CHAPTER 5
METHODOLOGY FOLLOWED

5.1: FACTS devices and capabilities

Recently, FACTS-based devices have been used for power flow control and power system oscillation damping. They can also be used to increase transmission line capacity, steady state voltage regulation, to provide transient voltage support to prevent system collapse and to damp the power system oscillations. FACTS devices can be used in wind power systems to improve the transient and dynamic stability of the overall power system. The STATCOM is from the family of FACTS devices that can be used effectively in wind farms to provide transient voltage support to prevent system collapse. In other words a STATCOM is an electronic generator of reactive power. Transmission of power ‘S’ (P+ jQ) over a power line with impedance ‘Z’(R+jX) results in a voltage drop (Δ V) [89].

\[ \Delta V = RP + \frac{XQ}{V} \]  \hspace{1cm} (5.1)

For larger wind farms connected to transmission systems X >> R and, from equation 5.1, ΔV is directly proportional to the reactive power (Q) transferred. From this equation, it is clear that for efficient voltage control, an effective reactive power strategy is required. FACTS devices can provide dynamic and steady state support. They can improve dynamic and transient stability; control dynamic over voltages and under voltages and also support against frequency and voltage collapses [89].

5.2: SVC/STATCOM/UPFC Comparisons

The thyristor protected series compensation (TPSC), thyristor controlled series compensation (TCSC) is those FACTS devices that have a strong influence on the system stability and small or no influence on the voltage quality. The SVC and STATCOM have a strong influence on voltage quality improvement and show
medium performance with respect to overall system stability. The unified power flow controllers (UPFC) have shown efficient performance in terms of load flow support, stability and voltage quality. The main objective of this thesis is to look for solutions to provide voltage stability to the system in order to operate wind turbines in accordance with the grid codes. The STATCOM is the best option available for providing efficient voltage quality in the power system. A STATCOM is a shunt-connected reactive power compensation device that is capable of generating and / or absorbing reactive power and in which the output can be varied to control the specific parameters of an electric power system. The STATCOM is a static compensator and is used to regulate voltage and to improve dynamic stability. A STATCOM can supply the required reactive power under various operating conditions to control the network voltage actively and thus, improve the steady state stability of the network. The STATCOM can be operated over its full output current range even at very low voltage levels and the maximum VAR generation or absorption changes linearly with the utility or AC system voltage. The maximum compensating current of the SVC decreases linearly with the AC system voltage and the maximum VAR output decreases with the square of the voltage. This implies that for the same dynamic performance, a higher rating SVC is required when compared to that of a STATCOM. For an SVC, the maximum transient capacitive current is determined by the size of the capacitor and the magnitude of the AC system voltage. In the case of a STATCOM, the maximum transient capacitive over current capability is determined by the maximum turn-off capability of the power semiconductors employed [90].

The main function of a STATCOM is to provide reactive power support and thus improve voltage stability. The main objective of using a UPFC in a system is to be able to control both active and reactive power in the associated line in which it is placed. The STATCOM has better reactive power control than an SVC. Mechanically switched capacitors do not have a better performance at lower voltages and hence a higher rating device is needed for the same performance. Also, the reactive power support provided by the SVC is dependent on the AC system voltage and hence its capability is de-rated at lower voltages. The UPFC is not very economical and requires more complicated control techniques for exploiting its complete capabilities [91].

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5.3: Reasons for Choosing a STATCOM

Capacitors are usually connected to fixed speed wind turbines to enhance the system voltage because they are a sink of reactive power. Mechanically switched fixed shunt capacitors can enhance the system’s voltage stability limit, but is not very sensitive to voltage changes. Also, voltage regulated by the wind generators equipped with only fixed capacitors can become higher than the voltage limit of 1.05 pu. Hence, a fixed capacitor cannot serve as the only source of reactive power compensation. One of the most important advantages of using STATCOM over a thyristor based SVC is that it’s compensating current is not dependent on the voltage level at the connection point which means that the compensating current is not lowered as the voltage drops. The output of the wind power plants and the total load vary continuously throughout the day. Reactive power compensation is required to maintain normal voltage levels in the power system. Reactive power imbalances, which can seriously affect the power system, can be minimized by reactive power compensation devices such as the STATCOM. The STATCOM can also contribute to the low voltage ride through requirement because it can operate at full capacity even at lower voltages. In this thesis, a voltage source converter (VSC) PWM technique based STATCOM is proposed to stabilize grid connected generator based wind turbines [92].

