CHAPTER 3

REACTIVE POWER COMPENSATION AND HARMONICS
MITIGATION USING STATCOM

3.1 INTRODUCTION

The increasing penetration of wind energy into existing power systems has forced grid operators to place new requirements for this kind of generating plants. This is enforced with the aim of keeping acceptable and reliable operation of the system. In addition to the fault ride through capability, WES is required to participate in voltage support, stability enhancement and power quality improvement. This chapter presents a solution to the wind generator which is affected by power quality issues by using a shunt compensating device. The aim of the device is to guarantee the grid code agreement, when the wind generator is subjected to power quality issues and grid disturbances.

3.2 LITERATURE SURVEY

The grid connected induction generators are preferred in a WES due to its rigid construction, asynchronous operation, low cost and maintenance (Chen & Hsu 2006). Operation of such induction generator has been an issue of analysis in stability studies for a long time (Brereton et al 1957) (Merkle et al 2001) (Papadopoulos et al 1992). In the past, with low wind energy penetration, the essential need of the wind generator was to protect itself from the grid effects. This has enlarged the concern over the stability of the existing grid for a reliable operation (Erlich & Bachmann 2005). The stability, reactive power, power factor and power quality issues are
highly noticeable, while integrating a large scale WES in to a weaker grid (Han et al 2008).

Low price transformer tap changers and mechanical switched capacitor banks can address the power factor and steady state voltage regulation issues. But problems like harmonics are not addressed by these devices (Smith Jeff & Brooks Daniel 2001). Furthermore, the above devices are slow responding and switching type that may lead to resonance and transient over voltage problem. This will cause extra stress to the WES and leads to maintenance problems (Kehrli & Ross 2003). Another conventional reactive power compensation device is Static Var Compensator (SVC). It is an arrangement of the thyristor controlled reactors and fixed shunt capacitors. It can provide voltage support and also address the transient problems. SVC has the capability of providing dynamic reactive power regulation to the grid. But, the effective reactive power generated by the SVC is based on its terminal voltage. Thus, the maximum reactive power output is reduced, when the grid is subjected to severe voltage drop. Because of the reduced capacity, it is likely to be saturated and extends the response time. Also, it will not tackle the harmonic issues (Gyugyi 1979) (Tan Owen et al 1993) (Chen et al 2010). Hence, a rapid shunt VAR compensator is needed to handle these issues effectively.

One such device that provides power electronic based reactive power compensation is STATCOM. It will act fast to control the voltage quickly and continuously, than conventional devices. Improved harmonics mitigation and reactive power compensation, during severe voltage disturbances, make STATCOM an appropriate device to handle short duration voltage issues (Hingorani Narain & Gyugyi 2000). With the latest technological development in semiconductor switching devices, quick responding STATCOM at lower cost is emerging in the market (Han et al 2005).
The consequence of power quality issue in the wind energy system and the enhancement of the wind generators performance are essential to meet the grid code requirements. Induction Generator based WES consumes reactive power from the grid for its operation. During grid disturbances, reactive power requirement will vary in a rapid manner. The WES connected to utility grid is also affected by the harmonics generated by the non linear loads. Hence, to address the aforementioned problems, a suitable shunt compensation device like STATCOM becomes vital.

3.3 STATCOM

STATCOM is used to generate or absorb reactive power by controlling the magnitude of the dc link and ac voltage. It includes a Voltage Source Converter (VSC), a transformer and a dc link capacitor. Secondary winding of the transformer is connected in shunt with the grid. The VSC is constructed as an inverter. It has a capacitor bank to support and stabilize the dc voltage in order to enable converter operation. The converter also keeps the capacitor charged to the necessary voltage level by making its output voltage of VSC to lag the ac system voltage by a small phase angle (Hingorani Narain & Gyugyi 2000). The phase angle is maintained at smaller range in order to permit active power flow to compensate solid state switching and coupling transformer losses (El Moursi et al 2011).

Here, the Capacitor is not used intrinsically in the reactive power generation/absorption process. Instead, this process is carried out by switching action of the PWM control signals which shift the voltage and current waveforms within the VSC to yield either leading or lagging VAR operation and to satisfy operational requirements. (Acha & Kazemtabrizi 2013). By exactly modulating the VSI output voltage, the VSI output current will be varied concurrently. This will guarantee the dynamic active and reactive power exchanges between the STATCOM and grid (Chen et al 2010)
The main advantage of the STATCOM is that the compensating current does not depend on the voltage level of the PCC. Hence, it is not reduced as the voltage drops (Hingorani Narain & Gyugyi 2000). This is an important feature in new grid codes. Hence, reactive power is provided to the wind generators, steadily depending on the grid demand and actual voltage level. Another significant feature is its inherent capacity to increase the transient stability margin by injecting a controllable reactive current independently of the grid voltage and it also improves the power quality (Molinas et al 2008).

3.3.1 Principle of Operation

STATCOM has a VSC connected to a DC bus and its AC side is connected in parallel across the PCC as shown in Figure 3.1. The VSC uses PWM control; hence, it requires filters to overcome switching ripples. It uses necessary control algorithm to generate gating signals for the IGBT devices. The VSC is usually controlled in PWM current control mode to inject necessary current in to the system. STATCOM also requires passive elements like a DC bus capacitor, AC interacting inductors, injection transformers and passive filters (Singh et al 2004).

![Figure 3.1 STATCOM](image)

**Figure 3.1 STATCOM**
3.4 STATCOM DESIGN

The STATCOM is designed according to the requirement of wind generator. The electrical specifications of the WES are shown in Table 3.1. The STATCOM design includes the selection of DC bus voltage, DC bus capacitor, AC inductor, ripple filter values, voltage and current rating of the IGBT switches. The interfacing inductors and a ripple filter are used to limit the ripple in the currents and voltages. The required rating of the STATCOM depends on the reactive power demand in the system. Uncontrolled rectifier, that contributes lower order harmonics particularly fifth and seventh order, is considered as non linear load and is connected to the PCC.

