CHAPTER 3

WECS FED GRID THROUGH MATRIX CONVERTER
WITH OPTIMIZED PI CONTROLLER

3.1 INTRODUCTION

In this chapter, Input Power Factor (IPF) is improved and the harmonic distortion is also reduced for both light load and normal load conditions with the help of Genetic Algorithm based Proportional Integral (PI) controller applied to Space Vector Modulation technique of Matrix Converter (MC) based grid connected WECS. The methodology and the results of a comprehensive comparison of a direct MC, an indirect MC and a voltage dc link back to back converter have been discussed and concluded that MC enables, particularly at higher switching frequencies, better performance than the voltage dc link back to back converter (Friedli et al. 2012).

The Matrix Converter is having several control techniques such as direct transfer function approach (Venturini method), scalar method, PWM method carrier based Space Vector Modulation (SVM). The main drawback of Venturini method is that it gives voltage transfer ratio of 0.5. The carrier based MC contributes to the realization of low volume, sinusoidal input current, bidirectional power flow and lack of bulky reactive elements (Yoon and Sul 2006). The SVM is a well-known and commonly used modulation method due to its high performance, relative simple operation also it is a simpler method to control input power factor. It allows independent control of input current and output voltage at the same time. Voltage transfer ratio of SVM method is increased to 0.866 without adding any third harmonic.
compared to Venturini method. The various modulation methods of matrix converter are compared with each other and finally it is concluded that the space vector modulation technique is the best solution to increase the voltage transfer ratio and to optimize the switching pattern through a suitable use of zero configuration.

### 3.1.1 Space Vector Modulation Method

The SVM algorithm is mainly based on the representation of the three phase input current and three phase output line voltage on the space vector plane. With nine bi-directional switches the MC can theoretically assume 512 i.e., \(2^9\) different switching combinations.

![Matrix Converter Diagram](image)

**Figure 3.1 Matrix Converter**

The switching function of the switches, \(S_{kj}(t)\) in the above MC (Figure 3.1) is defined as “1” when it is ON and defined as “0” when it is OFF and given as Equation (3.1).
\[ S_{kj} (t) = \begin{cases} 
1 & \text{for } k \in \{a,b,c\} \text{ and } j \in \{A,B,C\} \\
0 & \text{otherwise} 
\end{cases} \quad (3.1) \]

The constraint of the switches is expressed by the following Equation (3.2).

\[ S_{aj} + S_{bj} + S_{cj} = 1 \quad \text{for } j \in \{A,B,C\} \quad (3.2) \]

With the above constraints, in the MC there are 27 different switching combinations for connecting output phase to input phases if the above mentioned combinations can be analyzed in three groups from 512 possible combinations. The SVM technique is a mathematical model which is using 27 switching combinations out of 512 switching combinations. The duty cycles of the switches are modulated for various voltage transfer ratio and finally it is increased from 0.5 to 0.866 by using this modulation technique. And this method is using 18 active switching combinations with 3 zero switching combinations to complete one full cycle. For three phase matrix converters there are 27 valid switch combinations giving thus 27 voltage vectors. These can be divided into three vectors, they are as follows synchronously rotating vectors, stationary vectors and zero vectors.

For each switching combinations, the input and output line voltages can be expressed in terms of space vectors as given in the Equations (3.3) and (3.4)

\[ V_i = 2/3(V_{ab} + V_{bc} e^{j2\pi/3} + V_{ca} e^{j4\pi/3}) = V_i e^{j\alpha_i} \quad (3.3) \]

\[ V_o = 2/3(V_{AB} + V_{BC} e^{j2\pi/3} + V_{CA} e^{j4\pi/3}) = V_o e^{j\alpha_o} \quad (3.4) \]

The output phase voltage of the matrix converter is a product of the switching function and the input phase voltages given by Equation (3.5).
The input line and output line currents can be written as per the Equations (3.6) and (3.7).

\[
i_i = \frac{2}{3}(i_a + i_b e^{j2\pi/3} + i_c e^{j4\pi/3}) = I_i e^{j\alpha_i} \quad (3.6)
\]

\[
i_o = \frac{2}{3}(i_A + i_B e^{j2\pi/3} + i_C e^{j4\pi/3}) = I_o e^{j\beta_o} \quad (3.7)
\]

In this modulation technique, three phase quantities can be transformed to their equivalent two phase quantity in synchronously rotating frame. From this two phase component, the reference vector magnitude can be found and used for modulating the converter output. SVM treats the sinusoidal voltage as a constant amplitude vector rotating at constant frequency. This technique approximates the reference voltage \(V_{\text{ref}}\) by a combination of the eight switching patterns (\(V_0\) to \(V_7\)) given in Figure 3.2.

