CHAPTER 4

IMPLEMENTATION OF BOOST CONVERTER WITH COMPOUND ACTIVE CLAMPING IN FOUR SWITCH THREE PHASE INVERTER FED INDUCTION MOTOR

4.1 INTRODUCTION

In this chapter the performance of FSTPI fed induction motor with boost converter associated with compound active clamping is observed. The reverse recovery of the boost converter causes significant reverse recovery losses and a severe electromagnetic interference (EMI) problem when the main switch operates in hard switching condition. Hence, the converter needs an additional diode and an inductor to reduce the resonance between the winding inductor and parasitic capacitance. The proposed boost converter with compound active clamp is implemented with the FSTPI fed induction motor to observe the performance of the induction motor.

Jovanovic (1998) introduced inductor in series path of the boost switch and rectifier to reduce the losses caused by the reverse recovery current of the rectifier. In the above technique the stress of the rectifier is increased due to parasitic ringing between junction capacitance and winding inductor. Carlos Alberto Canesin et al (1999) designed and analyzed ZCS-PWM boost rectifier with single phase load due to turn off losses which provides system efficiency and power factor to the minimum level. Bo Feng et al (2005) designed compound active clamping PFC
The designed converter implemented with single phase load and performances are analyzed in terms of power factor, THD and efficiency by hardware. In the above converter the performances are affected due to minimum switching losses. In the present research work the simulation of compound active clamping boost converter with FSTPI fed induction motor drive is analyzed in the view of power factor, THD and efficiency. In Compound active clamp converter, the active clamping branch composed of a clamping capacitor and an active switch are placed in parallel with the resonant inductor. In the circuit, the main switch, the auxiliary switch, the clamping capacitor, the boost diode and the output capacitor form a voltage loop. The key idea is that except the switching periods, at any time during operation, two switching devices are conducting among the main switch, the auxiliary switch and the diode. Therefore the voltage across the switching device which is off is clamped. Thus the parasitic oscillation between the junction capacitance of the boost diode and the resonant inductor is eliminated.

4.2 COMPOUND ACTIVE CLAMPING (CAC) BOOST CONVERTER

The circuit of CAC boost converter is shown in Figure 4.1. The inductor $L_1$ is the boost inductor. The inductor $L_2$ and $C_C$ are used for soft switching of $S_3$. The duty cycle of the auxiliary switch $S_3$ is fixed. The duty cycle of the main switch $S_1$ changes with the input voltage and adjusted to get the required output voltage. When $S_1$ is turned on, the energy is stored in the inductor $L_1$. When $S_1$ is turned off, the energy stored in the inductor is supplied to the capacitor $C_0$. The boost converter circuit consists of a bridge rectifier to rectify the AC supply, two inductors $L_1$ and $L_2$, two switches $S_1$ and
S₃ and comparator to compare the output with the reference wave. The AC supply that is fed to the circuit is rectified using a bridge rectifier.

![Figure 4.1 Basic Circuit of CAC Boost Converter](image)

During initial operation, inductors L₁, L₂ and switch S₁ are connected to the bridge rectifier. When the switch S₁ is on, the inductors L₁ and L₂ store energy. Switch S₃ is connected in parallel with the inductor L₂ and it acts as an auxiliary switch. During the next stage switch S₁ is off and voltage across L₂ will appear across the load.

The following assumptions are made to simplify the analysis of the proposed CAC PFC converter.

Metal oxide semiconductor field effect transistor (MOSFET) is considered as an ideal switch with its diode.

The capacitance C₁ and C₃ paralleled with switches S₁ and S₃ respectively, include parasitic capacitance and external capacitance. The capacitance C₂ paralleled with the boost diode D₂ also includes parasitic capacitance and external capacitance.
The input filter inductor $L_1$ is very large that the current $i_{L}$ hardly change and can be considered as a constant current source in one switching cycle.

The output filter capacitor $C_0$ is represented by a constant voltage source.

The value of $C_C$ is large enough so that the voltage ripple across it is small.

The resonant frequency of $C_C$ and $L_2$ is much lower than the operating frequency of the converter.

In the proposed converter the main switch $S_1$ and the auxiliary switch $S_3$ do not operate in complementary mode. To clamp the voltage across the main switch $S_1$ and the diode $D_2$, the auxiliary switch $S_3$ is off only during a short time when both the main switch $S_1$ and the diode $D_2$ are commutating circuit. Thus, the duty cycle of the auxiliary switch $S_3$ is fixed. The duty cycle of the main switch $S_1$ changes with the input voltage.