5.4: Introduction of STATCOM

The static synchronous compensator (STATCOM) is a three-phase and shunt connected, power electronics based device. It is connected near the load at the distribution systems. The major components of a STATCOM are, a DC capacitor, three-phase inverter (GTO) module, coupling transformer and a control strategy. The basic electronic block of the STATCOM is the voltage-sourced inverter that converts an input DC voltage into a three-phase output voltage at the fundamental frequency. The STATCOM is capable of generating and / or absorbing reactive power whose output can be varied so as to maintain control of specific parameters of the electric power system like reactive power, voltage sag and / or swell magnitude as well as phase angle.
The objective of the STATCOM is to provide fast and smooth voltage regulation at the point of common coupling (PCC). In this thesis work, the VSC is modeled as a six-pulse PWM GTO converter with a DC-link capacitance. The operation of each individual GTO switch (with a snubber circuit) in the VSC is fully represented [92].

5.5: Principle operation of STATCOM

Figure 5.1 shows the basic model of a STATCOM which is connected to the AC system bus through a coupling transformer. In a STATCOM, the maximum compensating current is independent of system voltage, so it operates at full capacity even at low voltages. A STATCOM’s advantages include flexible voltage control for power quality improvement, fast response and applicability for use with high fluctuating loads.

![Figure 5.1: Basic model of a STATCOM [93]](image)

The output of the controller $Q_c$ is controllable which is proportional to the voltage magnitude difference $V_c - V$ and is given by:

$$Q_c = V \frac{(V_c - V)}{X} \quad (5.2)$$
The STATCOM is a static VAR generator whose output can be varied so as to maintain or control certain specific parameters of the electric power system. The STATCOM is a power electronic component that can be applied to the dynamic control of the reactive power and the grid voltage. The reactive output power of the compensator is varied to control the voltage at given transmission network terminals, thus maintaining the desired power flows during possible system disturbances and contingencies. STATCOMs have the ability to address transient events at a faster rate and with better performance at lower voltages than a static voltage compensator (SVC). The maximum compensation current in a STATCOM is independent of the system voltage. Overall, a STATCOM provides dynamic voltage control and power oscillation damping, and improves the system’s transient stability. By controlling the phase angle, the flow of current between the converter and the AC system are controlled. A STATCOM was chosen as a source for reactive power support because it has the ability to continuously vary its susceptance while reacting fast and providing voltage support at a local node. The shunt inverter, transformer and connection filter are the major components of a STATCOM. The control system employed in this system maintains the magnitude of the bus voltage constant by controlling the magnitude and/or phase shift of the voltage source converter’s output voltage. The DC capacitor voltage is maintained at a constant value and this voltage error is used to determine the reference for the active power to be exchanged by the inverter.

The voltage source inverter generates an AC voltage from a DC voltage with a desired magnitude and frequency, so that it is often referred to as a DC-AC converter or inverter. The firing control signals applied to the transistors are controlled such that each GTO conducts over 180° conduction period. The voltage source inverter generates a controllable AC voltage source behind the leakage reactance. This voltage is compared with the AC bus voltage system. When the AC bus voltage magnitude is above that of the voltage source inverter voltage magnitude, the AC system sees the STATCOM as an inductance connected to its terminals. Otherwise, if the voltage source inverter voltage magnitude is above that of the AC bus voltage magnitude, the AC system sees the STATCOM as a capacitance connected to its terminals. If the voltage magnitudes are equal, the reactive power exchange is zero [93].
5.6: Active & reactive power exchange

The reactive power exchange between the AC system and the compensator is controlled by varying the magnitude of the fundamental component of the inverter voltage above and below that of the AC system. The compensator control is achieved by small variations in the switching angle of the semiconductor devices, so that the fundamental component of the voltage produced by the inverter is forced to lag or lead the AC system voltage by a few degrees. This causes active power to flow into or out of the inverter modifying the value of the DC capacitor voltage, and consequently the magnitude of the inverter terminal voltage and the resultant reactive power. The phase shift $\Phi$ across the AC power system and the fundamental compensator voltage decides how the active power & reactive power is exchanged.