**Figure 3.2 Output voltage space vector**
For example, if the reference voltage is located in sector 1 voltage vectors $V_1$ and $V_2$. $V_0$ and $V_7$ would be selected and applied within a sampling period.

### 3.1.2 Grid connected WECS

Wind energy can be harnessed by a Wind Energy Conversion System (WECS), composed of wind turbine blades, an electric generator, a power electronic converter and the corresponding control system. The function of an electrical generator is providing a means for energy conversion between the mechanical torque from the wind rotor turbine, as the prime mover and the local load or the electric grid. Different types of generators are being used with wind turbines. Induction Generator (IG) has been extensively used in commercial wind turbine units. Asynchronous operation of induction generators is considered as an advantage for application in wind turbine systems, because it provides some degree of flexibility when the wind speed is fluctuating. There are two main types of induction machines, squirrel cage and wound rotor. Another category of induction generators is the Doubly Fed Induction Generator (DFIG). The induction generator based on squirrel cage rotor is a very popular machine because of its low price, mechanical simplicity, robust structure and resistance against disturbance and vibration. The wound-rotor is suitable for speed control purposes. But it is more expensive than a squirrel-cage rotor.

From the survey, conventional converters (AC-DC-AC converter) are used in grid connected WECS (Nguyen and Lee 2014). The IPF of MC under light load conditions is low, so it is important to improve IPF. The output voltage references for Permanent Magnet Synchronous Motor (PMSM) drive and the input current references for unity input power factor are obtained from the control system of the motor and single phase to three phase
matrix converter (Takeshita & Yamashita 2011). The adjustment method of input power factor is presented based on the input current Space Vector PWM of the rectifier stage of indirect matrix converter (Lu et al. 2009). It is required to improve the power factor at any (even light) load conditions and also need of discussing about harmonics injected to load due to MC.

This chapter is dedicated to improve the input power factor under light load condition and also discusses the reduced Total Harmonic Distortion (THD) at any load condition. The values of proportional gain and integral gain are obtained using Genetic Algorithm (GA) in MATLAB to get better result.

This chapter evaluates the MC by comparing MC fed grid with and without optimized PI controller based compensation algorithm under light and normal load conditions. The input power factor differs under different load conditions. So it is necessary to compare the performance under different loads. The results proved that the output voltage THD, input current THD, lower order harmonics and input power factor for MC fed grid with optimized PI controller are better compared to MC without PI controller particularly for different loading condition.

3.2 OPTIMIZED MATRIX CONVERTER FED GRID FROM WECS

3.2.1 Matrix Converter Fed Grid from WECS without optimized PI Controller

The general circuit of the Matrix Converter contains three phase input supply with the voltage of 100V from wind energy system shown in Figure 3.3. The MC consists of nine bi-directional switches in which each switch comprises of two IGBTs connected in anti-parallel mode. The output
of MC is connected to grid (230V) through step up transformer of 100V /230V.

![Figure 3.3 Matrix converter fed grid without PI controller](image)

The input current quality of MC is improved by an input filter and also reduces the input voltage distortion supplied to the MC. The input filter is generally needed to smooth the input currents and to satisfy the Electro Magnetic Interference requirements. A reactive current flow through the input filter capacitor leads to a reduction of the power factor, especially at low output power. Input power factor varies for different load conditions. It is poor for light load condition and is nearly unity under normal or heavy loads. So the above set up is analyzed with light load (1A) and normal load (10A) condition. THD and lower order harmonics of load are also relatively high under any load condition in MC fed grid without PI controller. SVM control technique is used for MC. For MC without PI controller, three phase modulating signals are given as input of SVM block. The above circuit is modelled using MATLAB/Simulink for different load condition and results are discussed.
3.2.2 Optimized PI Controller Based Compensation Techniques for Matrix Converter Fed Grid

In the general circuit, GA based Optimized PI controller is introduced in gate pulse generation side to improve input power factor. Figure 3.4 shows the MC fed grid with optimized PI controller.