A three leg VSC is used in this design. This configuration has six IGBTs, three AC inductors, and a DC capacitor. The required compensation support from STATCOM decides the rating of the VSC components. The VSC is designed for compensating a reactive power of 1.53 MVAR in an 11 KV, 50 Hz, three phase system.

Table 3.1 Wind energy system electrical specification

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apparent Power</td>
<td>2.71 MVA</td>
</tr>
<tr>
<td>Real Power</td>
<td>2.5 MW</td>
</tr>
<tr>
<td>Voltage</td>
<td>11 kV</td>
</tr>
<tr>
<td>Frequency</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Reactive Power</td>
<td>1.023 MVAR</td>
</tr>
</tbody>
</table>

During grid drop, the reactive power demand may vary. Similarly, non linear load connected to the PCC contributes harmonics and considerably increases reactive power requirement. Considering both the aspects lead to 50 % variation in reactive power. Hence, it is selected to 1.53 MVAR.
i. Selection of DC Voltage

The dc voltage is selected by considering that minimum dc voltage of Voltage Source Converter (VSC) of the STATCOM should be greater than twice of the peak voltage of the system.

DC bus voltage is calculated from Equation 3.1

\[ V_{DC} = \frac{2\sqrt{2}V_{LL}}{m\sqrt{3}} \]  

\[ V_{DC} = \frac{2 \times \sqrt{2} \times 11000}{1 \times \sqrt{3}} \]

Where

\[ V_{DC} = \text{DC Bus Voltage}, \quad V_{LL} = \text{Voltage (Line to line)} = 11 \text{ KV} \] and

\[ m = \text{Modulation Index} = 1 \]

On substituting the above value

\[ V_{DC} = 17963.45 \text{ V} \]

ii. Selection of a DC Bus Capacitor

The value of the DC capacitor \( C_{DC} \) of the VSC of the STATCOM depends on the instantaneous energy required and available to the STATCOM during transients.

STATACOM is capable of operating even at 50% voltage variation in the line and with this condition, capacitance is calculated as follows

The principle of energy conservation is applied as shown in Equation 3.2

\[ \frac{1}{2} C_{DC} (V_{DC}^2 - V_{DC1}^2) = K_1 3V \alpha l t \]  

\[ \frac{1}{2} C_{DC} (17963.45^2 - 16167.10^2) \]

\[ = 0.15 \times 3 \times 5500 \times 1.2 \times 180 \times 1 \]
Where

\( V_{DC} \) is the nominal DC voltage equal to the reference DC voltage
\( V_{DC1} \) is the minimum voltage level of the DC bus (10 % drop in VDC during transients)

\( a \) = the overloading factor, \( V \) = phase voltage, \( I \) = phase current, (Reactive power/ rms phase voltage) = \((1140000/6351.03) = 178 \text{ A is rounded to 180 A}\), \( t \) = time by which the DC bus voltage is to be recovered.

Considering the minimum voltage level of the DC bus \((V_{DC1}) = 16167.10 \text{ V}\), \( V_{DC} = 17963.45 \text{ V}\), \( V = 5500 \text{ V}\), \( I = 180 \text{ A}\), \( t = 1 \text{ s}\), \( a = 1.2\), and variation of energy during dynamics = 15\% \((k_1 = 0.15)\), the calculated value of \( C_{DC} = 17439 \mu\text{F}\)

iii. Selection of an AC Inductor

The value of the AC inductance \((L_r)\) of a VSC depends on the current ripple, switching frequency \(f_s\), DC bus voltage \((V_{DC})\), and it is given as per Equation 3.3

\[
L_R = \frac{\sqrt{3} V_{DC} m}{12 a f_s I_{cr} - pp} \quad (3.3)
\]

\[
L_R = \frac{\sqrt{3} \times 17963.45 \times 1}{12 \times 1.2 \times 3970 \times 180 \times 0.2}
\]

where

\( m = \) modulation index, \( a = \) overloading factor, \( I_{cr - pp} = 20\%\)

Considering, \( f_s = 3970 \text{ kHz}\), \( m = 1\), \( VDC = 17963.45 \text{ V}\), and \( a = 1.2\) and the value of \( L_r \) is calculated to be 15.11 mH

iv. Selection of a Ripple Filter

A high pass first order filter has to be used to filter out the noise from the voltage at PCC. It has to be tuned to half the switching frequency.
The time constant of the filter should be very small compared with the fundamental time period (T), \( R_fC_f = T_f \), considering \( R_fC_f = T_s /10 \), where \( R_f \), \( C_f \), and \( T_s \) are the ripple filter resistance, ripple filter capacitance, and switching time, respectively. Considering switching frequency equal to 3970 Hz, the ripple filter parameters are selected as \( R_f = 10 \, \Omega \) and \( C_f = 2.5 \, \mu F \). The impedance offered for switching frequency is 18.9 \, \Omega \) and impedance offered to fundamental frequency is 1273.88 \, \Omega \), which is sufficiently large and hence, the ripple filter draws negligible fundamental frequency current.

Where \( T_f = \) time period with respect to fundamental frequency and \( T_s = \) time period with respect to switching frequency

v. Voltage and Current Ratings of the Solid-State Switches

The voltage rating (\( V_{sw} \)) of the device can be calculated under dynamic conditions as per Equation 3.4

\[
V_{sw} = V_{dc} + V_d
\]  

(3.4)

The voltage rating of the switch is calculated as

\[ V_S = 17963.45 + (17963.45 \times 0.1) \, V. \]
\[ V_S = 19759.79 \, V. \]

where \( V_d \) is the 10% overshoot in the DC link voltage under dynamic conditions.