During the fault condition, to meet extra demand of reactive power, the switching angle of semiconductor devices is varied in such a way that the fundamental component of inverter voltage lags the AC system voltage. This causes active power to flow from AC system to the compensator to increase the DC voltage level and hence to supply more reactive power to AC system [93].

If the amplitude of the inverter voltage is increased above the AC system, then the current flows from the inverter to the AC system. In this case the compensator is seen as a capacitor by the AC system as shown in figure 5.2.

![Figure 5.2: Operation modes of STATCOM -Capacitive Mode Vi > Vs [93]](image)

If the amplitude of the inverter voltage is decreased below that of the AC system, then the current flows from the AC system to the compensator. In this case the compensator is seen as an inductor by the AC system. The inductive operating mode of the STATCOM is shown in figure 5.3.
5.7: Capacitor sizing

The capacitor plays an important role in the STATCOM operation by acting as a DC source to provide reactive power to the load. Capacitor sizing is dependent on the fault current in the system. The difference in current between its value before and after the fault is considered as a step drop of load current. In capacitor sizing, a suitable range of DC capacitor is needed to store the energy to mitigate the voltage sag. The DC capacitance ($C_{DC}$) is used to inject reactive power to the STATCOM when the voltage is in a sag condition. To determine the capacitor size, first energy loss of the capacitor ($\Delta E_c(t)$) is considered in one period as [93].

$$\Delta E_c(t) = \frac{1}{2} C_{DC} \left[ V_{CMAX}^2 - V_{dc}^2 \right]$$  \hspace{1cm} (5.3)

$V_{CMAX}$ = pre-set upper limit for voltage (per phase),

$V_{dc}$ = voltage across C (per-phase).

$C_{DC}$ = DC Capacitance.

But the energy loss is also supplied by the utility voltage source, $V_{SC}$ and the peak value of the charging current $I_{SC}$, in which the energy loss can be written as,

$$\Delta E_c(t) = \int_0^T V_{SC} \sin \omega t \, I_{SC} \sin \omega t \, d\omega t$$  \hspace{1cm} (5.4)

Simplifying the equation (5.4),

$$\Delta E_c(t) = V_{SC} I_{SC} \int_0^T \sin^2 \omega t \, d\omega t = \frac{1}{2} V_{SC} I_{SC} T$$  \hspace{1cm} (5.5)

$V_{SC}$ or $V_S$ is the peak phase voltage of the STATCOM and $T$ is the period of one cycle.
Equating equations (5.3) & (5.5), gives,

\[\frac{1}{2} C_{DC} \left[ V_{CMAX}^2 - V_{dc}^2 \right] = \frac{1}{2} V_{SC} I_{SC} T \tag{5.6}\]

While the load current is reduced, the charging current \(I_{SC}\) will be equal to the change in load current \(\Delta I\), hence, substituting \(\Delta I\) for \(I_{SC}\), equation (5.6) becomes,

\[\frac{1}{2} C_{DC} \left[ V_{CMAX}^2 - V_{dc}^2 \right] = \frac{1}{2} V_{SC} \Delta I L T \tag{5.7}\]

Where: \(\Delta I L\) is the step drop of load current which can be determined by the difference between the load current before and during faults.

Therefore, using equation (5.7) the capacitance \(C_{DC}\) value of a three phase system can be derived as,

\[C_{DC} = 3 \times \frac{V_{SC} \Delta I L T}{\left[ V_{CMAX}^2 - V_{dc}^2 \right]} \tag{5.8}\]

And

\[V_{dc} = \frac{3 \times \sqrt{3} V_s \cdot \cos \alpha}{\pi} \tag{5.9}\]

Where, \(\alpha = \) delay angle. If \(\alpha = 0\), then equation become,

\[V_{dc} = \frac{3 \times \sqrt{3} V_s}{\pi} \tag{5.10}\]

The derivations of \(V_{dc}\) and equations (5.8) can be found in [94] & [95] respectively.

