Input Current Improvement of a Three Phase Rectifier by C^uk Regulator

By

Ruma

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APPROVAL

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<td>Switch Mode Power Supply</td>
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<tr>
<td>IGBT</td>
<td>Insulated Gate Bipolar Transistor</td>
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<tr>
<td>PWM</td>
<td>Pulse Width Modulation</td>
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<td>OPAMP</td>
<td>Operational Amplifier</td>
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<tr>
<td>rms</td>
<td>root mean square</td>
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<td>EMI</td>
<td>Electromagnetic Interference</td>
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<td>THD</td>
<td>Total Harmonic Distortion</td>
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<td>SMRR</td>
<td>Switch Mode Regulated Rectifier</td>
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AC to DC conversion is a very common need in many applications. The conversion is usually accomplished by controlled or uncontrolled single phase or three phase rectifiers. Rectifiers are popular in industrial and commercial applications due to their low ripple contents in the voltage waveform and capability of high power handling capacity with light weight small diode circuits. But their non sinusoidal input current, low power factor and low efficiency create problems for utilities. In this respect, switch mode regulated rectifier offer efficient, compact, high efficiency operation. The improvement of input current is possible by the addition of Boost or C^uk regulator with single or three phase rectifier. A high frequency pulse width modulation (PWM) technique is used to control the switching device of Boost or C^uk regulator in such rectifiers. In this thesis, a three phase rectifier is analyzed with Boost regulator and then with C^uk regulator. Same low pass filter made the input current almost sinusoidal in both the cases. But high THD and resonance problem remains. This thesis work shows, when a high frequency harmonics filter is attached with passive filter, the improvement of input current is observed at the highest level. Power factor is found almost unity and efficiency is improved in both cases. It is seen that, the C^uk rectifier is more advantageous than Boost rectifier. Because in C^uk rectifier the input current is smooth and continuous due to the capacitive energy transfer. It provides the facility of control of output voltage lower or greater than input voltage by the wide variation of duty cycle. Moreover, C^uk rectifier draws lower input current than that of Boost rectifier for similar loads.
1.1 Introduction

Majority of power electronic equipments are operated with dc supply. For reliable and stable operation, dc supply should be regulated. The regulation can be performed by using Buck, Boost, Buck-Boost and C^uk regulators. Power devices, circuits and techniques are available to improve the quality of the input power of these regulators. All power electronic equipments are fed from ac utility lines. Traditionally, ac to dc conversion is achieved by single phase or three phase diode bridge rectifier between source and load. Except single phase rectifier with resistive load all other rectifiers input currents are non-sinusoidal in nature. Input line current disturbance occurs due to variation of sources, variation of loads, voltage fluctuations, switching losses of diodes, iron losses of inductors, electromagnetic and radio frequency interference of inductors and capacitors. Input line current distortion leads to low power factor, high THD, distribution system losses, neutral harmonic currents, excitation of system resonances, over rated power equipments and other problems in a power system. In addition, the presence of harmonics in line currents may lead voltage and current distortion, create additional heating and over voltage problems, loading and losses in the utility distribution systems. Improvement of input current is a very important issue at present. By reduction of harmonics from distorted input current and improvement of power factor to unity better input current is possible. The addition of active or passive LC filter may be need for solution to this problem. Researchers have developed methods to reduce above mentioned problem. But large size and bulky filter are their drawbacks. Traditionally Boost converters has been proposed at the output of single phase or three phase diode bridge rectifiers. The limitation of this arrangement is that it provides only greater output voltage than input voltage and output voltage is uncontrollable. But both greater and less output voltage is practical requirement Few three phase Buck-Boost, C^uk ac/dc converters have been proposed to offer step-up/down capability to meet this requirement. So far, no study has been reported in literature to make input current sinusoidal using C^uk converter for three phase rectifiers. The aim of this research is to develop a C^uk
regulator with improved input current quality and good efficiency which will be practically implementable.

1.2 Literature Review

A switch mode regulator based on C^uk principle has been proposed in [1] to regulate ac voltage to a desired value irrespective of the input voltage and load. This regulator provides a negative polarity regulated output voltage with respect to the common terminal of the input voltage. It has the ability to change output voltage in wide range by variation of duty cycle. But, in this work limited range of variation of load and input voltage has been analyzed. The size of regulator becomes large which causes higher losses. As a result the efficiency is found to be poor. No analysis has been done to improve the input current. Where, input current quality is an important factor to improve the performance of any regulator. The proposed model of this thesis may be able to overcome the following problem by design of a proper filter and small size regulator.

A three phase rectifier based on Boost topology has been proposed in [2]. Here, active switching pulse width modulation (PWM) module has been studied to improve input side currents. The nature of Boost regulator is to provide greater output voltage than input voltage. But, both greater and less output voltage than input voltage is the practical requirement. The output voltage is very sensitive with change in duty cycle. So it is difficult to stabilize the regulator. In this work, large size EMI and series resonating filter have been used with parameter L_1=50mH, C_1=500uF, L_2=15.83mH and C_2=0.1mF. Though, input current is found sinusoidal with high efficiency, it is not practically implementable due to large voltage drop across filter. Electromagnetic interference also increases which badly affects the performance of the regulator.

A single stage push-pull Boost converter has been proposed in [3]. It presents a dc/dc Boost converter with improved integrated magnetic and low ripple input current. The proposed structure includes a Boost inductor, coupling capacitor and a capacitor network, a step-down transformer and four diodes for switching. A constant duty cycle (greater than 50%) is used to switch the diodes. At this duty cycle, overlapping conduction
problem occurs. Diodes are poor switching elements due to switching stresses, losses and commutation problem across them. Coupling capacitor should be nearly infinity to achieve low ripple input current which results high current stress. The amount of leakage reactance and mutual reactance is very high due to transformer and inductive network which influence the regulation of the transformer or the conversion efficiency of the Boost converter. Core losses and copper losses occur in magnetic core and coil of the transformer which dissipated in the form of heat and raises its temperature. If temperature exceeds the permissible limit, it may damage the insulation of the core and short the transformer. As a result, converter may burn out. The proposed model without transformer may be helpful to reduce such problem and become more useful.

