\text{ref}} - V_0) dt$$

(4.1)

The reference currents generated using $pq$ theory is used in the current controller available in all the three phases will be explained in the subsequent sections.

4.3.2 **Closed Loop Control using Linear Quadratic Controller**

The closed loop control system includes a PI based voltage controller in the outer voltage control loop and Linear Quadratic Controllers are employed in the inner current control loop in order to regulate the DC load voltage and to improve the supply side power factor. The schematic of the closed loop system using LQR is shown in Figure 4.4.

![Figure 4.4: Closed Loop Control using LQR](image-url)
The PI controller parameters $k_p$ and $k_i$ are tuned properly as explained in Section 3.7 and determined numerically as 0.004 and 0.5 respectively. In the outer voltage control loop, output voltage is scaled down suitably and compared with the reference voltage. This error $e_2$ is processed in the common PI controller. The output of this controller is $P_{loss}$ component, [56, 58, 59] which is then processed along with the sensed three-phase source voltages and currents in the reference current calculator. The three phase reference currents for balanced supply voltage conditions are generated using pq theory as explained in Figure 4.3. The actual currents are then compared with the reference currents, resulting in current errors $e_{1a}$, $e_{1b}$ and $e_{1c}$. The state feedback gains $K_1$ and $K_2$ are calculated using the design equations of LQR as explained in Section 3.9 and found to be 25.3 and 10.7 respectively. The control input of the LQR is calculated using the feedback gains $K_1$ and $K_2$ as $u_c = K_1 * e_1 + K_2 * e_2$ which is then compared with the carrier ramp signal of 10 kHz frequency. In each phase, an individual Quadratic Controller is employed in the inner current loop and the resultant Pulse Width Modulated (PWM) signal triggers the MOSFET switch in the respective phase.

4.3.3 Simulation Results

The MATLAB simulation schematic of the circuit in Figure 4.2 in open loop is created and the performance of the same is evaluated. The MOSFET switch in each module is triggered with a pulse obtained from a pulse generator of 10 kHz frequency. A fixed duty ratio of 50% is selected in order to get 24 V DC output from 12 V DC input. The performance parameters calculated from the simulation results for the three-phase boost converter without controller are given in Table 4.1 which shows very high THD, poor regulation and low power factor.
Improved performance parameters are obtained by employing appropriate controllers using feedback. In closed loop control, three-phase modular boost converters with common outer voltage loop control by PI controller and individual inner current loop control with LQR is modelled and simulated using MATLAB/SIMULINK. Here, the simulation schematics developed in Chapter 3 for single phase and shown in Appendix C is replicated to represent for three phases individually and run to cover the transient region till steady state is reached.

Figure 4.5 (a) shows the actual DC output voltage ($V_o$) at rated load current of 2.4 A. From Figure 4.5 (b), it is observed that the DC output voltage is maintained constant following a step change in load from 2.4 A to 3.2 A at $t = 0.35$ s. The output voltage settles to 24 V after a transient interval of 100 ms. Figure 4.5 (c) shows the output voltage when the load current increases in two steps. At $t = 0.35$ s, the step change in load results in an increase of load current from 1.6 A to 2 A and at $t = 0.5$ s, the current changes from 2 A to 2.4 A. During both the intervals, the actual load voltage gets back to the reference value within a settling time of 50 ms. The output voltage is

<table>
<thead>
<tr>
<th>Load Current $I_o$ in amps</th>
<th>Output Voltage $V_o$ in Volts</th>
<th>Regulation in %</th>
<th>THD in %</th>
<th>Power factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.26</td>
<td>25.21</td>
<td>5.04</td>
<td>64.99</td>
<td>0.7236</td>
</tr>
<tr>
<td>1.38</td>
<td>24.99</td>
<td>4.12</td>
<td>63.58</td>
<td>0.7202</td>
</tr>
<tr>
<td>1.63</td>
<td>24.59</td>
<td>2.45</td>
<td>60.97</td>
<td>0.7300</td>
</tr>
<tr>
<td>2.3</td>
<td>23.59</td>
<td>-1.71</td>
<td>54.59</td>
<td>0.7352</td>
</tr>
</tbody>
</table>
well regulated for an abrupt increase (1.6 A to 2 A) and decrease in load (2 A to 1.6 A) which are shown in Figure 4.5 (d). It is seen from Figures 4.5(e) and 4.5 (f) that all the supply side phase currents are sinusoidal and the same wave shape is continued with different amplitudes for load current variation. It is concluded that the controller makes the input current wave shape in all the three phases to be sinusoidal and in phase with the corresponding phase voltages. It is observed from the waveforms shown in Figures 4.5 (g) and (h) that the voltage controller acts effectively and brings the output voltage to the reference setting exactly. The servo response of the closed loop system is tested by changing the reference voltage and it is observed that output voltage is able to follow the change in the reference voltage from 20 V to 24 V and then to 28 V.
Figure 4.5: Simulation Waveforms of Three Phase Modular Boost Converter using LQR with $pq$ Theory
The effectiveness of the feedback controller is confirmed from Figure 4.6 showing a THD of 1.97%, which indicates a desirable result of the source current closely following the sinusoidal supply voltage.

