CHAPTER 4

STABILITY ANALYSIS OF INDUCTION GENERATORS USING STATCOM

4.1 RENEWABLE WIND POWER SUPPORT IN THE POWER SYSTEM

Wind energy is gaining rapid momentum in the world energy balance. The installation of wind turbine generators has increased to a large extent and it has been reported that 10% of the world’s electricity is targeted from wind power by 2020 (Salman and Anita 2003). Due to this increase in demand of wind energy, the research and development in the control of wind power to support the power system network with a constant voltage profile poses challenges. New grid codes from the different Transmission System Operation (TSO) represent how wind farms should behave in different grid disturbances in order to maintain stability in the grid. According to C.C.6.3.2, C.C.6.3.6 and C.C.6.3.8 of the grid code, wind farms must be able to provide automatic voltage control at the PCC by continuous changes to their reactive power output.

In recent years, several grids connecting Wind Energy Conversion Systems (WECSs) consists of Fixed Speed Induction Generators (FSIG) since they are robust, small size, ruggedness, brushless design, self protection against overload and short circuits, cost effective, simple construction, maintenance free operation, provides large damping torque and requires no synchronization device. FSIGs impose voltage
instability in the grid. At the instant when a large wind turbine with FSIG is connected to the grid, large transient inrush reactive current 2 to 3 times larger than the generator rated current is drawn from the grid for magnetizing the stator. High in rush currents causes both disturbances to the grid and high torque spikes in the drive train of wind turbines. Unless special precautions are taken, the inrush currents can be up to 5 to 7 times the rated current of the generator. This causes voltage dip in the network. For illustration voltage dip profile is shown in Figure 4.1. If the voltage dip exceeds 2 to 3%, the wind farm is disconnected from the grid to avoid further decrease in voltage which results in voltage collapse.

A transient like this disturbs the grid and the inability of a power system to meet reactive power demand will cause voltage instability, with the risk of eventual voltage collapse.

![Voltage dip profile](image)

**Figure 4.1 Voltage dip profile**

The island operation may occur in some situations incase of a grid collapse and the ability of operating in such a situation could be useful for minimizing the possible area of blackout. The IEEE 1547 and the IEC 61400-21 standards are the bases for evaluating the impact of such wind-turbine generation systems on the electric power system. Therefore,
reactive power control is necessary for Fixed Speed Wind Energy Conversion systems (FSWECS).

4.2 WIND POWER INTEGRATION CHALLENGES

One of the major challenges faced by the electricity industry is how to effectively integrate significant amount of wind power into the electricity system. A majority of the wind turbines installed are FSIGs that absorb reactive power from the system even during normal operating conditions. A fixed-speed wind-generator is usually equipped with a Squirrel-Cage Induction Generator (SCIG) whose speed variations are very limited. This configuration uses capacitor bank for reactive power compensation and has a gearbox to match the rotational speed of blades with that of the generator as shown in Figure 4.2, which illustrates the startup of a soft-starter-fed induction generator.

![Figure 4.2 Fixed-speed system with stall or active-stall control](image)

The induction generator based wind turbines are the consumer of reactive power. So they need a reactive power compensator to reduce the reactive power demand from the turbine generators to the grid. It is usually done by continuously switching capacitor banks as shown in
Figure 4.2. The value of the capacitor is so chosen that the power factor of the wind power station becomes unity when it is operating in the rated condition. The reactive power compensation can be adjusted linearly by controlling the firing angle of the thyristor switch in other technology, such as Fixed-Capacitor Thyristor-Controlled-Reactor (FC-TCR). However, this method will generate a harmonic problem, because the thyristor switch cannot conduct a full cycle.

Since the reactive power of SCIG varies significantly due to the variation in the rotor speed, a reactive power compensator, which can adjust the reactive power along with variations in wind speed, is required to obtain a high power factor for the SCIG (Pierre Bousseau et al. 2006, Slootweg 2003). Therefore, controllable reactive power (VAR) supporters, such as STATCOM are in some cases necessary to provide dynamic voltage support with their actively controllable VAR injection, especially under voltage depression.

This research work presents results from the investigation into the impact of installing a STATCOM at an existing wind farm. This wind farm consists of FSIGs and is integrated through a weakly connected utility system. A STATCOM is to be installed at the PCC, where the wind farm is integrated with the utility system. It utilizes a new power electronic device, the GTO, for enhanced high-power switching performance, simplified triggering technology, and overall reduced device and system costs. The controllers of the STATCOM are designed according to commonly known control principles already discussed in Chapter 2. The outputs of the STATCOM controller are amplified and used as the controllable inputs of the three-phase voltage source.
4.2.1 Low Voltage Ride Through (LVRT) Capability

The LVRT requires that a Wind Turbine (WT) does not trip even if the voltage drops to 0.15 per unit for about 0.625 seconds. If due to a fault, the voltage drops below this value, the wind turbine can be tripped until the system restores and the wind turbine can be resynchronized. As per FERC order No. 661, a WT can take a maximum of 2.375 seconds to restore to about 0.9 per unit voltage after the fault has been cleared (Chompoo-inwai et al. 2005).

![Figure 4.3 LVRT requirement for wind generation facilities](image)

These rules are more stringent for some grids which are derived based on grid reliability requirement (Ullah et al. 2007). Order No. 661 issued by FERC (Federal Energy Regulatory Commission) on June 2, 2005, sets specific wind power requirements as shown in Figure 4.3, namely, LVRT, power factor design criteria (reactive power) and Supervisory Control and Data Acquisition (SCADA) capability.

The grid codes are specific to a particular power zone and they vary with respect to the voltage profile requirement during system
disturbances. To obtain LVRT capability and to withstand the effects of voltage disturbances are the new challenges with the integration of wind farms into the power system. Under any voltage disturbances, the FSWTs must remain connected to the network to maintain voltage profile.