An active power factor correction technique for three phase diode rectifiers has been proposed in [4]. This paper addresses the analysis and design of a three phase ac to dc conversion with Boost topology. A three phase rectifier handles high input current harmonics and low input power factor. Low power factor increases the reactive power requirement causing increased losses. The output voltage of this topology is always greater than input voltage. With slight variation of duty cycle output voltage varies widely and becomes uncontrollable. The input and output current is found to be discontinuous. But for smooth load change input and output currents should be continuous. Discontinuous input current increases ripple amplitude and electromagnetic interference (EMI). Voltage stresses and switching stresses is another drawback of this method.

Three phase PWM Buck-Boost rectifier has been proposed in [5]. A C^\text{uk}-C^\text{uk} bidirectional ac-dc converter with power regenerating capability is presented in this references. This structure can process both inversion and rectification function. Here, gate pulses are generated by zero voltage space vector realization to control the switching element. High order harmonic control analysis has been done. Combination of rectification and inversion function increases the complexity of operation and control of the scheme. Pulse generation is difficult because it is divided into three classes which increases difficulty of implementation. But, simplicity is a high consideration to design a
regulator. The amount of input current was found very high. No analysis has been reported to reduce the input current.

A novel high performance voltage regulator for single-phase ac sources has been presented in [6]. It offers both rectification and inversion facility in the same circuit. It is a single phase regulator having a common capacitive arm between the rectifier and inverter. For switching function pulse generation, a digital signal processor TMS320F240 has been used. It is a fully digital controller. So proper algorithm and hardware have to be designed for each power converter and calculate the required PWM duty ratio. The size of regulator becomes large due to large number of self turn on/off switches. It has control complexity and high cost. From economical view, the design should be less expensive as much as possible with high power quality.

An ac voltage regulator based on Buck-Boost conversion principle has been proposed in [7]. The ac Buck-Boost regulator has the ability to regulate the output voltage to the desired value. But the input power factor of the regulator is very low, which is less than 0.5 and which decreases with duty cycle. Due to very low input power factor, the input current becomes high and distorted which causes higher loss. As a result the efficiency is found to be low. This inefficient design of the input and output filter lacks proper free-wheeling path.

A power factor correction of a diode bridge rectifier has been proposed in [8]. This rectifier uses duel slope delta modulation technique to generate gate pulses. Window width variation changes the switching frequency. Slope of modulated wave is varied for output voltage variation. Input current and output voltage wave forms are found distorted. Harmonic distortion is also high due to inefficient design of input and output filter.

An improved ac voltage regulator has been proposed in [9]. It has been analyzed for manual and automatic control of ac voltage regulator. The proposed configuration can maintain constant output voltage at various input voltage and load. Output voltage can be made constant by varying the duty cycle of the control circuit automatically through
electronic control circuit. The input current is found almost sinusoidal and power factor is also found almost unity. But, the regulator becomes bulky due to large input and output filter and for using a low frequency transformer at the output. From economical view, the design of input and output filter should be as small as possible. Efficiency decreased due to large impedance, high magnetic leakage and leakage reactance.

A unity power factor rectifier has been presented in [10]. In this paper a novel active power factor correction technique named scalar control is proposed and analyzed. The control scheme is provided for single phase Boost converter, where, power factor controller is independent of input voltage. A large output capacitor is used to correct the power factor. For large capacitor power factor will improve and ripple of output voltage will reduce but will create higher peak current in input side and cause unstable output. This method is suitable only to control the single phase power flow. If it is implemented to control three phase power flow then difficulty will arise.
1.3 Objective of Thesis

The objective of the thesis is to design, analyse and propose a practically implementable high frequency switching ac to dc voltage regulator. Through the proposed regulator output voltage can either be stepped up or stepped down. Switch mode converters are used to regulate dc to dc output voltage. To achieve the goal of ac to dc regulation here C^uk converter will be combined with a three phase full diode bridge rectifier. A control circuit with constant frequency switching is to be associated with the power circuit for generating gate pulse of the switching element. Output voltage can be made variable by changing duty cycle. Duty cycle is to be controlled by changing a reference voltage within a permissible limit. It is observed in recent works that rectifier size becomes bulky and to get ripple free sinusoidal input current, filter size also becomes large. Our objective is to obtain a regulator having small size by the design of a small size input filter to provide sinusoidal input current and a unity power factor.

The specific objectives of the present research work are as follows:

(a) A new modified C^uk topology will be investigated to shape the input current shapes of a three phase rectifier.
(b) Simulate and study of the proposed new scheme for input current improvement of a three phase rectifier.
(c) To design the input filter to reduce the total harmonic distortion and hence reduce the input current of the converter.
(d) To increase the efficiency of the converter by analyzing losses in the switching devices and other elements in the circuit and implement suitable remedies.
(e) To analyze the result, furthermore, comparison of performance between simulated result considering switches to be ideal and practical.

It is expected that this study will yield a three phase rectifier with better input power quality which will be practically implementable.
1.4 Outline of The Thesis

Chapter-1 contains introduction of three phase rectifier and switch mode regulated rectifier (SMRR). This chapter also includes objective of thesis work and outline of the thesis.

Chapter-2 deals with the major part of this thesis. A three phase diode rectifier without filter and then with passive filter has been studied. It also represents the analysis of three phase Boost rectifier without filter, with passive filter and with harmonic filter. The analysis of C^UK rectifier is also included in chapter- 2 without filter, with passive filter and with harmonic filter. Simulated results, wave shapes and graphical representations are also included in this chapter.