![Figure 4.6: THD of Current in Phase \(a (i_{sa})\) under Full Load Condition](image)

The source current waveforms and output DC voltage are shown in Figures 4.7 (a) and (b) for module loss operation. Figure 4.7 (a) conveys that under normal working condition, all the three modules share the current equally. At \(t = 0.3\) s, one module loss occurs (phase \(b\)) and the current in the other two phases (phases \(a\) and \(c\)) increase with slight decrease in output voltage. At \(t = 0.5\) s, loss of two modules occur due to which the entire current flows through one phase only (phase \(a\)). From Figure 4.7 (b), it is observed that during one module loss, the output voltage is around 22.3 V and the drop in voltage is 7.08% of the rated value. Further, for two module loss condition, the output voltage is nearly 18.95 V and the regulation is -21.04% of the rated voltage.

It is evident that the voltage regulation of the DC output following one/two module loss is relatively high and improvement in the schematic is called for.
This issue arises from inability of the reference current generation blocks to attain a sufficiently higher value as required and hence needs an adaptive mechanism. Accordingly, the control algorithm is augmented for taking into account one or two module loss through a logic and timing circuit which introduces an additional gain of nominal value of 1.5 for each reference current signal for the two remaining working modules, following one module loss situation. Similarly an additional gain of nominal value of 3.0 is introduced in the reference current path of one working module consequent on the event of two module loss condition. This enables the working module(s) to draw larger current(s) from the respective supply side and maintain DC output voltage very close to the reference value.

Additional work in the form of creating a subsystem in the gain path of reference current generation, which gets activated in the event of module loss condition, is shown in Figure 9 in Appendix C. This sub system has been incorporated in the Simulink schematic shown in Figure 4.3. The new simulation results for module loss condition shown in Figure 4.7 (d), which indicates very good regulation of the output DC voltage, close to reference voltage setting over successive time slots corresponding to failure of one and two modules. It is also observed from Figure 4.7 (c) that the working module(s) draw larger source current(s) for maintaining the regulated DC output voltage.
The performance of the converter is analyzed for varying load by examining THD, efficiency and voltage regulation as given in Table 4.2. It is observed that the efficiency is maintained around 87% when the load varies from full load (2.4 A) to half full load (1.2 A). The low value of THD indicates that the input current wave shape is also nearly sinusoidal when the load varies from 100% to 50% of its nominal value. The results reveal the effectiveness of the control scheme for wide range of load variation.

**Figure 4.7**: Simulation Waveforms for Normal and Module Loss Operation
(a) Source Currents (b) Output Voltage (c) Source Currents with Adaptive gain (d) Output Voltage with Adaptive gain
Table 4.2: Performance of the Modular Boost Converter using pq theory
(Linear Quadratic Controller)

<table>
<thead>
<tr>
<th>Load Current Io in amps</th>
<th>Output Voltage Vo in Volts</th>
<th>Regulation In %</th>
<th>THD in %</th>
<th>Efficiency in %</th>
<th>Power factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.198</td>
<td>23.97</td>
<td>- 0.125</td>
<td>2.57</td>
<td>87.03</td>
<td>0.9289</td>
</tr>
<tr>
<td>1.332</td>
<td>23.97</td>
<td>- 0.125</td>
<td>2.53</td>
<td>87.16</td>
<td>0.9288</td>
</tr>
<tr>
<td>1.598</td>
<td>23.98</td>
<td>- 0.083</td>
<td>2.21</td>
<td>87.21</td>
<td>0.9293</td>
</tr>
<tr>
<td>1.844</td>
<td>23.98</td>
<td>- 0.083</td>
<td>2.00</td>
<td>87.26</td>
<td>0.9289</td>
</tr>
<tr>
<td>2.399</td>
<td>23.99</td>
<td>- 0.041</td>
<td>1.97</td>
<td>87.10</td>
<td>0.9251</td>
</tr>
</tbody>
</table>