![Diagram of Matrix converter fed grid with optimized PI controller](image)

**Figure 3.4 Matrix converter fed Grid with optimized PI controller**

To control the IPF of the MC, sine value of the displacement angle $\psi_{est}$ between the input voltage vector and the corresponding input current vector is chosen. If the value of $\sin(\psi_{est})$ is maintained close to zero then the unity power factor at the power supply side of the MC is intrinsically satisfied. Due to input distortions, $\sin(\psi_{est})$ is not close to zero. This phase difference produces harmonics in the output. This actual phase difference is measured and compared with reference phase difference and given as compensating angle between modulating signals of SVM techniques. So IPF is improved and also it reduces the input harmonics.
The proposed PI controller is noted by the compensating angle and is given by Equation (3.8).

\[
\delta_{\text{comp}} = (K_p + \frac{K_i}{S})\Delta e
\]  
(3.8)

where \( \Delta e = Sin(\Psi_{\text{ref}}) - Sin(\Psi_{\text{est}}) \)  
(3.9)

\( \Delta e \) is the difference between actual phase angle and reference phase angle given by the Equation (3.9).

\( \delta_{\text{comp}} = \) Compensating angle

\( K_p = \) Proportional gain

\( K_i = \) Integral gain

However, the SVM algorithm method is only validated if the input voltage vector leads the input current vector to one sector, i.e., \( \delta \leq \pi/3 \). For each \( q \), there exists a possible maximum compensated displacement angle between the desired input current vector and the input voltage vector. The maximum compensated angle is given by the Equation (3.10).

\[
\delta_{\text{max}} = \begin{cases} 
\cos^{-1}\left(\frac{2q}{\sqrt{3}}\right), & \frac{\sqrt{3}}{4} \leq q \leq \frac{\sqrt{3}}{2} \\
\frac{\pi}{3}, & 0 \leq q \leq \frac{\sqrt{3}}{2}
\end{cases}
\]  
(3.10)

The limiter of the PI controller is always updated with the new maximum compensated angle \( \delta_{\text{max}} \) from Equation (3.10). The compensated angle is within \([0, \delta_{\text{max}}]\) and it will be inserted as the desired displacement angle between the modulating signals of the space vector modulation. In the case of IPF compensation, the stable response is more important than the fast response. Thus, PI gains are properly selected for the proposed algorithm. The \( K_p \) is low and the \( K_i \) is not so large to avoid large overshoot and to have stable performance.
3.2.3 Implementation of GA Based PI Controller

The transfer function of PI regulator is given by the Equation (3.11).

\[
\frac{u(s)}{e(s)} = K_p + \frac{K_i}{s}
\]  

(3.11)

Objective function is describing a measure of effectiveness of improving power factor. Coding for GA is performed in MATLAB code for the objective function given by Equation (3.8).

The value of compensated angle \( \delta_{comp} \) is maintained between the values 0 and \( \delta_{max} \). The suitable values of \( K_p \) and \( K_i \) are obtained using GA. The obtained compensated angle is fed as angle difference between the modulation signals of SVM technique. The IPF and harmonics are analyzed for different load conditions. For satisfactory results Genetic Algorithm program parameters are shown in Table 3.1.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial population size</td>
<td>50</td>
</tr>
<tr>
<td>Maximum number of generation</td>
<td>100</td>
</tr>
<tr>
<td>Probability of cross over</td>
<td>0.5</td>
</tr>
<tr>
<td>Mutation probability</td>
<td>0.012</td>
</tr>
<tr>
<td>Performance measure</td>
<td>compensating angle</td>
</tr>
</tbody>
</table>

The \( K_p \) and \( K_i \) values are calculated as 0.12 and 1 respectively (from GA) for change in difference (\( \Delta e \)). In this proposed work, the compensating period required is same as the PWM sampling period to
maintain a high power factor. Output changes within the range of light and normal load conditions, the PI works well in terms of the good steady-state and dynamic performance of the input. The proposed method is independent of power supply parameters, which are sensitive during real time operations.