4.3 STABILITY ANALYSIS OF INDUCTION GENERATOR BASED WIND TURBINES

In the WECS with fixed speed SCIGs, reactive power is required to maintain the air gap flux and this leads to high inrush current drawn from the power system. This in turn causes a voltage drop on the power system network. Due to voltage drop, the generator speed increases and the electromagnetic torque decreases. Under normal condition the electro-magnetic torque $T_e$ is equal to the mechanical torque $T_m$. But when $T_e$ decreases the generator accelerates and consumes more reactive power which decreases the voltage further. This instability pushes the machine beyond its pull out torque and the generator keeps increasing its speed. This results in over speeding of the generator and results in voltage collapse and disconnection of generators from the grid i.e., islanding operation. To re-establish the magnetic field in the air gap the voltage must be improved. Voltage improvement can be made possible by enhancing the reactive power supply which may pave way for the generators to ride through the low voltage (Arrillaga et al. 2007).

For stability analysis, consider a FSWECs which consists of a conventional SCIG (asynchronous) generator directly coupled to the grid as shown in Figure 4.4. At the instant when the FSIG is connected to the grid, high reactive current is drawn by the stator for magnetization.
Under normal operating condition:

\( T_e \) (electromagnetic torque) = \( T_m \) (mechanical torque).

In terms of tip speed ratio \( \lambda \), the equivalent electrical torque produced in the generator is given by (Saad Saoud et al. 1998, Arrillaga et al. 2007),

\[
T_e = \frac{1}{2} \pi \rho \, C_p \, (\lambda) R^3 V_{eq}^2
\]

(4.1)

where \( \rho \) - Air density (kg/m\(^3\)); \( R \) - Wind turbine rotor radius (m); \( V_{eq} \) - Equivalent wind speed (m/s); \( \beta \) - Pitch angle of wind turbine rotor (deg); \( C_p \) - power coefficient which is a function of both aerodynamic efficiency coefficient.

Mechanical Turbine torque is

\[
T_m = K (\theta_s - \theta_G)
\]

(4.2)

where \( K \) = Stiffness factor, \( \theta_s \) = Shaft angle, \( \theta_G \) = Gearbox angle.

Figure 4.4  Fixed speed wind energy conversion system
The Cp-λ curves are shown in Figure 4.5 for different values of β which depicts that as β increases, Cp decreases.

![Cp-λ curves for different pitch angles](image.png)

**Figure 4.5  \( C_p-\lambda \) curves for different pitch angles**

Wind power is converted into mechanical power by a wind turbine rotor. The wind speed and the aerodynamic torque can be related using the equation

\[
T_o = \frac{1}{2} \rho \pi R^3 \frac{v_{eq}^2 \ C_p(\beta, \lambda)}{\lambda} \quad (4.3)
\]

where \( T_o \) - Aerodynamic torque (Nm)

The electromagnetic torque equation of induction machine is

\[
T_e = \frac{R S V^2}{R^2 + X^2 S^2} = K S V^2 \quad (4.4)
\]

At start, due to high inrush stator currents voltage decreases. From Equation (4.4), when voltage decreases the electromagnetic torque decreases which results in voltage collapse and over speed of the generator.
According to Swing equation, the dynamic behavior of single rotating mass wind mill drive train is given by,

$$J \frac{dw}{dt} = T_m - T_e$$  \hspace{1cm} (4.5)

The over speed of the generator depends on the inertia and duration of the disturbance.

### 4.3.1 Voltage Stabilization and Fluctuation Mitigation

The dynamic voltage variations from the wind turbines during operation are quantified by flicker and step change. Voltage fluctuations or flicker during the induction generation switching should be limited to comply with the flicker emission limits. It is recommended in the previous research works that in 10 kV – 20 kV networks an installation of WT with a flicker emission of $P_{st} = 0.35$ as a weighted ten minute average can be accepted. However a wind turbine installation may be assumed as a PQ node, which may use 10 min average data ($P_{mc}$ and $Q_{mc}$) or 60 s average data ($P_{60}$ and $Q_{60}$) or 0.2 s average data ($P_{0.2}$ and $Q_{0.2}$). A wind farm with multiple wind turbines may be represented with its output power at the PCC. Ten-minute average data ($P_{mc}$ and $Q_{mc}$) and 60 s average data ($P_{60}$ and $Q_{60}$) can be calculated by summation of the output from each wind turbine, where as 0.2 s average data ($P_{0.2}$ and $Q_{0.2}$) may be calculated according to Equations (4.6) and (4.7).

$$P_{0.2} = \sum_{i=1}^{N_{wt}} P_{n,i} + \sqrt{\sum_{i=1}^{N_{wt}} \left( P_{0.2,i} - P_{n,i} \right)^2}$$  \hspace{1cm} (4.6)

$$Q_{0.2} = \sum_{i=1}^{N_{wt}} Q_{n,i} + \sqrt{\sum_{i=1}^{N_{wt}} \left( Q_{0.2,i} - Q_{n,i} \right)^2}$$  \hspace{1cm} (4.7)
where $P_{n,i}$ and $Q_{n,i}$ are the rated real power and reactive power of the individual wind turbine; $N_{wt}$ is the number of wind turbines in the group.

The flicker emission from a single wind turbine during continuous operation may be estimated by:

$$P_f = C_f (\psi_k, V_a) \frac{S_n}{S_k}$$

(4.8)

where: $C_f (\psi_k, V_a)$ is the flicker coefficient of the wind turbine for the given network impedance phase angle, $\psi_k$, at the PCC, and for the given annual average wind speed $V_a$, at hub-height of the wind turbine.

The flicker emission due to switching operations of a single wind turbine can be calculated as

$$P_{st} = 18x N_{10}^{0.31} x K_f (\psi_k) \frac{S_n}{S_k}$$

(4.9)

where: $P_{st}$ is the short term flicker level, $K_f (\psi_k)$ is the flicker step factor of the wind turbine for the given $\psi_k$ at the PCC.