4.3.4 Hardware Fabrication and Experimental Work

In order to validate the simulation result obtained by LQR, a prototype model of
three-phase modular boost converter system shown in Figure 4.8 is designed and
fabricated. It employs three individual modules with each phase consisting of a diode
bridge rectifier and a DC-DC boost converter. On the load side, the outputs of the three
modules are connected in parallel, so as to share a common load. The power and control
circuit of the modular boost converter along with dSPACE signal processor is shown in
Figure 4.8.
The parameters of the various components used to build the prototype are listed as follows: Inductors $L_a$, $L_b$, $L_c$ each of 2 mH. The DC bus capacitor of 9000 µF. The MOSFET IRF 250 as active switches $S_a$, $S_b$, $S_c$ and MUR 3060 as power diodes. In each module, the boost converter is designed for 24 V output from 12 V DC input voltage. On the rectifier side, potential transformer and current transformer are utilized for sensing the source voltage and currents respectively and voltage divider circuit is employed to scale down the DC output voltage. All the sensed signals are conditioned.
within the range ±10 V which is suitable for the analog to digital converter present in dSPACE. The entire process like PI controller tuning, reference current calculation and comparison with the actual current, control signal initiation by LQR algorithm and pulse generation are performed in the dSPACE unit. The PWM pulses are fed to the MOSFETs through a suitable driver circuit. The complete hardware which includes a three-phase modular boost converter with signal conditioning circuits, isolation and driver circuit along with dSPACE processor is shown in Figure 4.9. The real time experiments are executed with the following conditions: 230 V AC input, 24 V DC output, $f_s = 10$ kHz and $R_L = 20 \, \Omega$. 
Figure 4.9: Two Views of the Hardware for Experimental Set Up
The experimental results obtained for the three phase modular boost converter in open loop are shown in Figure 4.2. In order to obtain a desired output voltage of 24 V from 12 V input, a pulse train with a fixed duty cycle of 0.5 is applied to the controlled switches of the converter and the corresponding waveforms are shown in Figures 4.10 (a) and (b). From the open loop control, it is clear that the source current wave forms are not sinusoidal and the output voltage is not maintained constant for step load change.

![Waveforms](image)

**Figure 4.10:** (a) Output Voltage and Load Current for Step Load Change (b) Source Currents

The performance of the converter is enhanced by implementing closed loop control with suitable controllers along with necessary feedback signals and the experimental results are shown in Figure 4.11. The Figure 4.11 (a) represents the output DC voltage \(V_o\) for a load current of 1 A. It is understood from Figures 4.11 (b) to (d) that the output DC voltage is maintained constant for frequent step change in load and also for sudden increase/decrease in load. The response is quick and the transients are comparatively less. The waveforms in Figures 4.11 (e) and (f) reveal that the output
voltage follows the change in the reference voltage precisely. It is observed from the near sinusoidal phase current waveforms shown in Figure 4.11 (g) that the wave shaping technique has been implemented effectively. The DC output voltage with and without module loss condition is displayed in Figure 4.11 (h), which conveys that the controller varies the duty cycle of the operating unit effectively. This indicates that there is only a small drop in output voltage for module loss operation, even when one/two module failure(s) occur. The scale adopted for display of the experimental results in all the chapters is as follows:

Source Currents: 1 division = 500 mV (1 A), Output Voltage: 1 division = 5 V, Load Current: 1 division = 100 mV (1 A).
Figure 4.11: Experimental Waveforms of Three Phase Modular Boost Converter using LQR with $pq$ Theory
The change in the source current waveforms for various module loss operations are shown in Figures 4.12 (a) and (b). The power factor is monitored using power quality analyzer connected in the source side. It is found that the overall power factor remains at 0.97 and the displacement factor is also nearer to unity. The output voltage is recorded and regulation calculated for different load currents are shown in Table 4.3.

![Experimental Waveforms](image)

**Figure 4.12**: Experimental Waveforms (a) Source Currents for No Loss and One Module Loss (b) Source Currents for One Module Loss and Two Module Loss

<table>
<thead>
<tr>
<th>Load Current Io in amps</th>
<th>0.9</th>
<th>0.93</th>
<th>0.95</th>
<th>1</th>
<th>1.08</th>
<th>1.11</th>
<th>1.24</th>
<th>1.3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output Voltage Vo in Volts</td>
<td>23.99</td>
<td>23.96</td>
<td>23.92</td>
<td>23.87</td>
<td>23.8</td>
<td>23.79</td>
<td>23.72</td>
<td>23.46</td>
</tr>
<tr>
<td>Regulation in %</td>
<td>-0.041</td>
<td>-0.166</td>
<td>-0.333</td>
<td>-0.541</td>
<td>-0.833</td>
<td>-0.875</td>
<td>-1.16</td>
<td>-2.25</td>
</tr>
</tbody>
</table>
4.4 Performance of Boost Converter under 3-Phase Unbalanced Supply Conditions

The \( pq \) theory discussed earlier shows that it is possible to satisfy the following optimal performance characteristics simultaneously under sinusoidal balanced supply voltages [58, 59].

- Draw a sinusoidal current from the source
- Draw a constant instantaneous active power from the source
- Draw a source current proportional to the corresponding voltages.