**5.8: Rating of STATCOM**

Voltage profile in the system without STATCOM connected is shown in figure 5.4. The load current profile on the system without STATCOM connected is obtained 0.48 kA (rms). This current is dropped to 0.28 kA(rms) during voltage sag which is due to a three phase fault with time to apply fault is 3 second & durations of fault is 0.02 second as shown in figure 5.5. Time for recovery voltage & current is shown in table 5.1. From figure 5.5, \(\Delta I_L = 0.48 - 0.28 = 0.20 \text{ kA.} \)
Table 5.1: Recovery of voltage & current after fault

<table>
<thead>
<tr>
<th>Pre-fault value</th>
<th>During Fault</th>
<th>Recovery of voltage &amp; current after fault</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage (kV)</td>
<td>Current (kA)</td>
<td>Voltage (kV)</td>
</tr>
<tr>
<td>107</td>
<td>Max.: 0.69</td>
<td>59.65</td>
</tr>
<tr>
<td></td>
<td>RMS :0.48</td>
<td></td>
</tr>
</tbody>
</table>

The value of $\Delta I_L$ can be found by measuring the load current before and during the voltage sag. The value of $V_{dc}$ is given by

$$V_{dc} = \frac{3\sqrt{3}}{\pi} V_s \cos \alpha \quad \text{(5.11)}$$

Where, $\alpha$ = delay angle, if $\alpha = 0$, the equation become,
\[ V_{dc} = \frac{3\sqrt{3}}{\pi} V_L \]  

(5.12)

\[ V_{dc} = \frac{3\sqrt{3}}{\pi} V_L = \frac{3\sqrt{3}}{\pi} 69\text{kV} = 114.12 \text{kV} \]  

(5.13)

\[ V_{C_{\text{Max}}} = 1.1 V_{dc} = 1.1 \times 114.12 = 125.53 \text{kV} \]  

(5.14)

\[ \Delta I_L = 0.20 \text{kA} \]

\[ T = 0.02 \text{ sec. (One Cycle)} \]

\[ C_{\text{DC}} = 3 \frac{V_L \Delta I_L T}{V_{C_{\text{Max}}}^2 - V_{dc}^2} \]  

(5.15)

\[ C_{\text{DC}} = 3 \frac{(69 \times 0.20 \times 0.02) \times 10^6}{(125.53^2 - 114.12^2) \times 10^6} = 302\mu\text{F} \]  

(5.16)

1) Rating of STATCOM:

VAR Rating of STATCOM = \( V_L \times I_L \)  

(5.17)

\[ \text{VAR rating of STATCOM} = V_L \times I_L \]

\[ = V_L \times \frac{V_L}{X_C} \]

\[ = V_L^2 / X_C \]

\[ = 2\pi f C_{\text{DC}} \times V_L^2 \]

VAR rating of STATCOM = \( 2 \times 3.14 \times 50 \times 302 \mu\text{F} \times (69/\sqrt{3})^2 = 150.4 \text{ MVAR} \)

Q = 150.40 MVAR,

MVA = 150.40/0.99 = 151.91 MVA

(As Cos\( \theta \) = 0.1 p.f., \( \theta = 84.26 \), Sin \( \theta \) = 0.99)

P = 151.91 \times 0.1 = 15.19 MW

2) Actual MVAR required for under voltage

\[ \text{MVAR}_{\text{Actual}} = \text{MVAR}_{\text{Rated}} \times (V_{\text{Actual}}/V_{\text{Rated}})^2 \]

1) For 10% voltage drop
MVAR_{Actual} = MVAR_{Rated} \times (V_{Actual}/V_{Rated})^2
MVAR_{Actual} = 100 \times (69 \times 0.1/69)^2
MVAR_{Actual} = 1 \text{ MVAR}

2) For 20% voltage drop
MVAR_{Actual} = MVAR_{Rated} \times (V_{Actual}/V_{Rated})^2
MVAR_{Actual} = 100 \times (69 \times 0.2/69)^2
MVAR_{Actual} = 4 \text{ MVAR}