The flicker emission from a cluster of wind turbines connected to the PCC can be estimated from Equation (4.10).

$$P_{st}^\Sigma = \frac{18}{S_k} \left[ \sum_{i=1}^{N_{wt}} N_{10,i} \left(K_f (\psi_k) \frac{S_n}{S_k} \right)^{3.2} \right]^{0.31}$$

(4.10)
where \( N_{10,i} \) and \( N_{20,i} \) are the number of switching operations of the individual wind turbine within 10 minutes and 2 hours period respectively; \( K_{f,i} \) is the flicker step factor of the individual wind turbine and \( S_{n,i} \) is the rated apparent power of the individual wind turbine;

During continuous operation, the flicker coefficient of the wind turbine for the actual \( \Psi_k \) and \( V_a \) at the site can be calculated by applying linear interpolation. Voltage fluctuations or the flicker emissions of wind turbines may be estimated with the coefficient and flicker step factors, \( C_f \) and \( K_f \) by applying linear interpolation to the table of data obtained from the measurements, which are usually provided by wind turbine manufacturers (Pierre Bousseau et al. 2006).

From the table of data produced from the measurements at a number of specified impedance angles and wind speeds provided by wind turbine manufactures, the flicker emission from a group of wind turbines connected to the PCC is calculated using equation

\[
P_{st} \sum = \frac{1}{S_k} \sqrt{\sum_{k=1}^{S_{wt}} \left( C_{f,i} \left( \Psi_k, V_a \right) S_{n,i} \right)^2}
\]

(4.11)

where \( C_f \left( \Psi_k, V_a \right) \) is the flicker coefficient of the individual wind turbine;

\( N_{wt} \) is the number of wind turbines connected to the PCC.

If the limits of the flickers emissions are known, the maximum allowable number of switching operations in a specified period, the maximum permission flicker emission factor or the required short circuit
capacity at the PCC or the maximum allowable number of wind turbines for connection may be determined.

4.3.2 Electrical Modeling Issues and Requirements of Fixed Speed Induction Generators

Wind farms with induction generators generate real power and consume reactive power. Figure 4.6 illustrates the single line diagram of a wind power generation unit, connected to a power system network. The conventional steady state model is the most widely used model for the analysis of the reactive power response of an induction machine. To investigate the variation in the power output of the wind farms using induction generators consider the equivalent circuit of an induction machine as shown in Figure 4.7.

![Figure 4.6 Single line diagram of a WECS](image)

The equivalent impedance as seen across the stator terminal can be written as

\[ Z_{eq} = R_{eq} + jX_{eq} \]  

(4.12)

The current associated with an applied voltage \( V \) is

\[ I = IR + jIX \]  

(4.13)
where \( IR = \frac{VR_{eq}}{R_{eq}^2 + X_{eq}^2} \) \hspace{1cm} (4.14)

\[ IX = \frac{VX_{eq}}{R_{eq}^2 + X_{eq}^2} \] \hspace{1cm} (4.15)

**Figure 4.7 Equivalent circuit of an induction generator**

The transmission of real power over a power line with impedance \( Z_{eq} \) results in a voltage drop \( \Delta V \).

\[ \Delta V = \left( \frac{RP + XQ}{V} \right) \] \hspace{1cm} (4.16)

Wind turbines affect the voltage level in the PCC due to their power production. The active power produced by the turbine increases the voltage, whereas the reactive power can increase or decrease the voltage level. As active power increases reactive power consumption increases. On the grid with a high \( X/R \) ratio the voltage decreases and from Equation (4.16), \( \Delta V \) is directly proportional to the reactive power \( Q \) transferred. Hence for efficient voltage control an effective reactive power control strategy is required. In an induction machine, by running the machine at over-synchronous speed the slip is negative which acquires a generator character.
With the wind turbine acting as the prime mover, the mathematical relation for the mechanical power extracted from wind and the corresponding mechanical torque is given as

\[ P_m - \frac{1}{2} e A_r V w^3 C_p (\tau, \beta) \]  
\[ (4.17) \]

\[ T_m = K (\theta_s - \theta_G) \]  
\[ (4.18) \]

The electrical counter torque \( T_e \) set up in the stator connected to the grid at the voltage \( V \) is

\[ T_e = K R V^2 S / R^2 + X^2 S^2 \]  
\[ (4.19) \]

If any fault occurs in the grid the voltage decreases and the slip increases. As slip increases reactive power consumption increases which further decreases voltage. According to Equation (4.19), when voltage decreases tripping of the generator occurs (as discussed in section 4.2). For stable operation of a wind farm, voltage profile is the main issue.

To maintain voltage and to avoid over speed of the induction generators, dynamic stability improvements and voltage control technologies are taken into consideration during the analysis. To prevent voltage collapse and to obtain fast reactive power support the excellent controllability of FACTS devices has paved the way to flexible and dynamic controllers that are capable of regulating the flow of active and reactive power components. Stability can be enhanced by providing a dynamic compensation with STATCOM (Alan Mullane et al. 2005).
4.4 WIND TURBINE MODEL

Modeling of wind turbine rotor, blade and shaft needs complicated lengthy computations and needs information about rotor geometry. Considering only the electrical behavior of the system, a simplified method of modeling of the wind turbine blade and shaft is normally used.

4.4.1 Mechanical Model

The mechanical model is selected with emphasis to include only the parts of the dynamic structure of the wind turbine, which are important to the interaction with the grid, i.e. which influences significantly on the fluctuations of the power. Thus, only the drive train is considered in the first place because this part of the wind turbine has the most significant influence on the power fluctuations. The mechanical model is illustrated in Figure 4.8.