The current rating (\( I_{sw} \)) of the device can be calculated under dynamic conditions as per Equation 3.5

\[
I_{SW} = 1.25 (I_{crpp} + I_{peak})
\]  

(3.5)

\( I_{crpp} = \) ripple current, \( I_{peak} = \) peak current

The current rating (\( I_{sw} \)) of the device can be calculated under dynamic conditions as per Equation 3.6
\[ I_{SW} = 1.25(I_{crpp} + I_{peak}) \quad (3.6) \]

\[ I_{SW} = 1.25(180 \times .2 + 180 \times 1.25) \]

\[ I_{SW} = 1.25(36 + 225) \]

\[ I_{SW} = 326.25 \, A \]

On substituting the values from the equations (3.1) to (3.6), the STATCOM values are calculated, IGBT rating is limited to available rating size of 6.5 kV, transformer is selected accordingly. STATCOM data is shown in Table.3.2

Table 3.2 STATCOM design data

<table>
<thead>
<tr>
<th>STATCOM</th>
<th>Reactive Power</th>
<th>1.53 MVAR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Current</td>
<td>385 A</td>
</tr>
</tbody>
</table>

| Converter Ratings      | Voltage        | 19.7 kV   |
|                        | Current        | 326.25 A  |
|                        | Power          | 6446 kW   |

| IGBT Ratings           | Voltage        | 6.5 kV    |
|                        | Current        | 400 A     |
|                        | Power dissipation | 5900 W  |
|                        | Operating Temperature | 40°C to 125°C |

| Transformer Ratings    | Primary Voltage | 11 kV     |
|                        | Secondary Voltage | 6.5 kV   |
|                        | Primary Current   | 236 A     |
|                        | Secondary Current | 400 A    |
|                        | Turn ratio        | 1.69      |

| DC Bus                 | Voltage         | 17963.45 V |
|                        | Capacitor       | 17439 μF   |

| Filter                 | Inductor        | 15.11 mH   |

| Ripple Filter          | Resistance      | 10 Ω       |
|                        | Capacitance     | 2.5 μF     |
The structure of the test system is shown in the Figure.3.2. The WES is connected to the utility grid. A non linear uncontrolled rectifier is connected to the PCC. The wind generator consumes reactive power and due to non linear load, harmonics are also experienced at PCC. Hence, STATCOM is connected at PCC for compensation.

3.5 PARK’S TRANSFORMATION

The performance of three phase equipment is generally described with their voltage and current equations. The coefficients of the differential equations, that express their performance, is time varying. The mathematical modelling of such system tends to be complex, since the flux linkage, induced voltage and current change continuously as the electric circuit are in relative motion. For such complex analysis, mathematical transformations are often used to decouple variables and to solve equations involving time varying quantities by referring all variables to a common frame of reference (Park
Robert 1929). Among the various transformation methods available, the well known is Park Transformation.

It can be applied to any arbitrary three phase and time dependent signals.

The Park transformation (dq0) is defined as

\[
\begin{bmatrix}
 x_d \\
 x_q \\
 x_0
\end{bmatrix} = \frac{2}{\sqrt{3}} \begin{bmatrix}
 \cos \theta_d & \cos \left(\theta_d - \frac{2\pi}{3}\right) & \cos \left(\theta_d + \frac{2\pi}{3}\right) \\
 -\sin \theta_d & -\sin \left(\theta_d - \frac{2\pi}{3}\right) & -\sin \left(\theta_d + \frac{2\pi}{3}\right) \\
 \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}}
\end{bmatrix} \begin{bmatrix}
 x_a \\
 x_b \\
 x_c
\end{bmatrix}
\]

(3.7)

Where \( \theta_d = \omega_d + \phi \), \( \omega_d \) in equation (3.7) is the angular velocity of the signals to be transformed and \( \phi \) is the initial angle.

The main advantage of this transformation is the fundamental positive sequence component of the signal is transferred into a constant DC term under steady state conditions. The harmonic component with frequency \( \omega_h \) will appear as a sinusoidal signal with the frequency of \( \omega_h - \omega_d \) in the dq0 frame.

3.5.1 Control of the STATCOM

The generator current is sensed and then transformed into synchronous dq0 reference frame. If the current contains harmonics, the park transformation results as per Equation 3.8

\[
\begin{bmatrix}
 i_d \\
 i_q \\
 i_0
\end{bmatrix} = \frac{2}{\sqrt{3}} \begin{bmatrix}
 \cos \theta_d & \cos \left(\theta_d - \frac{2\pi}{3}\right) & \cos \left(\theta_d + \frac{2\pi}{3}\right) \\
 -\sin \theta_d & -\sin \left(\theta_d - \frac{2\pi}{3}\right) & -\sin \left(\theta_d + \frac{2\pi}{3}\right) \\
 \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}}
\end{bmatrix} \begin{bmatrix}
 i_a \\
 i_b \\
 i_c
\end{bmatrix}
\]

(3.8)
where $I_{WGP}$ is the positive sequence of wind generator current, $I_{WGN}$ is the negative sequence of wind generator current and $I_{WGSP}$ is the set point as mentioned in Equation 3.9.

The current will change with the non-linear load characteristics at the PCC. Therefore, the expected current in the dq0 frame is given by Equation 3.10

$$i_{exp} = \begin{bmatrix} I_{WGP} \cos \theta_p \\ 0 \\ 0 \end{bmatrix}$$

(3.10)

The compensation reference current is given by equation 3.11

$$i_{ref} = i_{exp} - i_{WGdq0}$$

(3.11)

Where $i_{WGdq0}$ is the distorted load current in the dq0 frame (Fuchs & Masoum Mohammad 2011).