3.3 RESULTS AND DISCUSSIONS

Simulation was carried out in MATLAB/Simulink with following input and output parameters shown in Tables 3.2 to 3.4.

Table 3.2 WECS parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind speed</td>
<td>12m/s</td>
<td>Rotor speed</td>
<td>1500rev/min</td>
</tr>
<tr>
<td>Initial speed</td>
<td>1.2m/s</td>
<td>Stator inductance</td>
<td>0.002p.u</td>
</tr>
<tr>
<td>Mechanical power</td>
<td>1MW</td>
<td>Magnetizing inductance</td>
<td>0.5 p.u</td>
</tr>
<tr>
<td>Rated capacity</td>
<td>3KW</td>
<td>Rotor time constant</td>
<td>0.08</td>
</tr>
<tr>
<td>Stator voltage</td>
<td>150V</td>
<td>Stator resistance</td>
<td>0.004 p.u</td>
</tr>
<tr>
<td>Number of poles</td>
<td>4</td>
<td>Rotor resistance</td>
<td>0.002p.u</td>
</tr>
</tbody>
</table>

Number of wind turbine = 1

Table 3.3 Matrix Converter parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input voltage</td>
<td>100V (Phase-peak)</td>
</tr>
<tr>
<td>Output voltage</td>
<td>100 V (Phase-peak)</td>
</tr>
<tr>
<td>Input filter Inductance &amp; capacitance</td>
<td>1mH, 19µF</td>
</tr>
<tr>
<td>Coupling Transformer ratio</td>
<td>100V : 230V</td>
</tr>
<tr>
<td>Bidirectional switch</td>
<td>IGBTs in parallel</td>
</tr>
</tbody>
</table>
Table 3.4 Grid parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid voltage</td>
<td>230V (Phase)</td>
</tr>
<tr>
<td>Grid frequency</td>
<td>50HZ</td>
</tr>
<tr>
<td>Damping filter R, L &amp; C (to</td>
<td>50 ( \Omega ), 100 mH, C=0.01 ( \mu )F</td>
</tr>
<tr>
<td>reduce switching frequency</td>
<td></td>
</tr>
<tr>
<td>ripple current in grid)</td>
<td></td>
</tr>
<tr>
<td>RL load</td>
<td>8( \Omega ),0.1mH (10A load)</td>
</tr>
<tr>
<td></td>
<td>70( \Omega ), 0.1 mH (1A load)</td>
</tr>
</tbody>
</table>

**PI controller specifications**

\( K_p \) and \( K_i \) are approximated as 0.12 and 1 from GA.

\[
\Delta_{\text{max}} = \left( \frac{n}{3}, \ 0 \leq q \leq \frac{\sqrt{3}}{2} \right)
\]

Transfer ratio \( q = 0.866 \)

\( \delta_{\text{comp}} \) is varying from 0 to \( \frac{n}{3} \).

### 3.3.1 Matrix Converter Fed Grid from WECS without Optimized PI Controller under Normal Load Condition

Harmonic studies have been carried out for load in the output of converter. Due to the introduction of PI controller, harmonics injected in to local load connected with grid have to be analyzed. So IPF, THD and lower order harmonics are analyzed in the output of converter with and without PI controller based compensation technique.
Figure 3.5  Output voltage and FFT spectrum under normal load without PI controller

Figure 3.6  Output current and FFT spectrum under normal load without PI controller
Output voltage and current waveforms with its FFT spectrum under normal load without PI controller are shown in Figures 3.5 and 3.6. Output voltage THD is 11.27% and output current THD is 3.92 %. Lower order harmonics are also analyzed due to introduction of this optimization technique in the next sections. Inter-harmonics are present in the system, because input is dynamic in nature. If stable input (three phase AC supply) is used then no inter-harmonics is produced in input and output side.

Figure 3.7  Input voltage and FFT spectrum under normal load without PI controller

From the Figures 3.7 and 3.8 of input voltage and input current waveforms and FFT spectrum, THD and lower order harmonics are high in input side compared to output side. Input voltage THD is 13% and input current THD is 36.58%. 
Figure 3.8 Input current and FFT spectrum under normal load without PI controller

Figure 3.9 Input voltage with peak at 0.161 s without PI controller
From the Figures 3.9 and 3.10 of input voltage and current waveforms, the phase difference is 0.0025 s, Power factor is 0.71 and is poor. Voltage transfer ratio is above 0.8.