However, under unbalanced supply voltage conditions, it is possible to satisfy only any one of the above optimal characteristics at a time. Based on this, there are three different control strategies,

(i) Sinusoidal Current Control Strategy
(ii) Constant Instantaneous Power Control Strategy
(iii) Generalized Fryze Current Control Strategy

The following Sections discuss the Sinusoidal Current Control Strategy and Generalized Fryze Current Control Strategy for unbalanced supply voltage conditions [62].

4.4.1 Closed Loop Control using Hysteresis Controller

The closed loop control of modular boost converter using Hysteresis Controller is implemented for unbalanced supply conditions and the simulation and experimental results are obtained. It is desired to achieve a well regulated low voltage DC and sinusoidal wave shaping of input current for power factor improvement. In order to meet these objectives, the output voltage \( (V_o) \), 3-phase input voltages and currents are sensed and conditioned within the range \( \pm 10 \, V \) to suit the ADC (Analog to Digital Converter)
of the dSPACE processor as shown in Figure 4.8. The voltage error obtained by comparing the DC output voltage with the desired reference voltage is processed in a PI controller. The output of this controller supplies the $P_{loss}$ component which is used along with the input voltages and currents for the generation of reference currents (Figure 4.13) through extended versions of $pq$ theory, viz., Sinusoidal Current Control Strategy and Generalized Fryze Current Control Strategy. The comparison between the reference currents generated and actual currents in each phase, results in current errors which are then fed to the hysteresis controller with a hysteresis band of $\pm 0.0005$. The PWM pulses generated by the controller are applied to the switches with proper isolation and amplification.

**Figure 4.13**: Closed Loop Control using Hysteresis Controller
4.4.2 Sinusoidal Current Control Strategy

This control strategy guarantees balanced, sinusoidal currents to be drawn from the supply, even when the supply voltages are unbalanced. The block diagram representation of Sinusoidal Current Control Strategy is shown in Figure 4.14. In order to draw balanced compensated currents, it requires a positive sequence extractor which calculates positive sequence voltages $V'_{sa}$, $V'_{sb}$ and $V'_{sc}$. These voltages along with the source currents $i_{sa}$, $i_{sb}$, $i_{sc}$ are transformed into $\alpha\beta$ coordinates using Clarke transformation. Then the instantaneous power is calculated from which oscillating components are eliminated using a low pass filter and only the average power is considered for further calculations. By following the steps dealing with compensation of switching and other losses in the boost converter through a PI controller for output DC voltage regulation, described in 4.3.1, the reference currents are calculated in $\alpha\beta$ coordinates. Using inverse Clarke transformation, the reference currents in the $abc$ frame are obtained as shown in Figure 4.14.
4.4.3 Simulation and Experimental Results

The SIMULINK schematic covering unbalanced supply, three modules of boost converter along with reference current calculator and Hysteresis Controller has been prepared as indicated in Appendix C. The simulation results of the above set up with Sinusoidal Current Control Strategy for reference current generation technique are shown in Figure 4.15.

The modular boost converter for power factor correction and maintaining 24 V DC is simulated using MATLAB/SIMULINK. Figure 4.15 (a) shows the response of the power circuit for a DC output voltage with a reference setting of 24 V, which consists of...
an initial transient period of 0.1 s and steady state for a rated load current of 2.4 A. From Figure 4.15(b), it is clear that the output DC voltage is well regulated for even 15% step increases in load current that occur at 0.3 s and 0.5 s. At both these instants, the load voltage has settled down to the reference voltage within an interval of 50 ms. Figures 4.15 (c) and (d) present the load voltage waveform and source current waveforms for sudden increase and decrease in load. There is a step increase in load current from 1.6 A to 2 A at $t = 0.3$ s and the same current is available for a duration of 0.15 s, after which there is a step decrease in load from 2 A to 1.6 A at $t = 0.45$ s. During these changes, it is found that the load voltage settles to the nominal value within a transient interval of 50 ms. It is inferred from Figure 4.15(d) that source current wave-shape is almost sinusoidal for the above loading conditions. Figure 4.15(e) depicts the source currents in all the phases which are now balanced and nearly sinusoidal, although the supply voltage is unbalanced. The important aim of power factor correction is verified by plotting the source voltage and source current of phase $a$ in Figure 4.15(f), where the above two waveforms appear nearly in phase. Further, the ability of the power and control circuits to meet any planned requirement of variable output voltage is portrayed in Figures 4.15(g) and (h), where successive increase/decrease of the reference voltage at $t = 0.3$ s and at $t = 0.45$ s are introduced and the corresponding variation of output DC voltage is presented. These results indicate a fast response of the output voltage with negligible steady state error.
Figure 4.15: Simulation Waveforms of 3-Phase Modular Boost Converter using Sinusoidal Current Control Strategy
The harmonic spectrum of source current is shown in Figure 4.16. It shows that the harmonics are reduced considerably and the THD is limited to 1.9% which is within the acceptable values specified by the standards [5-7].