### 3.5.2 Significance of STATCOM Control

In the case of balanced three phase system, the application of this transformation will reduce the three AC quantities to two DC quantities. Simplified calculations have to be carried out on these DC quantities for the control of three phase inverters.

The main intention of the control algorithm of STATCOMs is to estimate the reference current using feedback signals. These reference current along with corresponding sensed current is used in PWM current controllers to
obtain gating signals for IGBT (switching devices) of the VSC. Reference current for the control of STATCOMs has to be derived accordingly and these signals are estimated using a PI and Fuzzy control algorithms.

### 3.6 STATCOM WITH PI CONTROLLER

The control algorithm of the STATCOM with PI control technique is shown in the Figure 3.3. This is used for regulating the voltage at the PCC. The PCC voltage \((V_{GDa}, V_{GDb}, V_{GDC})\), wind generator current \((i_{WGa}, i_{WGb}, i_{WGe})\) and DC bus voltage \(V_{DC}\) of the STATCOM are sensed as feedback signals and are used to derive the three phase reference grid current.

The sensed currents are in three phase and they are converted into the two axis orthogonal reference frame quantities using Parks transformation. The d-q \((i_{WGa}, i_{WGb})\) current components consist of fundamental and harmonics components. Individual low pass filter is utilized to extract the DC \((i_{WGdDC}, i_{WGqDC})\) components of the dq components of wind generator.

The approach of reactive power control requires that the source has to deliver the DC component along with the active power component. This is for maintaining the DC bus voltage and for meeting the losses \((i_{loss})\) in the STATCOM. The output of the \(PI_d\) controller at the DC bus voltage is considered as the current \((i_{loss})\) and is shown in Equation 3.12

\[
i_{loss}(n) = i_{loss}(n-1) + K_{pd} (V_{de(n)} - V_{de(n-1)}) + K_{id} V_{de(n)} \quad (3.12)
\]

\[
V_{de(n)} = V^{*}_{DC} - V_{DC(n)} \quad (3.13)
\]

\(V_{de(n)}\) shown in Equation 3.13 is the error signal between the reference DC voltage \((V^{*}_{DC})\) and sensed DC voltage \((V_{DC})\) at the \(n^{th}\) sampling instant and \(k_{pd}, k_{id}\) are the required gains for the \(PI_d\) controller of the DC bus voltage.
The reference d-axis grid current is obtained from Equation 3.14
\[ i^*_d = i_{dDC} - i_{loss}^* \] (3.14)

The magnitude of the PCC terminal voltage \( V_{GDreq} \) is controlled to its reference voltage \( V^*_{GDref} \) using another PIq controller. The output of PIq controller is considered as the reactive component of current \( i_{qr} \) for regulating the voltage at PCC. The amplitude of the voltage \( V_{GDreq} \) at PCC is calculated from the grid voltage \( (V_{Ga}, V_{Gb}, V_{Gc}) \) using the Equation 3.15
\[ V_{GDreq} = \sqrt{(2/3) \times (V_{Ga}^2 + V_{Gb}^2 + V_{Gc}^2)} \] (3.15)

Then, a PIq controller is used to regulate this voltage to a reference value using the relation as shown in Equation 3.16
\[ i_{qr(n)} = i_{qr(n-1)} + K_{pq}(V_{te(n)} - V_{te(n-1)}) + K_{iq}V_{te(n)} \] (3.16)
\[ V_{te(n)} = V^*_{GDref} - V_{GDreq(n)} \] (3.17)

\( V_{te(n)} \) in Equation 3.17 denotes the error between the reference PCC terminal voltage \( (V^*_{GDref}) \) and actual PCC terminal voltage \( (V_{GDreq(n)}) \) which amplitudes at the nth sampling instant. \( k_{pq}, k_{iq} \) are the proportional and the integral gains of the PIq controller.

The reference load quadrature axis grid current is given Equation 3.18
\[ i^*_q = i_{qr} - i_{qDC} \] (3.18)

Three phase reference grid current \( (i_{Ga}^*, i_{Gb}^*, i_{Gc}^*) \) are obtained through inverse Parks transformation using the control inputs \( i^*_d, i^*_q \). This reference wind generator current along with sensed grid current \( (i_{GDa}, i_{GDb}, i_{GDC}) \) is given to the PWM unit for generating switching signals for the VSC of the STATCOM. These values, in turn, determine the modulation index and the inverter output (Mohagheghi et al 2009). The output
of the VSC is fed to the grid through transformer. This will improve the performance of the wind generator

![Figure 3.3 STATCOM with PI controller](image)

**Figure 3.3 STATCOM with PI controller**

### 3.6.1 Results of Test System without STATCOM

For the test system shown in Figure 3.2, the results are obtained without using the STATCOM. The results of the wind generator voltage, current, real, reactive power, Fast Fourier Transform (FFT) analysis of the generator voltage and current are shown in the Figure 3.4
(a) Wind Generator Voltage

(b) Wind Generator Current

(c) Real & Reactive Power
From the Figure 3.4, it is understood that the wind generator voltage and current are distorted due to nonlinear load. It is also observed through FFT of generator voltage (9.22 %) and current (21.64 %). The real power (0.5 pu to 1 pu) and reactive power (-0.1 pu to -0.5 pu) of the wind generator are also deviated from its expected value of 1 pu and -0.44 pu, respectively. Hence, the system needs control device like STATCOM to overcome the aforementioned issues.
3.6.2 Results of Test System with STATCOM Using PI Controller

In the same test system, STATCOM using PI control technique is introduced between the WES and PCC. The results of the wind generator voltage, current, real, reactive power, FFT analysis of the generator voltage and current are shown in the Figure 3.5

(a) Wind Generator Voltage

(b) Wind Generator Current
Figure 3.5  a. Generator voltage b. Generator current c. Real and reactive power d. FFT of generator voltage e. FFT of generator current
From the Figure 3.5, the following inferences are obtained. The generator voltage and current harmonics are reduced to 3.09 % and 5.75 % from its previous value of 9.22 % and 21.64 %, respectively. It is noticed in FFT analysis. The real and reactive power has also improved to 0.9 pu and -0.5 pu, respectively. In order to meet the expected requirements of generator voltage (1 pu), current (1 pu), real power (1 pu), reactive power (-0.44 pu) and also to achieve better performance, intelligent control logic using fuzzy logic controller is used for controlling the STATCOM.