3.3.2 Matrix Converter Fed Grid from WECS without PI Controller Under Light Load Condition

It is required to analyze the power factor and harmonics under light load condition (1A). Load is varied to light load and analysis have been performed.

Figure 3.11 Output voltage and FFT spectrum under light load without PI controller
Figure 3.12 Output current and FFT spectrum under light load without PI controller

Figure 3.13 Input voltage and FFT spectrum under light load without PI controller
Figure 3.14  Input current and FFT spectrum under light load without PI controller

From the Figures 3.11 to 3.14, THD and lower order harmonics on both input and output side are relatively high for light load condition compared to normal load condition. Output voltage and current THD are 13.87 % and 8.41% respectively. Input voltage and current THD are 14.46% and 39.13% respectively. Even input filter is included in MC to improve the input waveform quality, THD and lower order harmonics, that are poor.

Figure 3.15 Input voltage peak at 0.142 s without PI controller
From the input voltage and current Figures 3.15 and 3.16, IPF is calculated as 0.59 which is poor then normal load condition without PI controller.

### 3.3.3 Matrix Converter Fed Grid from WECS with Optimized PI Controller Under Normal Load Condition

![Figure 3.16 Input current peak at 0.145 s without PI controller](image1)

![Figure 3.17 Output voltage and FFT Spectrum under normal load with PI controller](image2)
From the Figures 3.17 and 3.18, output voltage and current spectrum with compensation method THD is reduced while compared to without compensation. Voltage and current THD with compensation are 9.76% and 1.59% which is less than voltage and current THD as 11.27% and 3.59 % without compensation method under normal load condition. Lower order harmonics are also relatively reduced with optimised PI controller. Due to reduced lower order harmonics in output with PI controller, THD is reduced.

From the input waveforms shown in Figures 3.19 and 3.20, it is observed that voltage THD is reduced to 9.14% in optimized PI controller based MC from 13% and current THD reduced to 32.97% from 36.58 %. Lower order harmonics are also reduced in input side under normal load condition.
Figure 3.19  Input voltage and FFT Spectrum under normal load with PI controller

Figure 3.20  Input current and FFT Spectrum under normal load with PI controller
From the Figures 3.21 and 3.22, input power factor with PI controller is calculated as 0.95 which is 26% greater than input power factor (0.71) calculated from MC without PI controller under normal load condition. Voltage transfer ratio is also above 0.84 with PI controller.

3.3.4 Matrix Converter Fed Grid from WECS with Optimized PI Controller Under Light Load Condition

![Figure 3.23 Output voltage and FFT spectrum under light load with PI controller](image-url)
From the Figures 3.23 and 3.24, output spectrum voltage and current THD with PI controller are reduced to 11.86% and 7.36% respectively from 13.87% and 8.4% without PI controller. Lower order harmonics are reduced further.

Figure 3.25 Input voltage and FFT spectrum under light load with PI controller
Figure 3.26 Input current and FFT spectrum under light load with PI controller

Input voltage and current THD with compensation is reduced to 8.77% and 34.09% compared to voltage and current THD without compensation of 14.46% and 39.13% under light load condition from the Figures 3.25 and 3.26. From Figures 3.27 and 3.28, Input Power Factor with PI controller under light load condition is 0.98 which is increased from 0.59 without PI controller. Power factor is increased by 40%. Due to improvement in power factor both input and output distortions are also reduced. Voltage transfer ratio is 0.84 under light load condition. Compared to MC with PI controller under normal load condition, voltage and current THD in both input and output side is high in MC with PI controller under light load conditions. But power factor is nearly unity under light load conditions. Input and output distortions are increased significantly in MC when load is changed to light load condition even with or without PI controller. But power factor reaches unity under light load than normal load with PI controller. In all the conditions, obtained voltage transfer ratio of MC is above 0.8.
Figure 3.27 Input voltage peak at 0.142 s with PI controller

Figure 3.28 Input current peak at 0.1425 s with PI controller

3.3.5 Comparison Of MC With and Without PI Controller Under Normal Load Condition

Figure 3.29 Comparison of voltage and current THD (for 10A load)