![Harmonic Spectrum](image)

**Figure 4.16**: THD of Current in Phase *a* (*i_{a}*a) under Full Load Condition

The module loss operation of the converter is shown in Figures 4.17 (a) and (b). The converter is working with three modules so that a normal three phase input is available up to \( t = 0.3 \) s and the current drawn from the supply is shared equally by all the three modules. During the interval from 0.3 s to 0.4 s, failure of one module occur due to which current in phase *b* becomes zero and there is an increase in current in the other two phases, but the continuity of power to the load is maintained with only 7.5% drop in load voltage. The system returns to the three phase condition from 0.4 s to 0.5 s and the output voltage is restored to the nominal value. At \( t = 0.5 \) s, two modules fail and the input current in the remaining phase increases, followed by a drop in the DC output voltage of about 23.75% of the rated value.
In order to improve the output voltage regulation under module loss conditions, a new subsystem with adaptive gain is created (Figure 9 in Appendix C) and incorporated in the reference current generation path of Figure 4.14 which gets activated on the occurrence of module loss conditions. The new simulation results are shown in Figures 4.17 (c), (d). These waveforms indicate very good regulation of the output DC voltage close to reference voltage and it is also observed that the working module(s) draw larger source current(s) for maintaining the required DC output voltage.

Figure 4.17: Simulation Waveforms for Normal and Module Loss Operation
(a) Source Currents (b) Output Voltage (c) Source Currents with Adaptive gain (d) Output Voltage with Adaptive gain
The performance of the converter is examined by calculating the power factor and the regulation. In the calculation of power factor under unbalanced supply conditions, effective apparent power is important. The effective phase voltage under unbalanced supply condition is given as [62]

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

(4.2)

Effective phase current is given as

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

(4.3)

where \(V_{sa}, V_{sb}, V_{sc}\) and \(I_{sa}, I_{sb}, I_{sc}\) represent rms values of the phase voltages and currents. The rms value of the line voltages are represented as \(V_{sab}, V_{sbc}, V_{sca}\). The effective apparent power is calculated as

\[
S_e = 3V_e I_e
\]

(4.4)

The power factor is calculated from \(S_e\) and \(P_{L(avg)}\) as

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

(4.5)

where \(P_{L(avg)} = \frac{V_0^2}{R_L}\)

(4.6)

The efficiency of the closed loop controlled boost converter is also evaluated by considering the final DC power output and power drawn from the secondaries of the three step down transformers.

The results obtained for load current variation from 1.17 A to 2.4 A in steps are presented in Table 4.4. The variation of load results only in a slight deviation in the output voltage and a smooth regulation is observed. Power factor is improved and
maintained above 0.9 for all loading conditions and the THD is around 1.8% over the full range of load current variations.

Table 4.4: Performance of the Modular Boost Converter using Sinusoidal Current Control Strategy (Hysteresis Controller)

<table>
<thead>
<tr>
<th>Load Current Io in amps</th>
<th>Output Voltage Vo in Volts</th>
<th>Regulation in %</th>
<th>THD in %</th>
<th>Efficiency in %</th>
<th>Power factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.17</td>
<td>23.90</td>
<td>- 0.416</td>
<td>2.15</td>
<td>91.93</td>
<td>0.9220</td>
</tr>
<tr>
<td>1.32</td>
<td>23.91</td>
<td>- 0.375</td>
<td>1.98</td>
<td>92.22</td>
<td>0.9237</td>
</tr>
<tr>
<td>1.59</td>
<td>23.99</td>
<td>- 0.041</td>
<td>1.73</td>
<td>92.57</td>
<td>0.9287</td>
</tr>
<tr>
<td>1.85</td>
<td>24.02</td>
<td>0.083</td>
<td>1.79</td>
<td>92.73</td>
<td>0.9316</td>
</tr>
<tr>
<td>2.18</td>
<td>24.03</td>
<td>0.125</td>
<td>1.78</td>
<td>92.79</td>
<td>0.9341</td>
</tr>
<tr>
<td>2.40</td>
<td>24.04</td>
<td>0.166</td>
<td>1.80</td>
<td>92.80</td>
<td>0.9352</td>
</tr>
</tbody>
</table>

The experimental set up shown in Figure 4.8 is operated in a three phase unbalanced supply system for validating the performance of boost converter using sinusoidal current control algorithm for reference current generation. The experimental results are shown in Figure 4.18.