4.3 SIMULATION RESULTS

4.3.1 Design procedure of simulation parameters

AC input voltage (rms) 90V-270V

Input frequency 47-53 Hz

Target efficiency is 95% (min) at 90V AC/1000W

The selection of CAC boost converter component is based on the following standard procedure:
Maximum input power, \( P_{in\ (max)} = \frac{P_o(max)}{\eta_{min}} = \frac{1000W}{0.95} = 1052 \text{ W} \)

Maximum rms input current, \( I_{in\ (rms)\ max} = \frac{P_{in\ (max)}}{V_{in\ (rms)\ min}} = \frac{1052}{90} = 11.69 \text{ A} \)

Maximum peak input current, \( I_{in\ (pk)\ max} = I_{in\ (rms)\ max} = 11.69 \times \sqrt{2} = 16.5 \text{ A} \)

Average input current, \( I_{in\ (avg)\ max} = \frac{2I_{in(pk)\ max}}{\pi} = \frac{2 \times 16.5}{\pi} = 10.5 \text{ A} \)

**Boost Capacitor**

Boost capacitor, \( C_{in} = K_{\Delta I_L} \cdot \frac{I_{in\ (rms)\ max}}{2\pi f_{sw} \times r \times V_{in\ (rms)\ min}} \)

\( K_{\Delta I_L} = \) Inductor current ripple factor (20% in this design)

\( r = \) maximum high frequency voltage ripple factor typically 3% to 9%

(5% used in this design).

Switching frequency, \( f_{sw} = 100000 \text{ Hz} \)

Boost capacitor \( C_{in} = 0.2 \times \frac{11.69}{2\pi \times 100000 \times 0.05 \times 90} \)

\( C_{in} = 10\mu\text{F}. \)

**Boost Inductor**

Peak input voltage, \( V_{in\ (pk)\ min} = \sqrt{2} V_{in(pk)\ min} = 90\sqrt{2} = 127\text{ V} \)

Peak boost transistor duty cycle

\[ D_{pk} = 1 - \frac{V_{in(pk)}}{V_o} = 1 - \frac{127}{400} = 0.6825 \]
Inductor ripple current

$$\Delta I_L = 0.2 \cdot I_{in} (pk) \max = 0.2 \times 16.5 = 3.3 \text{ A}$$

$$\Delta I_L$$ is based on the assumption of 20% ripple current

Peak inductor current, $$I_L (pk) \max = I_{in} (pk) \max + \frac{\Delta I_L}{2}$$

$$= 16.5 + \frac{3.3}{2} = 18.15 \text{ A}$$

Inductance, $$L = \frac{V_{in (pk) min \times Dpk}}{f_{sw} \times \Delta I_L}$$

$$= \frac{127 \times 0.6825}{100000 \times 3.3} = 5 \text{ mH}$$ is selected

Output Capacitor

The value of the output capacitor impacts hold up time and ripple voltage. In this design, the criterion for selection of this capacitor is the amount of tolerable ripple in the output voltage.

Output capacitor, $$C_{out} = \frac{P_o}{v_o \cdot 2\pi f_r \times \Delta V}$$

where $$f_r$$ is the frequency of the rectified sine wave and $$\Delta V$$ is desired peak to peak output voltage ripple. Therefore,

Output capacitor, $$C_{out} = \frac{1000}{2\pi \times 100 \times 0.03 \times 400} = \frac{2.5}{7536} = 330 \mu\text{F}$$
**Clamping Circuit**

Before the initial stage, the boost diode is conducting, the auxiliary switch $S_3$ is turned off. After that the current in $L_1$ charges the parasitic capacitance $C_3$ paralleled with $S_3$ and discharges the parasitic capacitance $C_1$ paralleled with the main switch $S_1$. At an initial stage, the voltage across $S_1$ decreases to zero and the diode of $S_1$ starts to conduct. Then $S_1$ is turned on under zero voltage condition. The voltage across $S_3$ is clamped at $V_o + V_{cc}$. During this stage, the current in $D_2$ is decreasing, while the current in $S_1$ is increasing at the same rate with $D_2$. The current changing rate is determined by the resonant inductor $L_1$.

\[
\frac{dI_{L1}}{dt} = \frac{V_o}{L_1}
\]

The design specifications of CAC PFC converter are presented as given below:

- Input voltage, $V_{in} = 90$ to $260 V_{rms}$
- Output voltage, $V_o = 400 V$
- Output power, $P_{out} = 1 KW$
- Switching frequency, $f_s = 100$ KHz

Maximum input current, $I_{L(max)} = \frac{P_{out}}{V_{in min}} \sqrt{2}$

\[= 15.7 A\]

The selection of the resonant inductor $L_1$ is determined by the need to suppress the diode reverse recovery current. Normally, the current change should be lower than $100 A/\mu s$. Therefore,

\[L_1 = \frac{400}{100 A/\mu s} = 4 \mu H\]
Increasing \( L_1 \) can achieve good effects in suppressing the reverse recovery current. But increasing \( L_1 \) can increase the voltage stress on the switches, which will make it hard to choose the power MOSFET. Hence the inductance of 10\( \mu \)H is selected. The selection of the clamping capacitor \( C_C \) should ensure that the resonant frequency of \( C_C \) and \( L_1 \) is much lower than the operating frequency of the main switch, so

\[
\frac{1}{2 \pi \sqrt{L_1 C_C}} \leq 100 \text{ KHz}
\]

Hence the selected capacitance of \( C_C \) is 4.7\( \mu \)F.