![Figure 4.8 Mechanical model for the wind turbine](image)

The aerodynamic torque $T_{ae}$ is provided by the aerodynamic model and the wind turbine rotor angle $\theta_{WTR}$ provides the rotor speed.
On the other side the mechanical model interfaces to the generator model with the air gap torque $T_{\text{ag}}$ and the generator speed $\dot{\theta}_{\text{gen}}$ which is derived from the generator angle position.

The drive train model is essentially a two mass model. To consider the electromechanical interactions between the shaft system and the grid, the rotating part of the wind turbine is given by the two mass model. The masses used in the model correspond to a large turbine rotor inertia $I_{\text{WTR}}$ representing the blades and hub, and a small inertia $I_{\text{gen}}$ representing the induction generator. Among all models, the two mass model is the most accurate model for WECS. The wind turbine and the generator rotor are modeled as two masses and the shaft as spring element. If $\omega_w$ is the turbine’s rotational speed (rad/s); $\omega_g$ is the generator’s speed; $K_s$ is the shaft stiffness (Nm/rad); $\theta_{wg}$ is the angular displacement between the shaft ends, then the two mass system with low stiffness shaft can be described as follows:

\[
J \frac{d\omega_o}{dt} = T_o - T_{\text{gen}} - D_s (\omega_g - \omega_o) \tag{4.20}
\]

\[
2H_g \frac{d\omega_o}{dt} = T_o - K_s \theta_{\omega_g} - D_s (\omega_g - \omega_o) \tag{4.21}
\]

\[
2H_g \frac{d\omega_g}{dt} = T_e - K_s \theta_{\omega_o} - D_s (\omega_g - \omega_o) \tag{4.22}
\]

where $H_g$ and $H_s$ are the inertia constants of the generator rotor respectively; $\omega_w$ and $\omega_g$ are the wind turbine and generator speed respectively; $K_s$ and $D_s$ are the drive train shaft stiffness and damping constants respectively; and $\theta_{\omega_g}$ is the shaft torsional twist angle. In the
above equation \( T \) is the torque, \( \theta \) is the angular displacement between the two ends of the shaft, \( \omega \) is the angular speed, \( H \) is the inertia constant and \( K_s \) is shaft stiffness. \( \omega \) and \( g \) here stands for wind turbine and generator parameters.

\[
\text{Tip speed ratio, } \lambda = \frac{\text{Blade tip speed} [\text{R w (m/s)}]}{\text{Wind speed} [v (m/s)]} \quad (4.23)
\]

### 4.4.2 Dynamic dq Model

Dynamic representation of FSIG is based on 5\textsuperscript{th} order model as shown in Figure 4.9 where all the differential equations are written in dq arbitrary reference frame. For short term voltage stability study, the 5\textsuperscript{th} order model provides the most accurate result. The 5\textsuperscript{th} order model involves both the stator and the rotor transients. The order of the model indicates the number of states involved in the electrical equations together with one state in the rotor speed equation. This model predicts the reactive power response also.

![Diagram of dq model of wind turbine](image)
To study the transient and dynamic stability of large power systems and for incorporating the dynamic characteristics of an induction machine into a digital computer program the synchronously rotating reference frame is more convenient (Paul C. Krause 1986). According to this model, the modeling equations in flux linkage form are as follows.

\[ V_S = i_s R_s + j \omega_s \Psi_s' + \frac{d\Psi_s'}{dt} \]  \hspace{1cm} (4.24)

\[ V_r = 0 = i_r R_r + j(\omega_s - \omega_r) \Psi_r' + \frac{d\Psi_r'}{dt} \]  \hspace{1cm} (4.25)

\[ \Psi_s' = i_s L_s + i_r L_m \]  \hspace{1cm} (4.26)

\[ \Psi_r' = i_r L_r + i_s L_m \]  \hspace{1cm} (4.27)

where \( L_m \) is the magnetizing reactance, \( L_s, L_r \) is the stator and rotor inductances.

\[ T_e = \Psi_s' i_s \]  \hspace{1cm} (4.28)

According to Mechanical dynamics

\[ J \frac{d\omega_r}{dt} = T_e - T_m \]  \hspace{1cm} (4.29)

\[ I_r = \frac{\Psi_r - i_s L_m}{L_r} \]  \hspace{1cm} (4.30)

\[ \Psi_s = i_s L_s + \frac{L_m}{L_r} \Psi_r - \frac{L_m^2}{L_r} i_s \]  \hspace{1cm} (4.31)
\[ x^1 = H_0 \left( L_s - \frac{L_m^2}{L_r} \right) + \frac{L_m}{L_r} \Psi_r' \]  

(4.32)

Transient reactance \( x^1 = \omega_s \left( L_s - \frac{L_m^2}{L_r} \right) \)  

(4.33)

\[ \Psi_s = i_s \frac{X^1}{\omega_s} + \frac{L_m}{L_r} \Psi_r' \]  

(4.34)

Introducing voltage components,

\[ V_e = j\omega_s \frac{L_m}{L_r} \Psi_r' \]  

(4.35)

\[ \Psi_s = i_s \frac{X^1}{\omega_s} - j \frac{V_e}{\omega_s} \]  

(4.36)

\[ V_s = R_s i_s - j X_s i_s + V_e + \frac{d\Psi_s}{dt} \]  

(4.37)

Eliminating the rotor current and expressing the rotor flux in terms of \( V_e \), the rotor equation is

\[ \frac{dV_e^1}{dt} = \frac{1}{T_o} \left[ V_e^1 - j (X_s - X_1) i_s \right] + JSV_e^1 + j \frac{X_m}{X_r} V_r \]  

(4.38)

\[ x^1 = \omega_s \left[ L_s - \frac{L_m^2}{L_r} \right] \]  

(4.39)
Transient open - circuit time constant of the induction generator is

\[ T_o = \frac{L_s}{R_r} \quad (4.40) \]

\[ T_e = \frac{V_{s1} l_s}{o_S} \quad (4.41) \]