From Figure 3.29, output and input THD for MC with compensation is less than MC without compensation under normal load. Output current THD is 1.59%. Input voltage THD is 9.14%.
From the Figures 3.30 and 3.31, lower order voltage and current harmonics in both input and output side are less in MC with PI controller compared to MC without controller. In input voltage and current, $5^{th}$ harmonic content is dominant than other harmonics. But it is less than MC without compensation. In output side, $11^{th}$ harmonic content is dominant than other harmonics, but it is less than MC without compensation under normal load.
Maximum harmonic content in output voltage is 0.06%, input voltage is 1.13%, output current is 0.06% and input current is 1.51%. Due to compensating angle in SVM technique, input performance is improved in addition to power factor improvement. Table 3.5 shows the harmonic content, THD and IPF for 10A load.

Table 3.5 Harmonic content, THD and IPF for 10A load

<table>
<thead>
<tr>
<th>Harmonics</th>
<th>Input voltage</th>
<th>Input current</th>
<th>Output voltage</th>
<th>Output current</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>with PI</td>
<td>without PI</td>
<td>with PI</td>
<td>without PI</td>
</tr>
<tr>
<td>h5</td>
<td>1.02</td>
<td>1.69</td>
<td>0.73</td>
<td>0.74</td>
</tr>
<tr>
<td>h7</td>
<td>1.13</td>
<td>1.85</td>
<td>1.51</td>
<td>1.58</td>
</tr>
<tr>
<td>h11</td>
<td>0.43</td>
<td>0.7</td>
<td>0.66</td>
<td>0.69</td>
</tr>
<tr>
<td>h13</td>
<td>0.37</td>
<td>0.61</td>
<td>0.5</td>
<td>0.69</td>
</tr>
<tr>
<td>h17</td>
<td>0.14</td>
<td>0.22</td>
<td>0.27</td>
<td>0.35</td>
</tr>
<tr>
<td>h19</td>
<td>0.13</td>
<td>0.21</td>
<td>0.28</td>
<td>0.44</td>
</tr>
<tr>
<td>THD</td>
<td>9.14</td>
<td>13</td>
<td>32.9</td>
<td>36.58</td>
</tr>
<tr>
<td>IPF</td>
<td>0.95</td>
<td>0.71</td>
<td>9.76</td>
<td>11.27</td>
</tr>
</tbody>
</table>

3.3.6 Comparison of MC With and Without PI Controller Under Light Load Condition

![Figure 3.32 Comparison of voltage and current THD (for 1A load)](image-url)
From the Figure 3.32, output and input THD for MC with compensation is less than MC without compensation under light load. Output current THD is 7.6% and input voltage THD is 8.77%. Compared to normal load, MC with compensation under light load has relatively high output...
current THD and reduced input voltage THD. Input performance is better due to PI control technique in input side.

From the Figures 3.33 and 3.34, lower order voltage and current harmonics in both input and output side are less in MC with PI controller compared to MC without controller under light load. In input voltage $7^{th}$ harmonic content is dominant than other harmonics. But it is less than MC without compensation. In input current $7^{th}$ and $13^{th}$ harmonic content is higher than other harmonics, but less than content without compensation. In output side $11^{th}$ harmonic content is dominant than other harmonics, but it is less than MC without compensation under light load. Maximum harmonic content in output side is 0.05% and input side is 1.36%. In terms of lower order harmonics with compensation there is no much difference under light and normal load conditions.

![Comparison of Input power factor](image.png)

**Figure 3.35 Comparison of Input power factor**

Input power factor of MC with PI controller is better than MC without PI controller which is shown in Figure 3.35. Under light load condition IPF is very poor (0.59). But employing optimized PI controller in MC, IPF improved close unity under light load without affecting voltage transfer ratio of 0.84 due to reduced distortions in input. Table 3.6 shows the harmonic content, THD and IPF for 1A load.
Table 3.6 Harmonic content, THD and IPF for 1A load