Simulation tests were performed on the proposed boost converter with compound active clamping FSTPI fed induction motor. The parameters of the induction motor are given below.

- Stator resistance, \( r_s \) = 1.11\( \Omega \), Rotor resistance, \( r_r \) = 1.08\( \Omega \)
- Stator inductance, \( l_s \) = 0.006H, Rotor inductance, \( l_r \) = 0.006H
- Mutual inductance, \( M \) = 0.20H
- Poles, \( P \) = 2
- Moment of inertia, \( J \) = 0.02Kg m\(^2\)
- Co. Efficient of viscous friction, \( F \) = 0.00575 Nm/ (rad/sec)

The parameters used in the simulation are

- Nominal line voltage \( (V_{ac}) \) :200V
- Output Voltage \( (V_o) \) :200V DC
- Output power \( (P_o) \) :1KW
Boost inductor : 2mH
Output capacitor : 330µF
Clamping Inductor : 4µH
Clamping Capacitance : 4.7µF
Switching frequency : 100 KHz

Figure 4.2 shows the circuit of FSTPI fed induction motor with boost converter with compound active clamping. Inductor $L_1$ is the boost inductor. Inductor $L_2$ and $C_c$ are used for soft switching of $S_2$. The duty cycle of $S_1$ is adjusted to get required DC voltage at the input of the three phase four switch inverter. When $S_1$ is turned on, the energy is stored in the inductor $L_1$ and when $S_1$ is turned off, the energy in the inductor is supplied to the capacitor $C_o$. Switch $S_2$ connected in parallel with the inductor acts as an auxiliary switch. This prevents resonance between $L_1$ and the internal capacitance of the diode $D_5$.

Figure 4.3 shows the power factor measurement circuit of boost PFC converter. It can be seen that the power factor achieved is 0.999 when compared to the power factor of 0.990 for the existing soft switched PFC boost converter. The power factor is improved due to the clamping of maximum voltage across the main switch and also the voltage ringing across the diode is removed. Figure 4.4 presents the switching pulses applied to switches M1 and M2. Figure 4.5 illustrates the phase voltage applied to the three phase induction motor.
Figure 4.2 Four Switch Three Phase Inverter Fed Induction Motor System with Compound Active Clamping
Figure 4.6 shows the efficiency of three phase induction motor in which boost converter with compound active clamping FSTPI is used. It can be seen that the efficiency has improved to 95%. In the proposed converter switching losses are reduced due to the implementation of a simple active snubber circuit, which provides zero voltage switching conditions for all the switches. The reduced number of components increases its efficiency and makes it suitable for practical applications including AC drive systems, power factor correction, UPS and induction heating. The result shows that the better performance of designed converter than existing soft switched PFC boost converter which has only 94% of efficiency as seen Figure 4.7.

![Power Factor Measurement of Boost Converter with Compound Active Clamping](image)

**Figure 4.3** Power Factor Measurement of Boost Converter with Compound Active Clamping
Figure 4.4  Driving Pulses

Figure 4.5  Phase Voltage
Figure 4.6 Output Power Vs Efficiency of Boost Converter with Compound Active Clamping FSTPI Fed Induction Motor

Figure 4.7 Output Power Vs Efficiency of soft switched PFC boost converter
Figure 4.8  FFT Analysis for Boost Converter with Compound Active Clamping FSTPI Fed Induction Motor

Figure 4.9  FFT Analysis for soft switched PFC boost converter
Figure 4.8 shows the FFT analysis for current of boost converter with compound active clamping FSTPI fed induction motor. It can be seen that the THD is reduced to 2.22% compared to the value of 4.85% in the case of the existing soft switched PFC boost converter designed by Luiz Henrique Silva Colado Barreto (2005). The THD waveform of existing soft switched PFC converter is shown in Figure 4.9. The performance comparison of designed converter and an existing CAC converter is revealed in Table 4.1.

Table 4.1 Performance comparison between existing converter and proposed CAC converter

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Performance of existing converter</th>
<th>Performance of proposed CAC converter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency</td>
<td>70</td>
<td>75</td>
</tr>
<tr>
<td>Power Factor</td>
<td>0.94</td>
<td>0.998</td>
</tr>
<tr>
<td>THD</td>
<td>2.22%</td>
<td>4.85%</td>
</tr>
</tbody>
</table>


4.5 CONCLUSION

The boost converter employing compound active clamping with FSTPI fed induction motor drive has been simulated using matlab/simulink in this chapter. The designed boost converter with compound active clamping needs an additional diode and an inductor to reduce the resonance between winding inductance and junction capacitance. The designed converter is
implemented with the FSTPI fed induction motor and performances have been observed. From the simulation results, the input power factor has been observed to be 0.999 compared to a value of 0.990 in the case of the existing soft switched PFC boost converter. The result shows that the efficiency of induction motor has improved to 95% compared to the existing converter which has only 94% of efficiency. From the result the THD is observed to be 2.22%. The THD is reduced much lower than the existing converter which has a value of 4.85%. The performance comparison shows that the designed converter provides better performance than the existing soft switched PFC boost converter.