### 3.7 FUZZY LOGIC CONTROLLER

A power system with generators and power electronic devices is an extremely nonlinear system. It is also a non stationary system because the power system configuration changes continuously, as lines and loads are switched on and off (Mohagheghi et al 2009).

In recent days, most of the researches have recommended techniques for designing controllers using linear control methods. In such method, the system equations are linearized at a precise operating point. Based on the linearized model, Proportional Integral (PI) controllers are tuned to obtain the finest possible performance (Dong et al 2004) (Shen & Lehn 2002) (Schauder & Mehta 1993).

The main disadvantage of PI controllers is that their performance degrades with change in the system operating conditions. On the other hand, nonlinear adaptive controllers may provide better control ability over a broad range of operating conditions. They have an additional complicated structure and are more difficult to realize compared to linear controllers. Furthermore, most of these designs need access to the mathematical model of the system, which, in most cases, is very difficult to obtain (Liu et al 2003) (Lu et al 2001) (Yao et al 1998).
Fuzzy logic controllers provide solutions to the above mentioned problems. They are capable to deal with such nonlinear system. With little or no need for prior information, it can provide proficient control over a wide range of system operating conditions (Mohagheghi et al 2009).

### 3.7.1 Structure of FLC

The fuzzy logic controller has four main components as shown in Figure 3.6

![Figure 3.6 Fuzzy logic controller](image)

- **Fuzzy rule-base** holds the knowledge, in the form of a set of rules, of how best to control the system.

- **Fuzzy inference engine** evaluates which control rules are relevant at the current time and then, decides what the input to the process should be.

- **Fuzzification** interface simply modifies the inputs so that, they can be interpreted and compared to the rules in the rule base.

- **Defuzzification** interface converts the conclusions reached by the fuzzy inference engine into inputs to the process (Passino Kevin et al 1998).
3.7.2 STATCOM with Intelligent Fuzzy Controller

The control algorithm of the STATCOM with Fuzzy control technique is shown in the Figure 3.7. It performs the same function as mentioned in PI controller. The sensed inputs for the PI controller are utilized in the same manner for the fuzzy controller. The entire control process is same till the generation of firing pulse by the PWM controller. The change is that the two PI controllers are replaced by the fuzzy controllers.

This controller is tuned based on the fuzzification. Due to simplicity, the input/output fuzzy membership sets are designed using the standard equal span mathematical functions, such as the triangular functions (Mohagheghi et al 2009). It is one of the widely used models (Ying 2010).

![Figure 3.7 STATCOM with Fuzzy controller](image-url)
Table 3.3 Fuzzy rule base

<table>
<thead>
<tr>
<th>Input</th>
<th>NB</th>
<th>NM</th>
<th>NS</th>
<th>Z</th>
<th>PS</th>
<th>PM</th>
<th>PB</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB</td>
<td>NB</td>
<td>NM</td>
<td>NL</td>
<td>PB</td>
<td>PL</td>
<td>PM</td>
<td>PB</td>
</tr>
<tr>
<td>NM</td>
<td>NM</td>
<td>NB</td>
<td>NM</td>
<td>PM</td>
<td>NL</td>
<td>PM</td>
<td>PB</td>
</tr>
<tr>
<td>NS</td>
<td>NL</td>
<td>NM</td>
<td>NB</td>
<td>PL</td>
<td>NM</td>
<td>NL</td>
<td>PL</td>
</tr>
<tr>
<td>Z</td>
<td>PB</td>
<td>PM</td>
<td>PL</td>
<td>NB</td>
<td>NL</td>
<td>NM</td>
<td>NB</td>
</tr>
<tr>
<td>PS</td>
<td>PL</td>
<td>NL</td>
<td>NM</td>
<td>NL</td>
<td>NB</td>
<td>NM</td>
<td>NL</td>
</tr>
<tr>
<td>PM</td>
<td>PM</td>
<td>PL</td>
<td>NL</td>
<td>NM</td>
<td>NM</td>
<td>NB</td>
<td>NM</td>
</tr>
<tr>
<td>PB</td>
<td>PB</td>
<td>PM</td>
<td>PL</td>
<td>NB</td>
<td>NL</td>
<td>NM</td>
<td>NB</td>
</tr>
</tbody>
</table>

3.7.3 Fuzzy Membership Function ($F_d$)

![Graph (a)](image1)

![Graph (b)](image2)
Figure 3.8 Membership function for inputs a. VDC (KT)  
b. VDC ((K-1) T) c. iloss

3.7.4 Fuzzy Membership function ($F_q$)
3.7.5 Description of FLC

The linguistic variables are defined for input and output variables namely Negative Big (NB), Negative Medium (NM), Negative Small (NS), Zero, Positive Small (PS), Positive Medium (PM) and Positive Big (PB). The Fuzzy rules for the two controllers (Fuzzy\(_d\) and Fuzzy\(_q\)) are listed in the Table 3.3. The input/output fuzzy membership sets for the two fuzzy controllers are designed using the standard equal span mathematical triangular function and are shown in Figures 3.8 and 3.9. For example, in the Fuzzy\(_d\) controller of STATCOM a membership function is defined for regulating the DC bus voltage. Here, if the error difference between the sensed DC voltage (\(V_{DC}\)) to its reference DC voltage (\(V^{*}_{DC}\)) at a particular k th instant \(\delta(V_{dc}(KT))\) to its value on previous instant \(\delta(V_{dc}(K-1)T))\) is very low [Negative Big(NB)] then, it indicates error signal \(V_{dec(n)}\) is high. Hence, in order to reduce the error it requires more current \(i_{loss}\). Hence, it is Negative Big (NB).