Chapter-3 concludes the thesis with conclusion, summary and suggestion on future works.
2.1 Input Current of Three Phase Uncontrolled Rectifier

In industrial and commercial applications where three phase ac voltage are available, it is preferable to use three phase rectifier circuits, compared to single phase rectifiers because of their lower ripple content in the waveforms and a higher power handling capability. There are two types of rectifiers namely diode rectifier (uncontrolled) and thyristor rectifier (controlled) for ac to dc conversion. Since these rectifiers draw non-sinusoidal currents, the power quality of the distribution network is greatly deteriorated, resulting in low efficiency of utilities. The power factor of a three phase rectifier with resistive load remains close to unity. But with reactive load the power factor becomes lower. It is possible to improve input current to sinusoidal and power factor to unity by applying various control strategy. Here a diode bridge three phase rectifier is discussed with resistive load because of their simplicity and ideal characteristics.

Figure 2.1: Circuit diagram of three phase rectifier with resistive load

A three phase six diode full wave rectifier is shown in Figure 2.1. The rectifier is fed from a three phase star connected ac utility source having constant voltage of amplitude and at constant frequency. Each phase is apart by 120° from each other. If $V_m$ is the peak
value of the phase voltage, then the instantaneous phase voltages can be described by equation (1), (2) and (3) respectively.

\[
V_a = V_m \sin(\omega t) \quad (1) \\
V_b = V_m \sin(\omega t - 120^\circ) \quad (2) \\
V_c = V_m \sin(\omega t - 240^\circ) \quad (3)
\]

Figure 2.2: Input voltage of three phase rectifier

The input voltage wave form in the circuit is shown in Figure 2.2. The diode of each phase conducts in \(D_1D_2, D_3D_2, D_3D_4, D_5D_4, D_5D_6\) and \(D_1D_6\) sequences through highest positive line to line voltage. The input current waveforms in the circuit of phase a, b and c are shown in Figure 2.3.
The operation of the rectifier can be explained from the above figure. It is seen that the period of one cycle is 20ms. Consider the first period of each phase. From 0 to 5ms, diode $D_1$ and $D_3$ conducts with highest positive voltage in phase a and b, diode $D_2$ is conducts with highest negative voltage in phase c. Then $D_3$-$D_2$ and $D_1$-$D_2$ makes close path and allows to flow of current from phase b to c and a to c through load. From 5 to 10ms, diode $D_1$ and $D_5$ conducts with highest positive voltage in phase a and c, at the same time diode $D_6$ conducts with highest negative voltage in phase b. Then $D_1$-$D_6$ and $D_5$-$D_6$ makes close path and allows to flow of current from phase a to b and c to b through load. Similarly, from 10 to 15ms the current flows from phase c to b and then from c to a, from 15 to 20ms the current flows from phase b to a and b to c. It is seen that, in every cycle diode $D_1$, $D_3$, $D_5$ conducts positively for 120° and $D_2$, $D_4$, $D_6$ conducts negatively for 120°. No diode conducts for 120° in a cycle. So, input current in each phase is found zero at that time. The waveforms of output voltage ($v_o$) and current ($i_o$) across the load $R$ is shown in Figures 2.4 and 2.5 respectively.
It is observed that the instantaneous waveforms of $v_o$ and $i_o$ consists of six segments per cycle. Each segment belongs to one of the six line to line voltage combinations.

The performance parameter of three phase rectifier with resistive load is shown in Table 1. The above analysis shows that input current is non-sinusoidal and contains THD% of 30.89%. The output voltage and current are not pure dc. The solution of such problem is to use filter in input and output side.
Table 1: Performance parameter of three phase rectifier with resistive load

<table>
<thead>
<tr>
<th>THD</th>
<th>PF(cose)</th>
<th>Iin(rms)amp</th>
<th>Vin(rms)volt</th>
<th>Vout(dc)volt</th>
<th>Iout(amp)volt</th>
<th>Efficiency(η%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3089</td>
<td>0.86</td>
<td>11</td>
<td>212.13</td>
<td>500</td>
<td>10</td>
<td>100</td>
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</tbody>
</table>
2.1.1 Input current shaping of three phase rectifier by passive filter

The efficient performance of a three phase rectifier depends on the quality of input current, output voltage and power factor. The input and output power is calculated from the equation (4) and (5).

\[ P_{in} = 3V_{in} I_{in} \cos \theta \]  
\[ P_o = V_o I_o \]

It is observed from discussion that input current becomes non-sinusoidal. The presence of harmonics in input current can cause several problems as follows,

i) Draws large rms values of the input current which increase the volt ampere ratings of the utility equipments such as generator, transmission line and transformer,

ii) Causes stability problem in source application.

iii) Reduce power factor means reduced capacity of the line to supply energy.

iv) Create noises, over voltage and loading in power equipments.

v) Resonance may occur between the capacitors and rectifiers circuit in the system which can blown fuses and damage capacitors and other electronic equipment.

vi) Create additional heating problem due to \( I^2R \) losses in wire

vii) Causes lower rectifier efficiency due to large rms value of input current and

viii) Can lead to flow large current in neutral conductor in three phases, four wire system which may easily exceed the conductor's rms current rating.

Owing to these facts and the adoption of IEEE standards 1000-3-2 [20], there is need for power supply that draws current with low harmonic content and also have power factor close to unity. In this respect, the use of the passive and active filter may be one of the desired solutions.
Now, the three phase rectifier is analyzed with passive LC filter to combat such problem. Passive filter acts as a sink to the harmonic current. The circuit is simulated with various filter parameters. When input filter is designed with parameter $L = 25\,\text{mH}$ and $C = 100\,\mu\text{F}$, then the input current is observed to be pure sinusoidal with low harmonics. The output voltage ripples can be eliminated using another filter in output before load. When use output filter with parameter $L = 25\,\text{mH}$ and $C = 100\,\mu\text{F}$ is used, the output voltage and current observed are nearly dc. The circuit diagram including input and output filter is shown in Figure 2.7. The wave shapes of output voltage and currents are shown in Figure 2.8. The input current and its spectrum are shown in Figures 2.9 and 2.10 respectively. The performance parameter of three phase rectifier with passive filter is shown in Table 2.
Figure 2.8: Output voltage and Output current of three phase rectifier with input and Output filter

Figure 2.9: Input current of three phase rectifier with input and output filter
From the above discussion, it is seen that, though harmonics becomes low and output voltage becomes ripple free, the filter size is very large. For this, reactive component of the circuit increases which increase the input and output impedance. A large amount of voltage is dropped across them and increases the energy losses. As a result desired level of gain and efficiency will not be achieved.