The d-q transformation equations (Paul C. Krause 2002) in the synchronous reference frame are

\[
\begin{bmatrix}
V_{qs}^c \\
V_{ds}^c \\
V_{qr}^c \\
V_{dr}^c
\end{bmatrix}
= 
\begin{bmatrix}
R_s + L_s p & \omega_s L_s & L_m p & \omega_s L_m \\
-\omega_s L_s & R_s + L_s p & -\omega_s L_m & L_m p \\
L_m p & (\omega_s - \omega_r) L_m & R_s + L_r p & (\omega_s - \omega_r) L_r \\
-(\omega_s - \omega_r) L_m & L_m p & -(\omega_s - \omega_r) L_r & R_s + L_r p
\end{bmatrix}
\begin{bmatrix}
i_q^c \\
i_d^c \\
i_q^r \\
i_d^r
\end{bmatrix}
\]

\quad (4.42)

This model represents the number of systems involved in the electrical equations together with one state in the rotor speed equation. In this work, using the squirrel-cage induction generator detailed model, \( V_{qr}^c \) and \( V_{dr}^c \) are set to zero.

Transforming from abc to dqo variables, the torque is given as

\[
[T_{abc}^c] = \frac{2}{3}
\begin{bmatrix}
\cos \theta_s & \cos \left( \theta_s - \frac{2\pi}{3} \right) & \cos \left( \theta_s + \frac{2\pi}{3} \right) \\
\sin \theta_s & \sin \left( \theta_s - \frac{2\pi}{3} \right) & \sin \left( \theta_s + \frac{2\pi}{3} \right) \\
\frac{1}{2} & \frac{1}{2} & \frac{1}{2}
\end{bmatrix}
\]

\quad (4.43)
The electromagnetic torque is given as

\[ T_e = \frac{3}{2} P L_m \left[ i_{qs}^c i_{dr}^c - i_{ds}^c i_{qr}^c \right] Nm \]  

(4.44)

4.5 FACTS BASED SOLUTIONS

New network technologies that facilitate increased power transfers on the grid including voltage regulation, system damping and power flow control have been through by the use of FACTS. FACTS controllers control the voltage from the high side of the network during steady state and transient conditions incorporating power electronic devices. FACTS devices can be used in wind power systems to improve the transient and dynamic stability of the overall power system (Garcia Gonzales et al. 2000, Sirisukprasert et al. 2002). A fast dynamic var compensator is needed to address these issues more effectively, as has been pointed out in many literature papers (Haizea Gaztanaga et al. 2007, Dong et al. 2001). Compared to all conventional FACTS controllers STATCOM has many advantages with its natures (Rao et al. 2000).

STATCOM is a power electronic based FACTS device that can typically provide much faster control and with lower losses than the traditional compensators such as synchronous condensers. The main motivation for choosing STATCOM in wind farms is its ability to provide bus bar system voltage support either by supplying and/or absorbing reactive power into the system. The STATCOM is the best option available for providing efficient voltage quality in the power system. One of the most important advantages of using STATCOM over a thyristor based SVC is because of its compensating current is not lowered as the voltage drops. The major applications are: voltage stability enhancement, damping
torsional oscillations, power system voltage control and power system stability improvement. These applications can be implemented with a suitable control (voltage magnitude and phase angle control) as discussed in Chapter 2.

Hence in this chapter a CMC based STATCOM controller is proposed for improved power flow control. Secondly, a model of the WECS and STATCOM for steady-state and dynamic impact study is developed in the MATLAB simulation environment. Moreover the system voltage control and stability issues are analyzed, and finally, a STATCOM control strategy for voltage fluctuation suppression is presented, and the dynamic simulations are used to verify the performance of the proposed CMC based STATCOM and its control strategy.

4.5.1 Proposed CMC based STATCOM

The advanced high power electronics promise revolutionary increase in their performance, flexibility and cost effectiveness of the electricity transmission and distribution. These electronics enable full realization of FACTS technologies with potential for optimum tuning and precise control of all power circuits. With recent power semiconductor technologies, a traditional 2-level is not competent for FACTS controller applications because of the needing for bulky zigzag transformers and series/parallel switches to match harmonics, voltage and power specifications (Wells et al. 2007, Jiang et al. 2005). To eliminate the coupling transformer a high voltage converter has to be tied to the PCC of the grid. To achieve this, identical H-bridge converters with same series output terminals are connected in series and large voltage blocking capacity is achieved. In this work, a high power modular VSC using H-Bridge Building Block (HBBB) is proposed for stability analysis of
FSWTs. To implement STATCOM at MVA level, a CMC as shown in Figure 4.10 is used due to its high voltage output without transformer. In reactive power compensation, CMC based STATCOM with separated dc sources are preferred due to many reasons (Tolbert et al. 2005) as already discussed in detail in Chapter 3.

The cascaded converter requires fewer main components and has the same structure for each level; the desirable power rating of the system can therefore be simply adjusted by connecting a different number of the identical modules (Lee et al. 2003). A great combination of the STATCOM concept and the CMC topology connected to a wind generator is shown in Figure 4.10.

![CMC based topology](image)

**Figure 4.10  CMC based topology**

The main advantage of the multi-level inverter circuits is the desirability to produce quasi-harmonic neutralized output voltage waveforms without magnetic waveform summation circuits.
4.6 STEADY STATE VOLTAGE CONTROL WITH STATCOM

A STATCOM can continuously provide the reactive power demand of a wind farm under various conditions with rapid control (Qingguang et al. 2004). The STATCOM continuously maintains the voltage at the wind farm connection by injecting or absorbing reactive power. PI control scheme is used for maintaining the reference voltage of the wind farm. PI controller is applied for its simplicity and robustness. All voltage control blocks and their interconnection is shown in Figure 4.11.