Similarly, in Fuzzy\(_q\) controller, for regulating the grid voltage a membership function is defined. In that function if the error between the amplitudes of the reference wind generator terminal voltage (\(V^{*}_{WG}\)) and the actual wind generator terminal voltage (\(V_{WG}\)) at a particular k th instant...
δ VGrid[KT] and on its previous instant ie δ (VGrid[(K-1)] is low [Negative Big (NB)], then, it indicates that the system need more reactive component of voltage (Vqr) for regulating the wind generator terminal voltage and hence, Vqr is Negative Big [NB].

The fuzzy_d controller has two inputs, one from DC bus reference voltage and the other is actual sensed DC voltage across the capacitor. It will give current (i_loss). It forms the real component of the reference current. In the mean time, the sensed wind generator current is transformed into iWGd and iWGq using Parks transformation. The current inputs i_loss and iWGd are given to a comparator and its output gives the control signal i*_d. Similarly, fuzzy_q receives sensed PCC voltage and VGDreq and its output gives the reactive component of the reference current i*_q. The current signals i*_d and i*q are given to a comparison block that gives the control signal i*_q. The two control outputs (i*_d, i*_q) are transformed into three phase signal using inverse Park transformation and are given as one input to the current controlled PWM unit. The other input to the PWM unit is the actual sensed grid current. Now, the PWM unit generates switching signals for the IGBT of the VSC. The output of the VSC is coupled with grid through a transformer. This reduces the non linearity in the wind generator current and improves the power quality.

3.7.6 Results of Test System with STATCOM Using Fuzzy Logic Controller

STATCOM using fuzzy logic control technique is introduced into the same test system. The results of the wind generator voltage, current, real, reactive power, FFT analysis of the generator voltage and current are shown in the Figure 3.10
Figure 3.10 a. Generator voltage  b. Generator current  c. Real and reactive power  d. FFT of generator voltage  e. FFT of generator current

Following data are obtained from Figure 3.10. Wind generator voltage and current have improved significantly and the effect of harmonics is also reduced. It is reflected in the FFT analysis. The THD values of the generator voltage and current have been reduced to \(2.21\%\) and \(4.19\%\), respectively. The real and reactive power of the wind generator also settles at their required value of 1 pu and \(-0.45\) pu.
Table 3.4  Performance comparison of STATCOM with PI and Fuzzy controller

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Target Value</th>
<th>Actual value of uncontrolled non linear Load (400 KW)</th>
<th>With STATCOM</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Without STATCOM</td>
<td>With STATCOM</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>PI Controller</td>
</tr>
<tr>
<td>Wind Generator Voltage</td>
<td>1 pu</td>
<td>1 pu</td>
<td>1 pu</td>
</tr>
<tr>
<td>Wind Generator Voltage THD</td>
<td>5 %</td>
<td>9.22 %</td>
<td>3.09 %</td>
</tr>
<tr>
<td>Wind Generator current</td>
<td>1 pu</td>
<td>1.1 pu</td>
<td>1 pu</td>
</tr>
<tr>
<td>Wind Generator current THD</td>
<td>15 %</td>
<td>21.64 %</td>
<td>5.75 %</td>
</tr>
<tr>
<td>Wind Generator Real Power</td>
<td>1 pu</td>
<td>0.5 pu to 1 pu</td>
<td>0.9 pu</td>
</tr>
<tr>
<td>Wind Generator Reactive Power</td>
<td>-0.44 pu</td>
<td>-0.2 pu to -0.6 pu</td>
<td>0.5 pu</td>
</tr>
</tbody>
</table>

The comparison of control technique for the STATCOM is shown in Table 3.4. From the comparison, it is inferred that STATCOM with Fuzzy logic controller gives better performance in maintaining the wind generator parameters to the required value. Further, the THD of generator voltage and current are also brought to lower value to 2.21 % and 4.19 % from the values of 9.22 % and 21.64 %, respectively. The comparison result of the test system also shows that STATCOM with PI as well as Fuzzy controllers is capable of addressing the reactive power and harmonics.

Since, the speed of the wind is varying in nature, the reactive power requirement of generator will also vary with respect to the output power of the
WES. Therefore, the performance of the STATCOM has to be tested for different wind speed conditions.

3.8 PERFORMANCE OF STATCOM FOR VARYING WIND SPEED CONDITIONS

The reactive power requirement of the WES will vary with variation in output power during change in wind speed. Hence, the performance of the STATCOM shown in the test system 3.2 has been tested for different wind speed conditions. First, the varying wind conditions are tested in the test system without STATCOM. In the test system, initially the wind speed is set to 10 m/s for period of 0 to 0.5 s and increased to the optimum period of 20 m/s from 0.5 s to 1 s. Again, the wind speed is decreased to 15 m/s for the period between 1 sec to 1.5 sec and it is increased to optimum speed of 20 m/s from 1.5 s to 2 s. Wind speed, generator voltage, generator current, real and reactive power are obtained as shown in Figure 3.11.
Figure 3.11  a. Wind speed  b. Generator voltage  c. Generator current  
 d. Real and reactive power
From the Figure 3.11, it is inferred that the wind generator current is reduced +4.5 pu to -4.5 pu for the wind speed 10 m/s and +0.75 pu to -0.75 pu for the wind speed 15 m/s and it settles at the target value of 1.1 pu for 20 m/sec. The wind generator voltage settles at 1 pu. Real power is varied from 0.4 pu to 1 pu and reactive power is varied from -0.2 pu to -0.65 pu. Both real and reactive power are oscillating during the initial time period from 0 to 0.1 sec and they also changes from its target value 1 pu and -0.44 pu, respectively.