Table 2: Performance parameter of three phase rectifier with passive filter

<table>
<thead>
<tr>
<th>THD</th>
<th>PF(cosa)</th>
<th>Iin(rms)amp</th>
<th>Vin(rms)volt</th>
<th>Vout(dc)volt</th>
<th>Iout(amp)volt</th>
<th>Efficiency(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.782</td>
<td>70</td>
<td>212.13</td>
<td>1100</td>
<td>22</td>
<td>100</td>
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</tbody>
</table>
2.1.2 Input current shaping of three phase rectifier by Boost regulator and passive filter

From previous discussion it is clear that, a three phase rectifier suffers from several problems such as power flows from input to output unidirectionally and it cannot be controlled. The output voltage is uncontrolled. The filter size becomes very large. In many applications output voltage is required to be regulated and power is required to be controlled. In this circumstance, switch mode rectifiers have gained attention as a solution, since they draw almost sinusoidal current with low harmonics and provide a voltage control strategy. The addition of a single switch boost regulator between rectifier and load can be a good solution. Boost rectifier is very popular because of simple control strategy and high output voltage with small ripple. The power factor correction is also possible by shaping of input current. Here, a control circuit is used to control the boost switch. In control circuit, pulse width modulation (PWM) technique is used to generate required gate pulse of Boost switching element of varying duty cycle. Duty cycle is varied with change of reference voltage $V_{dc}$ in control circuit. The PWM control not only can manage the active power, but reactive power also, allowing this type of rectifier to correct power factor. Besides, the ac current waveforms can be maintained almost sinusoidal, reducing harmonic contamination to the main supply.

2.1.2.1 Boost rectifier analysis without filter

The circuit diagram of single switch Boost rectifier is shown in Figure 2.11. The wave shape of input current and frequency spectrum at $D=0.2$, $D=0.5$ and $D=0.8$ are shown in Figures 2.12 to 2.17 respectively. It is found that, input current is non-sinusoidal in nature and it has harmonic contents including $5^{th}$, $7^{th}$, $11^{th}$, $13^{th}$, $17^{th}$ and so on. The current distortion is quantified by the total harmonic distortion (THD) parameter. The value of THD is calculated by the equation (6)

$$\text{THD}\% = \frac{\sqrt{\sum_{h=2}^{b=\infty} (I_h)^2}}{I_1} \times 100 \quad (6)$$

Where, $I_h$ is the harmonic components of input current and $I_1$ are the fundamental component of the input current. The performance parameter of a single switch boost
rectifier is shown in Table 3. Performance parameter represents the quality of input current, output voltage, THD and power factor. It is seen that, at duty cycle \( D = 0.2 \) the rms values of input current is 49.49 amp, output voltage is 800V, pf is 0.845 and THD\% is 32.91\%. For others values duty cycle of the parameter are presented in the Table3. Higher THD\% is observed at \( D = 0.95 \) and it is 71.35\%.

Figure 2.11: Circuit diagram of a Boost rectifier without filter

The wave shape of output voltage is shown in Figures 2.18 to 2.20 for duty cycles of 0.2, 0.5 and 0.8 respectively. It is seen that, output voltage has large ripple. For switching action output voltage ripple increases, which is also represented as current harmonics in input side. The higher the ripple, the larger the input current harmonics. The improvement can be achieved in two ways. First one, elimination of harmonics from input current adding a passive filter in input side and second one, reduction of the ripple at the output using LC filter at output. Results of Table 3 are presented in graphical form in Figures 2.21 to 2.24.
Figure 2.12: Input current wave shape of Boost rectifier without filter at D = 0.2

Figure 2.13: Frequency spectrum of Boost rectifier without filter at D = 0.2
Figure 2.14: Input current wave shape of Boost rectifier without filter at D=0.5

Figure 2.15: Frequency spectrum of Boost rectifier without filter at D=0.5
Figure 2.16: Input current wave shape of Boost rectifier without filter at $D=0.8$

Figure 2.17: Frequency spectrum of Boost rectifier without filter at $D=0.8$
Figure 2.18: Output voltage wave shape of Boost rectifier without filter at $D = 0.2$

Figure 2.19: Output voltage wave shape of Boost rectifier without filter at $D = 0.5$
Figure 2.20: Output voltage wave shape of Boost rectifier without filter at D=0.8

Figure 2.21: The graph of THD vs duty cycle of Boost rectifier without filter
Figure 2.22: The graph of power factor vs duty cycle of Boost rectifier without filter

Figure 2.23: The graph of output voltage vs duty cycle of Boost rectifier without filter
Figure 2.24: The graph of Efficiency vs duty cycle of Boost rectifier without filter
Table 3: Performance parameter of Boost rectifier without filter