Figure 4.18 (a) represents the regulated DC output Voltage \( (V_o) \) of the boost converter when supplying a load current of 1 A. It is observed from Figures 4.18 (b) to (d) that the output DC voltage is maintained constant for frequent step changes in load and also for sudden increase/decrease in load. The response is quick and the transients are comparatively lesser. The waveforms in Figures 4.18 (e) and (f) reveal that the output voltage follows the change in the reference voltage settings precisely. It is also observed from the nearly sinusoidal phase current waveforms in Figure 4.18 (g) that the wave shaping technique is effective. The DC output voltage under normal and module loss condition is displayed in Figure 4.18 (h). It indicates that the controller varies the
duty cycle effectively for the operating module(s), so that there is only a small drop in output voltage under this condition.

Figure 4.18: Experimental Waveforms of Three Phase Modular Boost Converter with Sinusoidal Current Control Strategy
The harmonic spectrum of current in phase $a$ under normal operating conditions is depicted in Figure 4.19. Despite THD being equal to 18.7%, the power factor has improved significantly as indicated by Power Quality Analyzer, which is connected across the mains at the primary side.

![Figure 4.19: Experimental Results - Harmonic Spectrum](image)

The change in the source current waveforms for various module loss operations are shown in Figure 4.20.

![Figure 4.20: Experimental Results- Source Currents for Module Loss Operation](image)
The output DC voltage is recorded and the regulation calculated for different load currents ranging from 0.9 A to 1.3 A are shown in Table 4.5.

<table>
<thead>
<tr>
<th>Load Current Io in amps</th>
<th>0.9</th>
<th>0.93</th>
<th>0.95</th>
<th>1</th>
<th>1.03</th>
<th>1.15</th>
<th>1.24</th>
<th>1.3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output Voltage Vo in Volts</td>
<td>23.99</td>
<td>23.96</td>
<td>23.92</td>
<td>23.87</td>
<td>23.85</td>
<td>23.75</td>
<td>23.72</td>
<td>23.46</td>
</tr>
<tr>
<td>Regulation in %</td>
<td>-0.041</td>
<td>-0.166</td>
<td>-0.333</td>
<td>-0.541</td>
<td>-0.625</td>
<td>-1.04</td>
<td>-1.16</td>
<td>-2.25</td>
</tr>
</tbody>
</table>

4.4.4 Sinusoidal Current Control based PWM Boost Rectifier

As an alternative to employing three modules made up of individual DC-DC boost converters fed from a 3-phase source, the power circuit can be selected having a three phase bridge rectifier configuration consisting of 6 numbers of semiconductor power switches which is as shown in Figure 4.21. While the entire control algorithm based on sinusoidal current reference generation and the subsequent stages for shaping the source current waveforms remain the same, the latter choice involves the application of complementary pairs of gate trigger signals for each arm of the rectifier, which are successively shifted by 120° as in the previous method. It is noted that both the power and control circuits become more complicated while implementing the PWM rectifier. Further modelling and analysis on a single phase basis, as in the previous modular approach is no longer possible. Accordingly, independent control of the individual
phases, required during failure of 3-phase supply is also not feasible while using the bridge rectifier.

![Image of Power Circuit of 3-Phase PWM Rectifier]

**Figure 4.21**: Power Circuit of 3-Phase PWM Rectifier

As a means of comparison of the performance of the two systems, a new simulation schematic has been created and run with identical input and output data. These results for both choices of power circuits are shown in Figure 4.22 where (a), (c), (e) and (g) are meant for PWM rectifier, whereas (b), (d), (f) and (h) pertain to modular DC-DC converter.
Figure 4.22: Simulation Waveforms of 3-Phase PWM Rectifier and 3-Phase Modular Boost Converter
The above simulation results indicate that almost all the new performance parameters match closely with the respective results of the modular boost converter setup. However, there is a slight improvement in source side power factor for the alternative PWM bridge rectifier circuit configuration. It is surmised that this improvement is essentially due to the elimination of minor disturbances in the source current near about zero crossing regions of the supply voltage, resulting in a reduction of the displacement angle. In spite of this minor advantage, the PWM rectifier circuit is not capable of handling failure of one / two phases of the input supply.

4.4.5 Generalized Fryze Current Control Strategy [59, 61]

In this control strategy, the source currents are made proportional to the corresponding phase voltages i.e., they have the same waveform and behave as in a pure resistive load. The block diagram representation of Fryze Current Control Strategy is shown in Figure 4.23. The instantaneous phase voltages and currents are used for calculating the instantaneous conductance. The oscillating component of instantaneous conductance is eliminated using a low pass filter. Then the active Fryze conductance \( \overline{G} \) is added with \( G_{\text{loss}} \) in order to calculate the reference currents. Although this strategy does not guarantee constant instantaneous active power from the supply, it requires fewer calculations due to the elimination of Clarke and inverse Clarke transformations.
4.4.6 Simulation and Experimental Results

The simulation schematic covering the power and control circuits where the Fryze reference current algorithm is incorporated has been prepared. This schematic was run after defining the various circuit and simulation parameters for a period of one second. The simulation results of the three-phase modular boost converter using Hysteresis Controller with Generalized Fryze Current Control Strategy as reference current generation technique under unbalanced supply voltage conditions are shown in Figure 4.24.