3.8.1 STATCOM with PI and Fuzzy Controller

Now in the test system, STATCOM with PI controller is introduced. The same variations in the wind speed as mentioned for the previous case are maintained here. Wind speed, generator voltage, generator current, real and reactive power are obtained as shown in Figure 3.12
Now, in the test system, STATCOM with Fuzzy controller is introduced. The same variations in the wind speed as mentioned above for PI controller is maintained here. Wind speed, generator voltage, generator current, real and reactive power are obtained as shown in Figure 3.13
Figure 3.13  STATCOM with fuzzy Controller a. Generator voltage b. Generator current c. Real and reactive power
Following data are obtained from Figure 3.12 and Figure 3.13. Wind generator voltage is maintained at the target value of 1 pu for STATCOM with PI and Fuzzy controller under varying wind speed conditions. The generator current is varied from 0.5 pu for wind speed of 10 m/s, 0.75 pu for 15 m/sec and 1 pu 20 m/sec for STATCOM with PI and Fuzzy controllers. The reactive power is varied from -0.4 pu and -0.5 pu for STATCOM with PI and fuzzy controllers respectively. In both the cases reactive power is close to the target value of -0.44 pu. Compared to Figure 3.11, the oscillation in the Reactive power between the time period 0 to 0.1 s has been reduced and it is also improved to -0.5 pu from -0.2 pu. Hence, it is understood that the STATCOM is capable of supporting the test system with required reactive power even under varying wind speed conditions.

![Figure 3.14 Test system with STACOM and fault](image-url)
But in the grid, voltage disturbance in the form of voltage sag is also common and it needs to be addressed with care. Hence, in the same test system, a three phase fault is made as shown in Figure 3.14 in order to test the ability of the STATCOM in enhancing the fault ride through capability.

3.9 RESULTS OF TEST SYSTEM WITHOUT STATCOM DURING THREE PHASE FAULT

The results are obtained from the test system without STATCOM after introducing three phase fault. The wind generator voltage, current, real, reactive power, FFT analysis of the generator voltage and current are shown in the Figure 3.15

![Wind Generator Voltage](image1)

![Wind Generator Current](image2)
Figure 3.15  
a. Generator voltage b. Generator current c. Real and reactive power d. FFT of generator voltage e. FFT of generator current
In the test system, a three phase fault is made during the time interval 0.5 s to 0.7 s. This has created a significant impact in the wind generator parameters. As a result, wind generator voltage is reduced during the fault and resumed back with small transient at the time of fault clearance. But, the wind generator current is affected more. It has high transient in the beginning and at the end of the fault. The generator current has not been recovered after the fault. From the Figure 3.15, following data are obtained. The THD values of the generator voltage and current has increased to 27.12 % and 40.15 % respectively. THD is calculated at the time of fault clearance. The real power has reduced to 0.2 pu and reactive power has increased to 0.1 pu from the expected value of 1 pu and -0.44 pu, respectively during the fault.

3.9.1 Results of Test System with STATCOM during Three Phase Fault

The results are obtained from the test system after introducing three phase fault in the system with STATCOM supported with PI controller. The wind generator voltage, current, real, reactive power, FFT analysis of the voltage and current are shown in the Figure 3.16
The results of STATCOM with Fuzzy Controller under fault situation are shown in Figure 3.17.

**Figure 3.16** a. Generator voltage b. Generator current c. Real and reactive power d. FFT of generator voltage e. FFT of generator current
Wind Generator Current

(b)

Real & Reactive Power

(c)

(d)
Three phase symmetric fault is made in the test system during the time 0.5 s to 0.7 s to both the cases i.e. STATCOM with PI and fuzzy controllers. The behaviour of the wind generator parameters including voltage, current, real and reactive power at the time of fault and after its clearance has to be investigated in both the cases.

From the Figures 3.16(a) and 3.17(a) it is inferred that the wind generator voltage is reduced during the fault and is recovered to its normal value with a small transient of + 1.5 pu – 1.5 pu at the time of fault clearance. But in the case of wind generator current shown in Figures 3.16(b) and 3.17(b), during the fault, the current value has increased to a higher transient value of + 3 pu to 3 pu and + 2.5 pu to -2.5 pu for PI and Fuzzy controllers, respectively and oscillates at same value after the clearance of fault. In both cases (i.e. STATCOM with PI and Fuzzy controller), the wind generator current is well above the required value of 1 pu.
The real and reactive power variation shown in Figures 3.16(c) and 3.17(c) at the time of fault is another important issue to be noticed. The reduction in real power to 0.2 pu at the time of fault has increased the reactive power consumption by the generator to a higher value of 0.8 pu and 0.6 pu for PI and Fuzzy controllers respectively. At the time of fault clearance, the real power and reactive power are changed to 1.5 pu and -1 pu for PI controller and 1 pu and -0.8 pu for fuzzy controller. These values also deviate from its reference value of 1 pu and -0.44 pu, respectively. This will disturb the stability margins of the grid as well as wind generator. The THD values of generator voltage as well as current have increased to 16.12 % and 36.07 %. This is due to non linear behaviour of voltage and current after the clearance of fault. There is no much variation in THD in both the cases. The overshoot in fuzzy controller is limited to 2%. In this application it is not affecting the system performance to much extent.