<table>
<thead>
<tr>
<th>Duty cycle (D)</th>
<th>THD</th>
<th>PF(cosθ)</th>
<th>lin(rms)amp</th>
<th>Vin(rms)volts</th>
<th>Vout(dc)volts</th>
<th>Ion(amp)volts</th>
<th>Efficiency(%)</th>
</tr>
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<td>0.2</td>
<td>0.3291</td>
<td>0.845</td>
<td>49.49</td>
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<td>800</td>
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<td>0.4</td>
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<td>35.35</td>
<td>212.13</td>
<td>1000</td>
<td>20</td>
<td>98.54</td>
</tr>
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<td>0.5</td>
<td>0.55</td>
<td>0.867</td>
<td>29.69</td>
<td>212.13</td>
<td>900</td>
<td>18</td>
<td>98.86</td>
</tr>
<tr>
<td>0.6</td>
<td>0.5749</td>
<td>0.869</td>
<td>22.62</td>
<td>212.13</td>
<td>780</td>
<td>15.4</td>
<td>97.23</td>
</tr>
<tr>
<td>0.8</td>
<td>0.6205</td>
<td>0.903</td>
<td>12.72</td>
<td>212.13</td>
<td>600</td>
<td>12</td>
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<tr>
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<td>0.6392</td>
<td>0.86</td>
<td>11.45</td>
<td>212.13</td>
<td>560</td>
<td>11.2</td>
<td>100</td>
</tr>
<tr>
<td>0.9</td>
<td>0.5939</td>
<td>0.847</td>
<td>11.17</td>
<td>212.13</td>
<td>550</td>
<td>11</td>
<td>100</td>
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<td>0.95</td>
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<td>0.819</td>
<td>10.46</td>
<td>212.13</td>
<td>520</td>
<td>10.4</td>
<td>100</td>
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2.1.2.2 Boost rectifier analysis with passive filter

To improve the performance of a switching mode rectifier with power factor correction, the quality of input current is an important parameter. To improve the input current quality the Boost rectifier is analyzed with passive input filter and output LC filters. The best model for passive filter is obtained with parameter $L = 10\, \text{mH}$ and $C = 5\, \text{uF}$. At first, it is analyzed with single passive filter with parameter $L = 10\, \text{mH}$ and $C = 70\, \text{uF}$. But the performance parameter of the rectifier was not found good. Then it is analyzed with the filter as shown in Figure 2.25. The wave shapes of input current, frequency spectrum and output voltage at duty cycle 0.2, 0.5 and 0.8 are shown from Figures 2.26 to 2.35. The performance parameter is shown in Table 4. It is found that, the ripple of output voltage is greatly reduced. The input current becomes near to sinusoidal and power factor is also improved. The THD% is reduced from 32.91% to 4.35% at $D= 0.2$ and from 71.35% to 24.26% at $D= 0.95$. Even though the quality of input current is improved than previous condition, some distortion is still present. Analyzing the input current with Fourier spectrum, it is seen that input current contains $5^{\text{th}}$, $7^{\text{th}}$, $11^{\text{th}}$ harmonics. Among these the value of $5^{\text{th}}$ order harmonics are higher than others. If it is possible to eliminate the $5^{\text{th}}$ order harmonics from input current then the quality of current will improve. The THD values will be decreased and power factor will also increase. A simple way to reduce the $5^{\text{th}}$ order harmonics and to improve the THD with variable duty cycle is to use a harmonics filter with passive filter. Results of Table 4 are presented graphical form in Figures 2.36 to 2.39.
Figure 2.25: Circuit diagram of Boost rectifier with input passive filter and output LC filter.

Figure 2.26: Input current and input voltage of Boost rectifier with passive filter at D=0.2.
Figure 2.27: Input current wave shape of Boost rectifier with passive filter at $D=0.2$

Figure 2.28: Frequency spectrum of Boost rectifier with passive filter at $D=0.2$
Figure 2.29: Input current wave shape of Boost rectifier with passive filter at D=0.5

Figure 2.30: Frequency spectrum of Boost rectifier with passive filter At D=0.5
Figure 2.31: Input current wave shape of Boost rectifier with passive filter at D=0.8

Figure 2.32: Frequency spectrum of Boost rectifier with passive filter at D=0.8
Figure 2.33: Output voltage of Boost rectifier with passive filter at $D = 0.2$

Figure 2.34: Output voltage wave shape of Boost rectifier with passive filter at $D = 0.5$
Figure 2.35: Output voltage wave shape of Boost rectifier with passive filter at $D = 0.8$

Figure 2.36: The graph of THD vs duty cycle of Boost rectifier with passive filter
Figure 2.37: The graph of Power factor vs duty cycle of Boost rectifier with passive filter

Figure 2.38: The graph of Output voltage vs duty cycle of Boost rectifier with passive filter
Figure 2.39: The graph of Efficiency vs duty cycle of Boost rectifier with passive filter
Table 4: Performance parameter of Boost rectifier with passive filter

<table>
<thead>
<tr>
<th>Duty cycle (D)</th>
<th>THD</th>
<th>PF (cos φ)</th>
<th>(\text{lin(rms)} \text{amp} )</th>
<th>(\text{Vin(rms)} \text{volt} )</th>
<th>(\text{Vout(dc)} \text{volt} )</th>
<th>(\text{lout(amp)} \text{volt} )</th>
<th>Efficiency (η%)</th>
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<td>14</td>
<td>73.5</td>
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<td>212.13</td>
<td>700</td>
<td>14</td>
<td>85.9</td>
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<td>0.121</td>
<td>0.964</td>
<td>15.55</td>
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<td>0.1813</td>
<td>1</td>
<td>10.6</td>
<td>212.13</td>
<td>560</td>
<td>11.2</td>
<td>92.5</td>
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<td>8.13</td>
<td>212.13</td>
<td>500</td>
<td>10</td>
<td>96.6</td>
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2.1.2.3 Boost rectifier with harmonics filter