<table>
<thead>
<tr>
<th>Harmonics in %</th>
<th>Input voltage with PI</th>
<th>Input voltage without PI</th>
<th>Input current with PI</th>
<th>Input current without PI</th>
<th>Output Voltage with PI</th>
<th>Output Voltage without PI</th>
<th>Output current with PI</th>
<th>Output current without PI</th>
</tr>
</thead>
<tbody>
<tr>
<td>h5</td>
<td>1.03</td>
<td>1.94</td>
<td>0.66</td>
<td>0.8</td>
<td>0.05</td>
<td>0.07</td>
<td>0.05</td>
<td>0.06</td>
</tr>
<tr>
<td>h7</td>
<td>1.14</td>
<td>2.13</td>
<td>1.08</td>
<td>1.96</td>
<td>0.01</td>
<td>0.04</td>
<td>0.01</td>
<td>0.03</td>
</tr>
<tr>
<td>h11</td>
<td>0.43</td>
<td>0.81</td>
<td>0.25</td>
<td>1.24</td>
<td>0.04</td>
<td>0.18</td>
<td>0.04</td>
<td>0.13</td>
</tr>
<tr>
<td>h13</td>
<td>0.37</td>
<td>0.71</td>
<td>1.36</td>
<td>1.83</td>
<td>0.03</td>
<td>0.06</td>
<td>0.03</td>
<td>0.08</td>
</tr>
<tr>
<td>h17</td>
<td>0.14</td>
<td>0.26</td>
<td>0.41</td>
<td>0.7</td>
<td>0.05</td>
<td>0.08</td>
<td>0.04</td>
<td>0.06</td>
</tr>
<tr>
<td>h19</td>
<td>0.13</td>
<td>0.24</td>
<td>0.39</td>
<td>0.42</td>
<td>0.04</td>
<td>0.04</td>
<td>0.05</td>
<td>0.07</td>
</tr>
<tr>
<td>THD</td>
<td>8.77</td>
<td>14.46</td>
<td>34.09</td>
<td>39.13</td>
<td>11.86</td>
<td>13.87</td>
<td>7.36</td>
<td>8.4</td>
</tr>
<tr>
<td>IPF</td>
<td>0.98</td>
<td>0.59</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3.7 shows the comparison with other methods.

Table 3.7 Comparison with other methods

<table>
<thead>
<tr>
<th>Authors</th>
<th>Technique</th>
<th>Parameter</th>
<th>Proposed system parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sato et al. (2007)</td>
<td>EPC</td>
<td>$I_{THD}=3.81%$</td>
<td>$I_{THD}=1.59%$</td>
</tr>
<tr>
<td>Kim et al. (2010)</td>
<td>PWM</td>
<td>$I_{THD}=16.91$</td>
<td>$I_{THD}=1.59%$</td>
</tr>
<tr>
<td>Nguyen et al. (2011)</td>
<td>New direct SVM</td>
<td>IPF &gt;0.9 at q=0.7</td>
<td>IPF &gt;0.9 at q=0.84</td>
</tr>
</tbody>
</table>

3.4 INTEGRATED APPROACH IN GRID CONNECTED WIND ENERGY CONVERSION SYSTEMS

It is standard practice to implement each Wind energy generation system in micro-grid connected wind mills with same AC-DC-AC converter technique (Grigoletto & Pinheiro 2014). Harmonic cancelling is effective but
not complete in standard approach due to the dc-link voltage difference. But the proposed system uses optimized MC to one of the WECS and conventional converter to other WECS connected to same grid to reduce harmonics in load and improve the input power factor of wind system. Optimized PI controller based MC explained in the same chapter can be used for all WECS connected to same grid. There is an improvement in the performance of the system but cost of the system will be increased.

In order to reduce the cost and to improve the performance, one of the wind system is based on the optimized MC and other wind system with conventional converter can be used. The above discussed model is developed in MATLAB/ Simulink. Harmonic Performance analysis has been done with only conventional converters and with integrated approach. Induction Generator based Wind energy system is modelled to generate 100V as the input for converter. Harmonic study and input power factor measurement has been done in the output of converter at load side. Wind energy systems connected through only conventional converters give poor performance and proved. In integrated approach harmonic elimination and IPF improvement is achieved by GA based MC to one wind energy system connected to grid and conventional converter to another wind energy system connected to same grid. Optimized PI controller based MC (with same specifications) designed in previous section is considered for integrated approach to give good power factor. The above system is also verified with both wind systems connected through optimized MCs.
Figure 3.36 Integrated approach of Wind Energy Conversion System

The Figure 3.36 shows the integrated approach of WECS. Harmonic study has been carried out in load side under normal and light load conditions.