Figure 4.23: Reference Current Generation using Generalized Fryze Current Control Strategy

\[
G_s = \frac{v_{sa} i_{sa} + v_{sb} i_{sb} + v_{sc} i_{sc}}{v_{sa}^2 + v_{sb}^2 + v_{sc}^2}
\]

\[
G_{loss} = G_s
\]

\[
\begin{align*}
    i_{sa}^* &= (\overline{G}_s + G_{loss}) v_{sa} \\
    i_{sb}^* &= (\overline{G}_s + G_{loss}) v_{sb} \\
    i_{sc}^* &= (\overline{G}_s + G_{loss}) v_{sc}
\end{align*}
\]
Figure 4.24: Simulation Waveforms of Three Phase Modular Boost Converter with Generalized Fryze Current Control Strategy
Figure 4.24 (a) shows a constant DC output voltage with an initial transient period of 0.05 s for a rated load current of 2.4 A. From Figure 4.24 (b), it is clear that the output DC voltage is well regulated for even 15% step increases in load current that occur at 0.3 s and 0.55 s. At both these instants, the load voltage settles down to the expected reference voltage after a transient interval of 100 ms. Figures 4.24 (c) and (d) present the load voltage waveform and source current waveforms for sudden increase and decrease in load. There is a step increase in load current from 1.6 A to 2 A at \( t = 0.3 \) s and the same current is available for a duration of 0.2 s, after which there is a step decrease in load from 2 A to 1.6 A at \( t = 0.5 \) s. During these changes, the load voltage settles to the nominal voltage within a transient interval of 100 ms. From Figure 4.24 (d), it is concluded that the source current wave shape is almost sinusoidal for a range of loading condition. Figure 4.24 (e) depicts the source currents in all the phases which are nearly sinusoidal and Figure 4.24 (f) represents the source voltage and current of phase \( a \). It is inferred from these figures that the source current wave shape becomes sinusoidal and is in phase with the voltage which in turn makes the power factor nearly unity. It is seen from Figure 4.24 (g) and (h) that the change in the reference voltage from 20 V to 24V at \( t = 0.3 \) s and from 24 V to 28V at \( t = 0.5 \) s are exactly tracked by the output voltage with a minimum settling time of 40 ms.

The harmonic spectrum of the source current is shown in Figure 4.25 which conveys that the harmonics are reduced effectively and the THD value of 1.9% is within the acceptable value specified by the standards [5-7].
The module loss operation of the converter is outlined in Figure 4.26(a) and (b). The converter is working normally with three modules so that normal three phase supply is available upto $t = 0.3$ s and the total current drawn from the mains is shared equally by all the three modules. During the interval from 0.3 s to 0.4 s, there is one module failure due to which the current in phase $b$ becomes zero and the current in the other two phases increases. However, the continuity of supply to the load is maintained with only 6.25% drop in the load voltage. The system returns to three phase condition from 0.4 s to 0.5 s and the output voltage reaches the nominal value. At $t = 0.5$ s, two modules fail and so the current in one phase increases with a drop in the DC voltage of about 25% of the rated value.

In order to improve the output voltage regulation under module loss conditions, new subsystem with adaptive gain is created as shown in Figure 9 in Appendix C. The same is incorporated in the reference current generation path of Figure 4.23, which gets activated on the occurrence of module loss conditions. The new simulation results are shown in Figures 4.26 (c), (d). These waveforms indicate very good regulation of the

**Figure 4.25**: THD of Current in Phase $a$ ($I_{sa}$) under Full Load Condition
output DC voltage close to reference voltage. Further it is observed that the working module(s) draw larger source current(s) for sustaining the required DC output voltage.

In Fryze Current Control Strategy, the impedance of each of the three phases remains the same which is understood from Figures 4.27 (a) to (c). The performance of the converter is analyzed by calculating various parameters as discussed in Section 4.4.3 and the results obtained are shown in Table 4.6.
The experimental results of the three phase modular boost converter using Hysteresis Controller with Generalized Fryze Current Control Strategy as reference current generation technique under unbalanced supply voltage conditions is shown in Figures 4.28.