In order to eliminate 5th harmonics of 250Hz, a harmonics filter at the input side is added with Boost rectifier. A filter is designed using formula with resonating frequency 250Hz. Putting the resonating frequency, the product of LC is calculated as 4.053*10^-7. Changing the various values of L and C, it is closely observed that better performance of the filter is found by L=8.106mH and C=50uF. An output filter with low parameter is added before load to eliminate the ripple of output voltage. The schematic circuit diagram is shown in Figure 2.40. The wave shapes of input current, frequency spectrum and output voltage at duty cycle 0.2, 0.5 and 0.8 are shown in Figures 2.41 to 2.49. The performance parameter is shown in Table 5. It is observed that, the input current becomes near to sinusoidal and power factor is found very close to unity. The THD% is reduced from previous results. When duty cycle is 0.2 then THD% is found 4.1%, power factor is 0.972, input current is 48.08 ampere and output voltage is observed 720V. When duty cycle is 0.4 then THD% is found 2.8%, power factor is unity, input current is 34.08 ampere and output voltage is observed 900V. When duty cycle is 0.5 then THD% is found 3.0%, power factor is unity, input current is 28.28 ampere and output voltage is observed 890V. When duty cycle is 0.95 then THD% is found 12.9%, power factor is 0.99, input current is 10.6 ampere and output voltage is observed 560V. It is observed that, output voltage varies from 560V to 900V with variation of duty cycle. So it is seen that, it is always greater than input voltage. With small variation of duty cycle the output voltage varies widely. Though, Boost rectifier offers several advantages with good power factor, lower THD and better efficiency, practically where variation of output voltage is required slightly and where it is required lower than input voltage, Boost regulated rectifier is not practical. For this purpose C^uk rectifier may be suitable. Therefore, the aim of this thesis is to analyze C^uk rectifier to achieve this goal. Results of Table 5 are presented graphically in Figures 2.50 to 2.53.
Figure 2.40: Circuit diagram of Boost rectifier with harmonics filter

Figure 2.41: Input current wave shape of Boost rectifier with harmonics filter at D=0.2
Figure 2.42: Frequency spectrum of Boost rectifier with harmonics filter at D= 0.2

Figure 2.43: Input current wave shape of Boost rectifier with harmonic filter at D= 0.5
Figure 2.44: Frequency spectrum of Boost rectifier with harmonics filter at D=0.5

Figure 2.45: Input current wave shape of Boost rectifier with harmonics filter at D=0.8
Figure 2.46: Frequency spectrum of Boost rectifier with harmonics filter At D = 0.8

Figure 2.47: Output voltage wave shape of Boost rectifier with harmonics filter at D = 0.2
Figure 2.48: Output voltage wave shape of Boost rectifier with harmonic filter at D=0.5

Figure 2.49: Output voltage wave shape of Boost rectifier with harmonics filter at D=0.8
Figure 2.50: The graph of THD vs duty cycle of Boost rectifier with harmonics filter

Figure 2.51: The graph of Power factor vs duty cycle of Boost rectifier with harmonics filter
Figure 2.52: The graph of Output voltage vs duty cycle of Boost rectifier with harmonics filter

Figure 2.53: The graph of Efficiency vs duty cycle of Boost rectifier with harmonics filter
<table>
<thead>
<tr>
<th>Duty cycle (D)</th>
<th>THD</th>
<th>PF (cos)</th>
<th>Ilin(rms)/amp</th>
<th>Vin(rms)/volt</th>
<th>Vout(dc)/volt</th>
<th>Iout(amp)/volt</th>
<th>Efficiency (η%)</th>
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<td>890</td>
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<tr>
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<td>1</td>
<td>24.04</td>
<td>212.13</td>
<td>840</td>
<td>16.8</td>
<td>92.23</td>
</tr>
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<td>92.35</td>
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<tr>
<td>0.95</td>
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<td>10.6</td>
<td>212.13</td>
<td>560</td>
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<td>96.5</td>
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2.1.2.4 C^uk rectifier without filter

C^uk voltage regulator is similar to Buck-Boost regulator with some modification in the circuitry. The C^uk regulator provides a negative polarity regulated output voltage with respect to the common terminal of the input voltage. The Buck, Boost, Buck-Boost regulators all transfer energy between input and output using the inductor. Their analysis is based on voltage balance across the inductors. The C^uk regulator uses capacitive energy transfer and its analysis is based on current balance of the capacitor. The advantages of C^uk regulator is that the input and output inductors create a smooth current at both sides of the regulator while the Buck, Boost and Buck-Boost have pulsed current at one side at least. C^uk regulator provides continuous current due to the capacitive energy transfer. With C^uk regulator three phase rectifier has low switching losses and has high efficiency.

![Circuit diagram of C^uk rectifier without filter](image)

Figure 2.54: Circuit diagram of C^uk rectifier without filter

Similar to Boost rectifier, at first C^uk is analyzed with three phase rectifier without any filter. The circuit diagram of C^uk rectifier without filter is shown in Figure 2.54. The wave shapes of input current and frequency spectrum at D= 0.2, D= 0.5 and D= 0.8 are shown in Figures from 2.55 to 2.63. The wave shape of current shows that it is distorted and is non-sinusoidal. The frequency spectrum shows that input current carries harmonics.
The output voltage is shown in Figures 2.61, 2.62 and 2.63 at duty cycle 0.2, 0.5 and 0.8 respectively. The performance parameter is shown in Table 6. It is observed that, during duty cycle 0.2 the rms value of input current is 28.28 amp, output voltage is 390V, pf is 0.91 and THD% is 35.80%. When duty cycle is 0.5 the rms value of input current is 17.67 amp, output voltage is 420V, pf is 0.892 and THD% is 59.70%. When duty cycle is 0.8 the rms value of input current is 4.94 amp, output voltage is 350V, power factor is 0.91 and THD% is 110%. It is seen that, input current is lower compared to Boost rectifier. The output voltage is found lower than input current in particular duty cycle. But the THD values are higher. Results of Table 6 are presented graphically in Figures 2.64 to 2.67. Next to reduce the harmonic components in current wave shapes, passive filter is used in Čuk regulated three phase rectifier.