![Figure 4.11 Block diagram for voltage control using STATCOM](image)

The function of PI is to regulate the multilevel inverter so that it stays close to the nominal operating point in the presence of disturbances and noise. The input to the PI controller is the voltage error signal from the
voltage comparator. The output of the PI controller is the modulating signal which is used to generate the gating pulses. A step response of 10% change in the controller voltage reference is used for tuning the PI controller of the STATCOM. Under the weakest system condition, the maximum percentage overshoot is 10.6% of the step change for the STATCOM controllers. The settling time at which the error reduced to a value within 1% of the steady state value is 2.8 cycles for STATCOM. Two PI controllers can be implemented to regulate the dc link voltage and the reactive current respectively. STATCOM improves the steady state stability limit when the real power produced by an induction generator exceeds and large amount of reactive power is consumed. The STATCOM control scheme is shown in Figure 4.12.

![Figure 4.12 STATCOM control scheme](image)

In steady state, the firing pulses for the STATCOM switches have to be synchronized to the bus voltage such that the fundamental component of the voltage injected by the converter leads the supply voltage
by the control angle ($\omega$). This synchronization can be achieved by a PLL as shown in Figure 4.12 which produces the phase angle of the bus voltage as an output ($\theta_t$).

$$\theta_t = \theta + \omega t \quad (4.45)$$

where $\theta$ is the relative phase of the bus voltage with respect to a synchronously rotating reference frame, $\omega$ is the operating frequency in rad/sec, $\theta_t$ ranges from 0 to $2\pi$ and is produced by a PI controller (saw tooth generator). An oscillator produces the output, $\sin \theta_t$ and $\cos \theta_t$, which are used to compute the quantities $V_p$ and $V_r$ as

$$V_p = V_\alpha \sin \theta_t + V_\beta \cos \theta_t \quad (4.46)$$

$$V_r = V_\alpha \cos \theta_t - V_\beta \sin \theta_t \quad (4.47)$$

where

$$V_\alpha = \sqrt{\frac{2}{3}} \left[ v_a - \frac{1}{2} v_b - \frac{1}{2} v_c \right] \quad (4.48)$$

$$V_\beta = \frac{1}{\sqrt{2}} \left[ v_c - v_b \right] \quad (4.49)$$

In steady state

$$V_{\alpha s} = V_s \sin \theta_t \quad (4.50)$$

$$V_{\beta s} = V_s \cos \theta_t \quad (4.51)$$
If $V_p(\text{ref}) = V_s$

$$V_r(\text{ref}) = 0$$  \hspace{1cm} (4.52)

where $V_s$ is the line to line voltage at the converter bus.

PLL tracks the phase of the voltage by feedback control of $V_r$ and driving it to zero. $K_c$ and $T_c$ are the controller parameters. Under voltage unbalance, the PLL operates satisfactorily (Peng et al. 2001). The feed forward of frequency variation ($\Delta f$) compensates for the change in frequency. If the change in frequency is not predictable, an additional integral term may be used in the controller to achieve the same result.

**Figure 4.13** Simplified model of the CMC based STATCOM in both abc and dqr coordinates

The effective mitigation of sag and harmonics depends on the effectiveness of the controller design. The control system employed in the STATCOM 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. Reactive power exchange is achieved by properly controlling $i_q$, (Rodriguez et al. 2007). 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 total instantaneous power in abc quantities can be transformed into q-d-o quantities as follows

$$P_{abc} = V_a I_a + V_b I_b + V_c I_c$$

$$= \frac{3}{2} (V_{dq} I_{dq} + V_{q} I_{q}) + \frac{1}{3} V_0 I_0$$

$$L \frac{d}{dt} \begin{bmatrix} I_d \\ I_q \end{bmatrix} + \begin{bmatrix} 0 & -\omega L \\ \omega L & 0 \end{bmatrix} \begin{bmatrix} I_d \\ I_q \end{bmatrix} = \begin{bmatrix} V_{sd} - V_{cl} \\ V_{sq} - V_{cq} \end{bmatrix}$$

$$\omega = \frac{d\theta}{dt}$$

$$\begin{bmatrix} V_{cdref} \\ V_{eqref} \end{bmatrix} = \begin{bmatrix} V_{sd} + \omega L I_{qref} - L \frac{d}{dt} I_{dref} \\ V_{sq} - \omega L I_{dref} - L \frac{d}{dt} I_{qref} \end{bmatrix}$$

$$V_{Cref} = \sqrt{V_{cdref}^2 + V_{eqref}^2}$$

$$\delta = \tan^{-1} \left( \frac{V_{eqref}}{V_{cdref}} \right)$$

$$V_{dc} (t) = \frac{1}{c} \int_{-\alpha}^{t} i_{dc} (t) dt$$
To regulate the capacitor voltage, a small phase shift \( \delta \) is introduced between the converter voltage and the power system voltage. A small lag of the converter voltage with respect to the voltage at the PCC causes real power to flow from the power system to the STATCOM, while the real power is transferred from the STATCOM to the power system by controlling the converter voltage so that it leads the voltage at the PCC. The phase angle of the utility voltage is of vital importance for the operation of most of the advanced power electronic devices connected to the electric utility, since it has a direct effect on their control algorithms. In order to lock the phase angle of the utility voltage in a robust way, a PLL is used. The outputs of the controller are \( i_{d\text{ref}} \) and \( i_{q\text{ref}} \) which are the reference currents in the dq coordinates which are needed to calculate the power injections by the STATCOM as in Equations (4.61) and (4.62).

\[
P = V_i (i_d \cos \phi + i_q \sin \phi) = v_d i_d + v_q i_q
\]

\[
Q = V_i (i_d \sin \phi - i_q \cos \phi) = -v_d i_d + v_q i_q
\]

where \( i_d \) and \( i_q \) are the reference d and q axis currents of the ac system. The fundamental magnitude and the harmonic spectrum are controlled varying the switching angles, \( \alpha \).