3) For 30% voltage drop
MVAR_{Actual} = MVAR_{Rated} \times (V_{Actual}/V_{Rated})^2
MVAR_{Actual} = 100 \times (69 \times 0.3/69)^2
MVAR_{Actual} = 9 \text{ MVAR}

4) For 50% voltage drop
MVAR_{Actual} = MVAR_{Rated} \times (V_{Actual}/V_{Rated})^2
MVAR_{Actual} = 100 \times (69 \times 0.5/69)^2
MVAR_{Actual} = 25 \text{ MVAR}

5) For 75% voltage drop
MVAR_{Actual} = MVAR_{Rated} \times (V_{Actual}/V_{Rated})^2
MVAR_{Actual} = 100 \times (69 \times 0.75/69)^2
MVAR_{Actual} = 56.25 \text{ MVAR}

6) For 90% voltage drop
MVAR_{Actual} = MVAR_{Rated} \times (V_{Actual}/V_{Rated})^2
MVAR_{Actual} = 100 \times (69 \times 0.90/69)^2 = 81 \text{ MVAR}

3) Actual MVAR required for over voltage:

1) For 10% voltage rise
MVAR_{Actual} = MVAR_{Rated} \times (V_{Actual}/V_{Rated})^2

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MVAR_{Actual} = 100 \times (69 \times 1.1/69)^2

MVAR_{Actual} = 121 \text{ MVAR}

2) For 20% voltage rise

MVAR_{Actual} = MVAR_{Rated} \times (V_{Actual}/V_{Rated})^2

MVAR_{Actual} = 100 \times (69 \times 1.2/69)^2

MVAR_{Actual} = 144 \text{ MVAR}

4) Rating of GTO:

\[ I_{ac} = \frac{MVAR}{\text{Voltage} \times \sqrt{3}} = \frac{150.4 \text{ MVAR}}{69 \text{ kV} \times \sqrt{3}} = 1.25 \text{ kA} \]  \hspace{1cm} (5.18)

\[ I_{ac} = 1.11 I_{dc} \]

\[ 1.25 \text{ kA} = 1.11 I_{dc} \]

\[ I_{dc} = 1.12 \text{ kA} \]

1) Forward voltage drop:
For 6 kV, voltage drop = 3.7 V
For 69 kV, voltage drop = 42.55 V

2) Forward break over voltage = \( V_{C_{\text{Max}}} \times 1.3 \) (safety factor)

\[ = 125.53 \text{ kV} \times 1.3 = 163.18 \text{ kV} \]

3) Reverse withstand voltage = \( V_{C_{\text{Max}}} \times 1.3 \) (safety factor)

\[ = 125.53 \text{ kV} \times 1.3 = 163.18 \text{ kV} \]

4) Switching frequency: It should be in between 20-50 kHz.
Less than 20 kHz – Audible Noise
More than 50 kHz – Extra switching loss

Conclusion:

Rating of STATCOM is shown in following table 5.2.
Table 5.2: Rating of STATCOM

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>STATCOM Rating</th>
<th>GTO Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Active power (P)</td>
<td>15.19 MW</td>
</tr>
<tr>
<td>2</td>
<td>Reactive power (Q)</td>
<td>150.40 MVAR</td>
</tr>
<tr>
<td>3</td>
<td>Apparent power (S)</td>
<td>151.91 MVA</td>
</tr>
<tr>
<td>4</td>
<td>DC link voltage $V_{dc}$</td>
<td>114.12 kV</td>
</tr>
<tr>
<td>5</td>
<td>$V_{C_{MAX}}$</td>
<td>125.53 kV</td>
</tr>
<tr>
<td>6</td>
<td>$C_{DC}$</td>
<td>302 µF</td>
</tr>
</tbody>
</table>

5.9: PWM controller configuration

This PWM controller is divided into two parts:

1) Reactive power control
2) Sinusoidal pulse width modulation (SPWM)