Figure 2.55: Input current wave shape of Čuk rectifier without filter at D=0.2
Figure 2.56: Frequency spectrum of C^uk rectifier without filter at D=0.2

Figure 2.57: Input current wave shape of C^uk rectifier without filter at D=0.5
Figure 2.58: Frequency spectrum of C\textsuperscript{uk} rectifier without filter at $D=0.5$

Figure 2.59: Input current wave shape of C\textsuperscript{uk} rectifier without filter at $D=0.8$
Figure 2.60: Frequency spectrum of Ćuk rectifier without filter at $D=0.8$

Figure 2.61: Output voltage wave shape of Ćuk rectifier without filter at $D=0.2$
Figure 2.62: Output voltage wave shape of C\uk rectifier without filter at D=0.5

Figure 2.63: Output voltage wave shape of C\uk rectifier without filter at D=0.8
Figure 2.64: The graph of THD vs duty cycle of Ĉuk rectifier without filter

Figure 2.65: The graph of Power factor vs duty cycle of Ĉuk rectifier without filter
Figure 2.66: The graph of Output voltage vs duty cycle of C^uk rectifier without filter

Figure 2.67: The graph of Efficiency vs duty cycle of C^uk rectifier without filter
Table 6: Performance parameter of C^uk rectifier without filter

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<th>Duty cycle(D)</th>
<th>THD</th>
<th>PF(cosθ)</th>
<th>lin(rms)amp</th>
<th>Vin(rms)volt</th>
<th>Vout(dc)volt</th>
<th>Iout(amp)volt</th>
<th>Efficiency(η%)</th>
</tr>
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2.1.2.5 C^uk rectifier with passive filter

C^uk rectifier is analyzed with passive filter having same parameters (L= 10mH, C= 5uF) as has been considered for Boost regulator three phase rectifier. The schematic circuit diagram of C^uk rectifier with passive filter is shown in Figure 2.68. The wave shapes of input current, frequency spectrum and output voltage at duty cycle 0.2, 0.5 and 0.8 are shown in Figures 2.69 to 2.77. The performance parameter is shown in Table 7. Similar to Boost rectifier, it is found that, the ripple of output voltage is greatly reduced. The input current is improved to almost sinusoidal and the power factor is also improved. The value of THD% is reduced from 35.8% to 6.50% at duty cycle 0.2 and from 134% to 63.50% at duty cycle 0.95. Although, the improvement of input current is observed, some distortion is presented still now due to the presence of some harmonic components. It is seen that, in C^uk rectifier the value of input current is lower than Boost rectifier, but the amount of THD is higher than Boost rectifier. Analyzing the input current with Fourier spectrum, it is observed that 5^{th}, 7^{th}, 9^{th}, 11^{th}, 13^{th} harmonic components are present in input current. Among these values 5th harmonics is higher than others. The improvement of input current is typically possible by the reduction of 5^{th} harmonics. Results of Table 7 are presented graphically in Figures 2.78 - 2.81. Next the C^uk regulated rectifier is studied with input harmonic filter for reduction of the 5^{th} harmonics and obtain a better input current than obtained at present.
Figure 2.68: Circuit diagram of Ĉuk rectifier with passive filter

Figure 2.69: Input current wave shape of Ĉuk rectifier with passive filter at \( D = 0.2 \)

Figure 2.70: Frequency spectrum of Ĉuk rectifier with passive filter at \( D = 0.2 \)
Figure 2.71: Input current wave shape of Čuk rectifier with passive filter at D=0.5

Figure 2.72: Frequency spectrum of Čuk rectifier with passive filter at D=0.5
Figure 2.73: Input current wave shape of Cuk rectifier with passive filter at D=0.8

Figure 2.74: Frequency spectrum of Cuk rectifier with passive filter at D=0.8
Figure 2.75: Output voltage wave shape of Ćuk rectifier with passive filter at $D=0.2$

Figure 2.76: Output voltage wave shape of Ćuk rectifier with passive filter at $D=0.5$
Figure 2.77: Output voltage wave shape of C^uk rectifier with passive filter at D=0.8

Figure 2.78: The graph of THD vs duty cycle of C^uk rectifier with passive filter
Figure 2.79: The graph of Power factor vs duty cycle of C^uk rectifier with passive filter

Figure 2.80: The graph of Output voltage vs duty cycle of C^uk rectifier with passive filter
Figure 2.81: The graph of Efficiency vs duty cycle of C^uk rectifier with passive filter
Table 7: Performance parameter of Cuk rectifier with passive filter

<table>
<thead>
<tr>
<th>Duty cycle (D)</th>
<th>THD</th>
<th>PF (cose)</th>
<th>Iin (rms) amp</th>
<th>Vin (rms) volt</th>
<th>Vout (dc) volt</th>
<th>Iout (amp)</th>
<th>Efficiency (η%)</th>
</tr>
</thead>
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<td>212.13</td>
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<td>2.8</td>
<td>34.2</td>
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2.1.2.6 C^uk rectifier with harmonic filter

To eliminate 5th harmonics a harmonic filter has been developed using the resonating frequency 250Hz. A C^uk rectifier with same harmonic filter as used for Boost regulated three phase rectifier is analyzed in this section. The schematic circuit diagram of C^uk rectifier with harmonic filter is shown in Figure 2.82. The wave shapes of input current, frequency spectrum and output voltage at duty cycle 0.2, 0.5 and 0.8 are shown in Figures 2.83 to 2.91. The performance parameter is shown in Table 8. It is found that, the input current becomes near to sinusoidal and power factor is found very close to unity. At duty cycle 0.6 the value of THD% is reduced from 14.4% to 7.0% and from 63.5% to 33.0% at duty cycle 0.95. From Table 8 it is seen that, the THD% is 4.70%, power factor is unity, input current is 29.69 ampere and output voltage is 492V during the duty cycle 0.2. When duty cycle is 0.5 then THD% is found 6.2%, power factor is 0.99, input current is 19.37 and output voltage is 570V. During the duty cycle 0.8 the value of THD% is found to be 14.20%, power factor is 0.91, input current is 7.353 ampere and output voltage is 430V. Higher efficiency is observed 88.83% at duty cycle 0.8 than other duty cycle. From comparison of Boost and C^uk rectifier with harmonic filter, it is observed that the value of input current is lower in C^uk rectifier than in Boost rectifier and it from 4.242 ampere to 29.69 ampere with variation of duty cycle, whereas, it varies from 10.6 ampere to 48.08 ampere in Boost rectifier. Output voltage varying from 250V to 570V in C^uk rectifier with variation of duty cycle, while, it varies from 560V to 900V in Boost rectifier. Though the value of THD% is slightly higher in C^uk rectifier than Boost rectifier, it is possible to implement in practical application where smooth regulation of output voltage is required. Results of Table 8 are presented graphically in Figures 2.92 to 2.95.
Figure 2.82: Circuit diagram of C^uk rectifier with harmonic filter