4.7 PERFORMANCE EVALUATION OF VSC BASED STATCOM

To evaluate the performance of the conventional STATCOM for a SCIG, a three-phase prototype with a utility line voltage of 25 kV and a utility frequency of 50 Hz is developed. Both the real power and the reactive power of induction generator are proportional to the rotor speed and the power factor of the induction generator is very poor. The DC bus
voltage of the STATCOM depends on the maximum and minimal values of compensation reactive power.

(a) without STATCOM                          (b) with STATCOM

Figure 4.14  Reactive power absorbed by the induction generator

The induction generators are connected to the system at the PCC where the conventional STATCOM is connected to compensate the reactive power absorbed by the induction generators during its starting. The utility system at the PCC is 25 kV. The STATCOM provides reactive power to the induction generator during its operation. So the power factor of the circuit gets improved after applying the STATCOM. Figures 4.14 (a) and (b) shows the simulation results of the reactive power absorbed by the induction generator with and without STATCOM. With STATCOM circuit the reactive power is compensated and becomes positive.
Figures 4.15 (a) and (b) shows the active power in the circuit with and without STATCOM in the circuit. The power factor of the system gets improved when the STATCOM is applied to the system. Figures 4.16 (a) and (b) shows the power factor of the circuit which is 0.78 when there is no compensation circuit in the system. With STATCOM the power factor is improved to 0.95.
Figures 4.17 (a) and (b) shows that the THD measured without STATCOM in the circuit is 5.28% and with STATCOM it is reduced to 2.38%.

4.8 TEST SYSTEM WITH CMC BASED STATCOM

Figure 4.18 shows the single-line diagram of the power system used for this study. A 220 kW wind farm consisting of SCIG driven by FSWT is connected to a power grid through a step-up transformer T₁ and a power line. The Wind Turbine Generator (WTG) with a rated power capacity of 220 kW is considered here. A STATCOM is shunt connected at the 22 kV bus (the high voltage terminal of the transformer T₁) to provide dynamic reactive compensation. To reduce the size of the STATCOM, a fixed capacitor bank is used to supply about 10 Mvar reactive power at the nominal voltage condition. The parameters of the system components are as follows. SCIG: rated power = 220 kW, rated stator voltage = 440 V, stator resistance = 0.0079 pu, rotor resistance = 0.025 pu, stator leakage inductance = 0.07939 pu, rotor leakage inductance = 0.4 pu, magnetizing
inductance = 4.4 pu; Transformer T₁: turns ratio = 440 V/22 kV, equivalent leakage reactance = 0.06 pu; Transformer T₂: turns ratio = 22 kV/13 kV.

Figure 4.18  Single line diagram of the test system

In the proposed work, a test system with a load requiring a voltage 22 kV is connected to the grid as shown in Figure 4.19 and simulated with CMC in Matlab/Simulink software package.

Figure 4.19  Active power without STATCOM
Figure 4.20 Reactive power without STATCOM

Figure 4.21 Grid voltage without STATCOM

Figure 4.22 Load voltage without STATCOM
Figure 4.23 Active power with 3-level inverter STATCOM

Figure 4.24 Reactive power with 3-level inverter STATCOM

Figure 4.25 Grid voltage with 3-level inverter STATCOM
The simulations are carried out with the incorporation of CMC based STATCOM in the system and the results obtained are compared with those obtained without the presence of STATCOM in the system. The parameters measured at three locations such as Grid side, Load side and Wind farm side are shown from Figure 4.19 to Figure 4.26. Table 4.1 gives the comparison of the simulation results obtained with and without CMC based STATCOM.

<table>
<thead>
<tr>
<th>Parameters Measured</th>
<th>Without STATCOM (Per Unit values)</th>
<th>With 3-level VSI STATCOM (Per Unit values)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid active power</td>
<td>0.2</td>
<td>0.28</td>
</tr>
<tr>
<td>Grid reactive power</td>
<td>0.21</td>
<td>0.2</td>
</tr>
<tr>
<td>Grid voltage</td>
<td>0.99</td>
<td>0.99</td>
</tr>
<tr>
<td>Load active power</td>
<td>0.29</td>
<td>0.38</td>
</tr>
<tr>
<td>Load reactive power</td>
<td>0.12</td>
<td>0.2</td>
</tr>
<tr>
<td>Load voltage</td>
<td>0.97</td>
<td>0.99</td>
</tr>
</tbody>
</table>
4.8.1 Reactive Power Compensation using 5-level CMC based STATCOM

The 5-level CMC STATCOM simulation circuit features two conventional full-bridges serially connected together with their power rails connected to separate isolated DC voltage supplies. This section presents the simulation results of the test system with CMC based STATCOM.

Figure 4.27 Active power with cascaded 5-level inverter STATCOM

Figure 4.28 Reactive power with cascaded 5-level inverter STATCOM
Figure 4.29  Load voltage with cascaded 5-level inverter STATCOM

Figure 4.30  Grid voltage with cascaded 5-level inverter STATCOM

4.9  COMPARISON OF RESULTS

The following simulation results from Figure 4.31 to Figure 4.36 shows the implementation of different STATCOM modules (multipulse, 3-level, 5-level) in the test system and its comparison without STATCOM.
Figure 4.31  Comparison of grid active power

Figure 4.32  Comparison of grid reactive power

Figure 4.33  Comparison of load active power
Figure 4.34  Comparison of load reactive power

Figure 4.35  Comparison of wind farm active power

Figure 4.36  Comparison of wind farm reactive power
Table 4.2 shows the comparison of results obtained for all the three cases.