5.9.1: Reactive power control

Reactive power and voltage is measured separately. Then reactive power is taken as a numerator for N/D block. Maximum of per unit voltage & the value 0.1 is taken to input as denominator to N/D block to prevent division by zero errors. Voltage is applied to maximum function to select maximum or minimum of several signals. These signals are then applied to gain block for the 3% drop calculation and both voltage and reactive power signal applied to filters to remove the unwanted signal and notching created by converter switching. The reference voltage is taken and multiplies with ramp function compare with the output of the filter and then applied to lead lag compensator where output can reset at any time. Maximum and minimum output limit also included in lead lag function. These signals applied to PI controller. The output of PI controller is the angle order which represents the required shift between system voltage and voltage generated by STATCOM. The output of PI controller is the angle order, which is used to maintain the phase shift as shown in figure 5.6. The reactive power flow of the system is compared to the reference per-unit voltage that contributes to a change of the phase shift. The difference in phase shift will provide the needed reactive power from the DC capacitor [96].
5.9.2: Generation of triangular waveform by using SPWM techniques

The sinusoidal PWM (SPWM) technique is divided into three parts that is the generation of triangular waveform, generation of reference wave formation and generation of firing pulse for voltage source converter (VSC).

The phase locked loop (PLL) plays an important role in synchronizing the switching to the distribution system voltage and lock to the phase of the fundamental frequency to generate the PWM triangular carrier signals.

Voltage input signal applied to PLL which generates ramp signal theta synchronized with input voltage. Theta applied to the multiplier block in which multiplication of the fundamental frequency is done to define carrier frequency. Its value has to be divisible by three; these signals given to modulo function and then nonlinear transfer characteristics by straight line approximation. These outputs are used to produce signals for the D block (triangular signals). Figure 5.7 illustrates the generation of triangular waveforms synchronized with system AC voltage [96].
5.9.3: Generation of sinusoidal waveform by using SPWM techniques

In this case input voltage signal applied to PLL six pulse block to generate a ramp signal which varies in between 0 to 360° synchronized with input voltage. Shift signal obtains from the voltage control loop are compared with 30° shift due to star-delta transformer and given to shift block which operates on 6-dimensional arrays. These 6 pulses have given to sin array which operates on 6 dimensional arrays to generate ON and OFF signal for the D block (reference signal). PLL are applied to generate sinusoidal curves at the wanted fundamental frequency. A shift is effectively the output coming from the reactive power control loop, i.e. the angle order. The difference in angle order will change the width of the PWM signal and ultimately the needed reactive power to be supplied to the system. Figure 5.8 illustrates the generation of reference waveforms synchronized with system AC voltage and shifted by the angle order [96].

Figure 5.7: Generation of triangular waveforms synchronized with system AC voltage [96]
5.9.4: Generation of firing pulse by using SPWM techniques

Firing pulses are generated using comparison of reference signals to triangular signals. Two sets of signals (reference and triangular ones) are needed, one set for turning on and the second one (complement of first set of signals) for turning off. Two signals are being sent to each switch, the first one tell to turn on/off and the second one determines an exact moment of switching and is used by the interpolation procedure which allows for switching between time steps as shown in figure 5.9.

Figure 5.8: Generation of reference waveforms synchronized with system AC voltage and shifted by the angle order [96]

Figure 5.9: Generation of firing pulse [96]
5.9.5: Location of STATCOM

The STATCOM is placed as close as possible to the load bus for various reasons. The first reason is that the location of the reactive power support should be as close as possible to the point at which the support is needed. Secondly, in the studied test system the location of the STATCOM on the load bus is more appropriate because the effect of voltage change is the highest at this point. The location of the STATCOM is based on quantitative benefits evaluation. The main benefits of using a STATCOM in the system are reduced losses and increased maximum transfer capability. Placement of a STATCOM at any load bus reduces the reactive power flow through the lines, thus, reducing line current and also the $I^2R$ losses. Shipping of reactive power at low voltages in a system running close to its stability limit is not very efficient. Also, the total amount of reactive power transfer available will be influenced by the transmission line power factor limiting factors. Hence, the sources and compensation devices are always kept as close as possible to the load as the ratio $\left| \frac{\Delta V}{V_{\text{nom}}} \right|$ will be higher for the load bus under fault conditions.