Figure 2.83: Input current wave shape of C^uk rectifier with harmonic filter at D=0.2
Figure 2.84: Frequency spectrum of C^uk rectifier with harmonic filter at D=0.2

Figure 2.85: Input current wave shape of C^uk rectifier with harmonic filter at D=0.5
Figure 2.86: Frequency spectrum of C^uk rectifier with harmonic filter at D=0.5

Figure 2.87: Input current wave shape of C^uk rectifier with harmonic filter at D=0.8
Figure 2.88: Frequency spectrum of Ĉ'uk rectifier with harmonic filter at D=0.8

Figure 2.89: Output voltage wave shape of Ĉ'uk rectifier with harmonic filter at D=0.2
Figure 2.90: Output voltage wave shape of C^uk rectifier with harmonic filter at D=0.5

Figure 2.91: Output voltage wave shape of C^uk rectifier with harmonic filter at D=0.8
Figure 2.92: The graph of THD vs duty cycle of C\textasciitilde uk rectifier with harmonic filter

Figure 2.93: The graph of Power factor vs duty cycle of C\textasciitilde uk rectifier with harmonic filter
Figure 2.94: The graph of Output voltage vs duty cycle of C^uk rectifier with harmonic filter

Figure 2.95: The graph of Efficiency vs duty cycle of C^uk rectifier with harmonic filter
Table 8: Performance parameter of C^uk rectifier with harmonics filter

<table>
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<tr>
<th>Duty cycle (D)</th>
<th>THD</th>
<th>PF (cos ε)</th>
<th>I_{in} (rms) amp</th>
<th>V_{in} (rms) volt</th>
<th>V_{out} (dc) volt</th>
<th>I_{out} (amp) volt</th>
<th>Efficiency (η %)</th>
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<td>5</td>
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CHAPTER 3
CONCLUSION

3.1 Conclusion

The quality of input current indicates the efficient performance of a rectifier. Normally a three phase rectifier draws distorted input current which causes many undesirable problems. The presence of harmonics components in input current is mostly responsible for the distortions of input current. In industrial and household applications, this distorted input current is harmful for stable and longer operations of power electronic equipments due to problems. Like, low power factor, additional heating, over voltage and over loading, increased volt ampere rating and increased line and utility losses etc. Distortion free sinusoidal input current is a major consideration in a rectifier design. Many techniques have been developed by researchers in previous works. But their large and bulky sizes are still to be solved. Input current shaping is possible using Boost and C^uk regulator with three phase rectifier where added inductor and capacitor smooth out the pulsating component from input current. In this thesis, a C^uk regulator is proposed for improvement of three phase rectifier input current.

At first a three phase rectifier has been studied only with resistive load. The input current is found non sinusoidal and THD% is found 30.89%. Then a passive filter has been attached with three phase rectifier which gives the input current sinusoidal and low THD%. But the filter size becomes very large (L= 50mH, C= 100uF).

Then a Boost regulator with three phase rectifier has been studied without filter. It has been observed that the input current is highly distorted with the maximum value of THD% at 71.35%. After that, Boost rectifier studied with a passive filter where input current is found sinusoidal with some distortion and the maximum value of THD% is reduced to 24.26%. With increasing the filter size the value of THD% is reduced further but the output voltage decreased from desired value and hence the regulation was not
possible. In this circuit, input current contains high peaks of harmonics components. Finally, a Boost rectifier has been studied with a high frequency harmonics filter to eliminate the undesired high peaks of harmonics components from input current. Thus total input filter size reduced. In this circuit input current was found sinusoidal with small ripples and power factor was very close to unity. The maximum efficiency was observed 99.82% at $D = 0.85$.

Similarly, C^uk rectifier has been studied with above mentioned three step keeping the filter size same. Without filter C^uk rectifier draws non sinusoidal input current with high total harmonics distortions which is 134%. With the same size passive filter it gives almost sinusoidal input current and THD% was reduced to 63.5%. The improvements of input current has occurred remarkably when same high frequency harmonics filter has been incorporated in with C^uk rectifier. Here power factor was found near to unity (unity with some duty cycle) and the value of THD% has reduced to 4.7% at 0.2 duty cycle and to 33% at 0.95 duty cycle. The efficiency gradually increases up to 0.85 duty cycle, then it reduces. The maximum value of efficiency is observed 88.83% at 0.85 duty cycle. Though, the efficiency is somewhat lower than Boost rectifier, C^uk rectifier provides some advantages over Boost rectifier. Such as, the input current is smooth and continuous due to capacitive energy transfer, The value of input current is lower than Boost rectifier. C^uk rectifier has low switching stresses and low switching losses. It also gives the facility of medium range variation of output voltage with the variation of duty cycle. So C^uk rectifier can be implemented where the output voltage is required lower or greater than input voltage.
3.2 Suggestions on Future Works

1. During change of output voltage by varying duty cycle, it has been observed that the input current also changes and becomes non sinusoidal. To overcome this problem, a new control strategy may be suggested which will change output voltage keeping input current sinusoidal. Variable carrier frequency may be considered for this purpose.

2. Modified C^uk converter topologies may be considered in future study for further improvement in performance.

3. One of the objectives of this thesis was to study the switching and other losses to provide guidelines for improvement of performance in a rectifier. But, the work was not carried out. This investigation can be carried out in future work.
REFERENCES