3.4.1 Results and Discussions

All the approaches are verified with same load (under normal load and light load), grid and input specifications used in previous section. Results are discussed in detail.
Figure 3.37  Load voltage and FFT spectrum for Wind energy systems with conventional converters (10A load)

Figure 3.38 Load current and FFT spectrum for Wind energy systems with conventional converters (10A load)
Figure 3.39  Load voltage and FFT spectrum for Wind energy systems with conventional converters (1A load)

Figure 3.40  Load current and FFT spectrum for Wind energy systems with conventional converters (1A load)
From the Figures 3.37 to 3.40, it is proved that WECS with conventional converters had high voltage and current THD (37.5% and 9.94% under normal load, 36.73% and 25.05% under light load). Maximum lower order harmonic content is 1.3%. THD is high due to inter harmonics and DC link. IPF is also poor (0.57 for normal load, 0.48 for light load).

Figure 3.41 Load voltage and FFT spectrum for Wind energy systems with optimized converters (10A load)
Figure 3.42  Load current and FFT spectrum for Wind energy systems with optimized converters (10A load)

Figure 3.43  Load voltage and FFT spectrum for Wind energy systems with optimized converters (1A load)
When both the converters of wind systems are replaced with PI controller based MCs then input power factor is nearly unity (0.98 for normal load and 0.94 under light load). Voltage and current THD are reduced to 9.81% and 4.02% for normal load and 14.05% and 13.04% under light load condition (Figures 3.41 to 3.44). Lower order voltage and current harmonics are less than 0.35%. Performance of the system is improved but cost of the system will be increased when more number of wind systems is used.
Figure 3.45  Load voltage and FFT spectrum for integrated approach of Wind energy systems (10A load)

Figure 3.46  Load current and FFT spectrum for integrated approach of Wind energy systems (10A load)
Figure 3.47 Load voltage and FFT spectrum for integrated approach of wind energy systems (1A load)

Figure 3.48 Load current and FFT spectrum for integrated approach of wind energy systems (1A load)
To reduce the cost, only 50% of wind systems are replaced with optimized PI controller based MCs. In Integrated approach (for 2 wind mills) in which one wind system with conventional converter and other system with optimized MC, the voltage and current THD is less (20%) compared to standard approach (37%) from the Figures 3.45 to 3.48. Maximum harmonic content is 0.7% which is less than 1.3% in standard approach. Input power factor also improved to 0.93 under normal load and 0.91 under light load.

3.4.2 Comparison of Results

Comparison of results of WECS with only conventional converters, only optimized converters and integrated approach (combination of conventional and optimized converter) under different load conditions are given.

![Comparison of Input power factor under different load](image)

**Figure 3.49 Comparison of Input power factor under different load**

From the Figures 3.49 and 3.50, a combination of conventional and optimized MC provides a better result compared to the implementation of system with conventional converters (THD is 37%) in micro grid. System with only optimized MCs gives better results (THD is 14.05%) than a system with combination of conventional and optimized MC (THD is 20%).
The integrated approach will be selected when cost is the factor and more number of wind mills is used. In the combination, the overall lower order harmonics (maximum of 0.7%), THD (20%) get reduced and IPF (0.93) also gets improved.

3.5 CONCLUSION

The optimized PI controller design for SVM technique in MC fed grid is proposed. Due to introduction of compensating angle in SVM technique according to the input phase difference, input side performance is improved. The results proved that introducing this optimized PI controller, input power factor (0.98) under light load is improved and THD (8.77%), lower order harmonics (maximum harmonic content of 1.51%) at different loads are also reduced. This also addresses some selective harmonics which are dominantly present in the system to avoid the major tribulations may occur due to that selective harmonics. The work is proven and validated by comparing with other methods. The MC fed grid is capable of operating at high power factor under any load condition with reduced harmonic distortion without affecting voltage transfer ratio which is 0.84. An integrated approach
is also introduced in this chapter, to use the PI controller based MC when number of wind mills are connected with grid. Instead of using MCs in all the wind systems connected to grid, half of the systems are replaced with optimized MCs then system performance has been improved (IPF is 0.93) and is proved, cost of the system also reduced.