Figure 4.28 (a) represents the regulated output DC Voltage \( V_o \) for a load current of 1.5 A. It is observed from Figures 4.28 (b) to (d) that the output DC voltage is maintained at the rated value for frequent step change in load and also for sudden increase/decrease in load. The waveforms in Figures 4.28 (e) and (f) show that the

---

**Figure 4.27**: Impedance of Phases \( a, b \) and \( c \)

**Table 4.6**: Performance of the Modular Boost Converter using Generalized Fryze Current Control Strategy (Hysteresis Controller)

<table>
<thead>
<tr>
<th>Load Current Io in amps</th>
<th>Output Voltage Vo in volts</th>
<th>Regulation in %</th>
<th>THD in %</th>
<th>Efficiency in %</th>
<th>Power factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.202</td>
<td>24.04</td>
<td>0.166</td>
<td>3.34</td>
<td>91.9</td>
<td>0.9247</td>
</tr>
<tr>
<td>1.335</td>
<td>24.04</td>
<td>0.166</td>
<td>3.27</td>
<td>92.2</td>
<td>0.9279</td>
</tr>
<tr>
<td>1.603</td>
<td>24.05</td>
<td>0.208</td>
<td>3.23</td>
<td>92.53</td>
<td>0.9325</td>
</tr>
<tr>
<td>1.85</td>
<td>24.05</td>
<td>0.208</td>
<td>3.18</td>
<td>92.7</td>
<td>0.9353</td>
</tr>
<tr>
<td>2.188</td>
<td>24.07</td>
<td>0.2916</td>
<td>3.18</td>
<td>92.82</td>
<td>0.9379</td>
</tr>
<tr>
<td>2.407</td>
<td>24.07</td>
<td>0.2916</td>
<td>3.17</td>
<td>92.8</td>
<td>0.9387</td>
</tr>
</tbody>
</table>
output voltage follows the change in the reference voltage accurately. It is observed from the nearly sinusoidal phase current waveforms shown in Figure 4.28 (g) that the wave shaping technique is effective. The DC output voltage with and without module loss condition is displayed in Figure 4.28 (h), which conveys that the controller varies the duty cycle of the operating module under module loss condition, so that there is only a small drop in output voltage under module loss condition.

Figure 4.28: Experimental Waveforms of Three Phase Modular Boost Converter with Generalized Fryze Current Control Strategy
The harmonic spectrum of current in phase $a$ is depicted in Figure 4.29 (a). Despite THD being equal to 18.2%, the power factor has improved significantly which is seen in Figure 4.29 (b). The power factor is monitored using power quality analyzer connected in the source side and it is found that the overall power factor remains at 0.96 and the displacement factor is also close to unity.

![Figure 4.29: (a) Harmonic Spectrum (b) Power, Power factor and Displacement factor](image)

One advantage of this circuit configuration is the ability to maintain the output voltage even under fault conditions leading to loss of one/two modules. This condition is introduced in the experimental set-up and the corresponding performance with respect to the effect on source current is examined. The source current waveforms for one and two module loss operations are shown in Figures 4.30 (a) and (b).
The output voltage is recorded and regulation is calculated for different load currents which are given in Table 4.7.

Table 4.7: Regulation of the Modular-Boost Converter using Generalized Fryze Current Control Strategy (Hysteresis Controller)

<table>
<thead>
<tr>
<th>Load Current $I_o$ in amps</th>
<th>0.96</th>
<th>0.97</th>
<th>0.99</th>
<th>1.02</th>
<th>1.09</th>
<th>1.13</th>
<th>1.17</th>
<th>1.2</th>
<th>1.26</th>
<th>1.3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output Voltage $V_o$ in volts</td>
<td>23.9</td>
<td>23.95</td>
<td>23.91</td>
<td>23.9</td>
<td>23.82</td>
<td>23.81</td>
<td>23.8</td>
<td>23.7</td>
<td>23.6</td>
<td>23.46</td>
</tr>
<tr>
<td>Regulation in %</td>
<td>-0.416</td>
<td>-0.208</td>
<td>-0.375</td>
<td>-0.416</td>
<td>-0.75</td>
<td>-0.79</td>
<td>-0.833</td>
<td>-1.25</td>
<td>-1.66</td>
<td>-2.25</td>
</tr>
</tbody>
</table>

4.5 Conclusion

In this chapter, the power factor correction and dc voltage regulation of Three Phase Modular Boost Converter using LQR and HC are presented. The regulation of DC bus voltage is achieved using PI based voltage controller in the voltage loop. The power
factor improvement by source current wave shaping is accomplished by employing suitable current controllers such as Linear Quadratic Controller and Hysteresis Controller in the respective phases under balanced and unbalanced supply voltage conditions respectively. The sinusoidal reference current template is generated by $pq$ theory for balanced conditions and extended $pq$ theory such as Sinusoidal Current Control method and Generalized Fryze Current Control method are used for unbalanced conditions. The simulation and experimental results for all the methods are observed and recorded. The performance of the suggested controllers is verified for module loss operation also. The results demonstrate that the input power factor is maintained more than 0.9, the DC voltage is well regulated for step load change and the dynamic response is good. The servo tracking of the output voltage to the desired reference value is also verified to be excellent.