**Table 3.5 Performance comparison of STATCOM with PI and Fuzzy controller during symmetric fault**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Target Value</th>
<th>Actual Value of Non linear Load (400 KW)</th>
<th>Without STATCOM</th>
<th>With STATCOM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind Generator Voltage</td>
<td>1 pu</td>
<td>0.2 pu to 1 pu</td>
<td>0.2 pu to 1 pu</td>
<td>0.2 pu to 1 pu</td>
</tr>
<tr>
<td>Wind Generator Voltage THD</td>
<td>5 %</td>
<td>27.12 %</td>
<td>16.39 %</td>
<td>16.12 %</td>
</tr>
<tr>
<td>(at the time of fault clearance)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wind Generator current</td>
<td>1 pu</td>
<td>-3.5 pu to 3.5 pu</td>
<td>-3 pu to 3 pu</td>
<td>-2.5 pu to 2.5 pu</td>
</tr>
<tr>
<td>Wind Generator current THD</td>
<td>15 %</td>
<td>40.15 %</td>
<td>38.29 %</td>
<td>36.07 %</td>
</tr>
<tr>
<td>(at the time of fault clearance)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wind Generator Real Power</td>
<td>1 pu</td>
<td>1.5 pu to 2 pu</td>
<td>1 pu to 2 pu</td>
<td>1 pu to 1.6 pu</td>
</tr>
<tr>
<td>Wind Generator Reactive Power</td>
<td>-0.44 pu</td>
<td>1 pu to -2.5 pu</td>
<td>0.1 pu to -1.5 pu</td>
<td>-0.2 pu to -1 pu</td>
</tr>
</tbody>
</table>
The comparison of control techniques of the STATCOM with three phase fault is shown in Table 3.5. It is inferred from the Figures 3.15, 3.16, 3.17 and Table 3.5, that STATCOM can support the system with reactive power at the time of fault clearance which will reduce the fault recovery time of the WES. But, it has not regulated the wind generator voltage during the fault.

At the same time, in the simulation for all above three cases, the mechanical energy to the WES remains unchanged (simulation time 0 to 1 sec and fault is made between 0.5 s to 0.7 s). Since there is no sufficient electrical power to balance the mechanical torque, the wind generator is not able to recover to its normal state after the fault and it has to be tripped out by protection systems (Chen et al 2007) (Chen & Hsu 2006). Fault of symmetric or asymmetric in the grid can lead to sudden drop (voltage sag) in grid voltage. This voltage drop can induce transient current at the wind generator terminal connected to the grid. Such transient current at the time of fault may not affect the wind energy system directly, but, it increases the operating temperature of the system, which then directly, affect the protection, processing and communication devices associated with the WES. Hence, there is a possibility for the above mentioned devices to get damaged.

Here, STATCOM will support the WES with reactive power at the time of fault to maintain the system stability, but, it will not support the transient issues and its associated problems.

Therefore, from the above discussion, it is understood that the STATCOM may not completely enhance the fault ride through capability of the WES during voltage sag which is very common in grid.
3.10 CONCLUSION

The successful operation of WES connected to a utility grid with non linear load may need dynamic reactive compensation and harmonic mitigation. With conventional methods, this support is provided through mechanical tap changers, switched capacitors and SVC. But, all these devices are inefficient to provide continuous reactive power support with respect to dynamic grid conditions and also they will not address harmonic issues. In most situations, the WES is tripped from the grid due to lack of reactive power support. This will affect the stability of the grid. In the mean time, the non linear load connected to the utility grid also limits the performance of the WES.

Hence, this work has investigated the application of a STATCOM to accomplish the continuous operation of a FSWES. The STATCOM is positioned at PCC for providing transient voltage support and harmonics mitigation. Two control schemes for the STATCOM, one with conventional PI controller and other with intelligent fuzzy controller have been suitably designed and investigated and the results are tabulated. Among the two, STATCOM with fuzzy controller has reduced the voltage and current THD of the WES by 76 % and 40 %, respectively compared to test system without STATCOM. Further, it has maintained the real and reactive power of the system at the required value of 1 pu and -0.44 pu, respectively. The performance of the STATCOM is also tested for varying wind speed conditions and it gives satisfactory performance. From the results, it is understood that STATCOM will avoid the tripping of WES due to reactive power variation and it also mitigates harmonics. Thereby, the stability of the grid and performance of the WES are enhanced. The existing system with STATCOM proposed by Mohod Sharad & Aware Mohan (2010) is validated for smaller Wind generator ratings (3.35 kVA, 415 V, 50 Hz, non linear load
25 KW) for the power quality issues such as reactive power support and harmonics mitigation. But, STATCOM proposed in this work addresses the reactive power support and harmonics elimination for higher Wind generator ratings (2.71 MVA, 11 KV and 50 Hz, non linear load 400 KW) and maintains the grid stability. The performance of the STATCOM in the existing system addresses the above mentioned power quality issues only for constant wind speed, but, in this work the STATCOM addresses the same power quality issues for both constant and varying wind speed conditions. Further the existing system addresses only reactive power and harmonics but its application for fault recovery is not discussed. Since, the tripping of wind generator in most cases is due to lack of reactive power support and hence, the system takes longer duration for fault recovery. With the aid of proposed STATCOM, the reactive power during fault recovery is supported and thereby the stabilization of the wind generator is improved.

In the mean time, the performance of the STATCOM is analyzed for fault ride through capability during voltage disturbance in form of voltage sag. Three phase fault is made to occur in the grid which causes voltage sag in the system and the impact of the voltage sag on WG is analyzed. From the results, it is inferred that STATCOM has not effectively handled the voltage sag. The response of wind generator parameters like voltage, current, real and reactive power has been changed drastically. Hence, shunt connected STATCOM may not enhance the fault ride through capability of the WES. To achieve the same, effective series compensation is essential to offer direct voltage restoration at the wind generator terminals.