**Table 4.2 Comparison of results with 3-level and 5-level STATCOM**

<table>
<thead>
<tr>
<th>Measured Parameters</th>
<th>Without STATCOM (p.u)</th>
<th>With 3-level VSISTATCOM (p.u)</th>
<th>With 5-level CMC STATCOM (p.u)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid active power</td>
<td>0.24</td>
<td>0.28</td>
<td>0.54</td>
</tr>
<tr>
<td>Grid reactive power</td>
<td>0.21</td>
<td>0.2</td>
<td>0.017</td>
</tr>
<tr>
<td>Grid voltage</td>
<td>0.99</td>
<td>0.99</td>
<td>1</td>
</tr>
<tr>
<td>Load active power</td>
<td>0.29</td>
<td>0.38</td>
<td>0.68</td>
</tr>
<tr>
<td>Load reactive power</td>
<td>0.12</td>
<td>0.2</td>
<td>0.18</td>
</tr>
<tr>
<td>Load voltage</td>
<td>0.97</td>
<td>0.98</td>
<td>1.0</td>
</tr>
</tbody>
</table>

**4.10 PERFORMANCE EVALUATION OF ACMC STATCOM**

The test system comprises of two 275 kVA wind farm being connected to a 440 V distribution system and exports power to a 22 kV grid through a step up transformer, with a 10 kW load has been connected to the PCC and in addition a STATCOM has been interfaced at the PCC. Wind turbines use FSIG consisting of SCIG and a pitch angle control system. In FSIG, the stator is connected directly to the 50 Hz grid and the rotor is being coupled to the prime mover. The FSIG technology allows extracting maximum energy from the wind for low wind speed by optimizing the turbine speed. The optimum turbine speed producing
maximum mechanical energy for a given wind speed is proportional to the wind speed. For wind speeds lower than 10 m/s the rotor is running at sub synchronous speed. At high wind speed it is running at hyper synchronous speed.

**Figure 4.37 Generation of carrier signals**

Phase Disposition Technique is used for Carrier Generation of Carrier frequency - 10 kHz. The Modulation index, $m_a$ is selected as 0.9. In multi carrier based sine PWM, Phase Disposition (PD) is chosen because of reduced switching losses at higher modulation index. Only four carriers are used as shown in Figure 4.37 to develop 9-level output instead of (M-1) carriers for the same “M” level output.
Figure 4.38  Switching signals using multicarrier based SPWM

Figure 4.38 shows the switching angles obtained using carrier based PWM control strategy.

Figure 4.39  Load voltage profile
For the test system which includes a grid, step down transformer and a non linear load the nominal voltage, current, real power and reactive power appears across the load that is observed as shown from Figure 4.39 to Figure 4.41. Without wind farm the voltage at PCC is around 380 V and when wind farm is integrated into the power system, the voltage profile reduces to 220 V. This drop in voltage profile is improved with STATCOM and the voltage improves again to 380 V.

Figure 4.40 Load current waveforms

Without wind farm the current at PCC is around 18 A. With wind farm the current at PCC increases and then decreases to about 30 A. With STATCOM the current at PCC is about 15 A.
Without wind farm the real power at PCC is around 10 kW. With wind farm the real power at PCC increases and it is about 10 kW. With STATCOM the real power at PCC is about 5 kW.

Figure 4.41 Real power waveforms

Figure 4.42 Reactive power waveforms
Without wind farm the reactive power at PCC is about 800 var. With wind farm the reactive power is consumed from the grid and with STATCOM the reactive power injected at PCC is around 5000 var. When wind farm is connected to PCC for the same test system without wind farm there is a voltage drop and there is also a reduction in the reactive power due to the reactive power being consumed by the induction generator. Finally when a CMC based STATCOM is incorporated to the test system, voltage profile gets improved as the reactive power has been injected from the STATCOM to the PCC.

![Figure 4.43 Per phase voltage output of CMC](image)

![Figure 4.44 7-level voltage output of CMC](image)
Figure 4.45   THD for 7-level CMC based STATCOM

Figure 4.46   THD for 9-level CMC based STATCOM

Figure 4.47   THD for 9-level ACMC based STATCOM
When compared to 9-level CMC STATCOM, 9-level ACMC STATCOM gives reduction in THD value as observed in Figure 4.46 and Figure 4.47.

4.11 HARDWARE IMPLEMENTATION

In hardware implementation, a 3-level, 5-level CMLIs based converter have been constructed using the MOSFET as the switching device.

The hardware model has been built as shown in Figure 4.48 and tested to verify the concept. For a 3-phase system, the number of pulses, \( p \), can be formulated by

\[
P = (M-1) \times 6
\]

(4.63)

where \( M \) is the number of levels;

![Hardware circuit implementation](image)
Figure 4.49  Single $H_1$ bridge output waveform in CRO

Figure 4.50  Single $H_2$ bridge output waveform in CRO
Figures 4.49 and 4.50 shows the per phase voltage output waveforms of bridges $H_1$ and $H_2$ respectively. Figure 4.51 shows the 3 phase cascaded 5-level inverter output waveform measured in CRO.

4.12 CONCLUSION

For the wind farm voltage fluctuation suppression using a CMC based STATCOM, the methodology to conduct an impact study of a STATCOM on the integration of a large wind farm into a weak loop power system is described. The specific issues and solutions of the studied wind farm system are illustrated. For the system study, the models for the system, wind farm and STATCOM are developed. This chapter discusses the application of conventional, CMC and ACMC STATCOMs to improve the voltage quality of grid connected fixed speed Induction generator wind turbine systems. The STATCOM when connected in shunt in the system can provide fast and smooth reactive power control and effectively control the system voltage level during the introduction of induction generators and also during the continuous operation. The proposed CMC and ACMC
STATCOM topologies offers several advantages over the conventional VSC STATCOM such as reduced power loss, modular layout, less harmonic contents, the output changing linearly with input and the absence of costly, bulky coupling transformer. The simulations made in Matlab shows the improvement made in the magnitudes of the reactive power and voltages when compared with the 3-level inverter based STATCOM. In the proposed work, a complete transient stability and steady state model for the STATCOM has been implemented and proved that by controlling reactive power the voltage regulation and maximum active power flow can be achieved.