CHAPTER 3

PERFORMANCE ISSUES IN WIND FARMS

3.1 INTRODUCTION

In India, the exploration of wind energy has already reached a mature stage of commercial development. In this stage, it is important to analyze the grid integration capability of modern WTG. Generally the Indian power systems are not stable and sufficient enough to cater to the needs of increase in wind farms in a few rural areas where the existing transmission and distribution grids are very weak. Hence rather than the technical advancements of WTG, the power quality issues such as steady state voltage, power factor, flicker and harmonic distortion are also to be studied. The power quality of the grid influences the performance and safety of the WTG and the life time of mechanical and electrical components. This chapter deals with the performance issues and solutions related to the reactive power management and other manufacturing designs in the wind farms based on a detailed study.

3.2 POWER QUALITY ISSUES

Most of the modern wind turbines employ induction generators that consume reactive energy under all load conditions. Due to the large integration of WTG to utility grids, the various issues related to the power quality are as follows:
a) Effect of variations in system voltage and frequency on the performance of wind turbine generators

b) Consumption of reactive power from the grid by the induction generators employed in wind turbines that results in low power factor

c) Effect of voltage transients on the wind turbine components

d) Generation of current harmonics by the WTG

e) Power fluctuations from WTG due to variations in wind velocity and frequent yawing

f) Reduced capacity factor of the WTG due to unpredicted stoppages such as damage of rotor blades due to lightning strokes, defect in hydraulic braking system, failure of power electronic components due to voltage surges

Among the power quality issues stated above, reactive power management in wind farms has become an important criterion in Tamil Nadu as TNEB is insisting penalty for the wind turbine promoters who are not maintaining the power factor above 0.85. Also to overcome the disadvantages of power fluctuations from WTG due to frequent yawing and unpredicted stoppages due to system failure, some technical modifications in the existing design WTG are essential.

3.3 REACTIVE POWER MANAGEMENT IN WIND FARMS

3.3.1 Concept of Power Factor in WTG

Power factor is the ratio of real power to the apparent power and this defines the proportion of total real power that can be obtained. Also, from the first principles power factor can be computed from Equation (3.1) as follows:
\[ \text{PowerFactor} = \cos \left( \tan^{-1} \frac{Q}{P} \right) \]  
(3.1)

where \( P \) is the real power in Watts and \( Q \) is the reactive power in VAR.

In a wind farm, the induction generator and transformer contribute to lagging reactive power and capacitors contribute to leading power factor. An induction generator is asynchronous in nature because of which it is commonly used as WTG at non-fixed speed. These are used in remote areas to supplement power received from weak transmission links. In negative slip region the machine draws lagging current whose phase angle with respect to applied voltage is greater than 90°. This means negative power factor or that the electric power flows out of the machine resulting in generating operation. The generating current fed to the line has a leading power factor. This alternately means that the machine draws a 90° lagging current component to provide its magnetic current need. Then the transmission line has to feed the lagging current component of the load as well as the magnetizing current of the induction generator and transformer. This places a severe lagging VAR load on the already weak lines, which results in more voltage drop and poor voltage regulation. The increased reactive power flow in lines also leads to poor power factor. These may lead to components failure and malfunctioning of electrical equipments connected to the power system. Hence, this burden must be relieved by connecting balanced shunt capacitors across the induction generator terminals. These draw leading current or equivalently feed lagging magnetizing current of the generator (Tarek Ahmed et al 2006).

The four quadrant operation of a wind turbine driven induction generator is explained below:

- I Quadrant: During starting of WTG, the induction machine runs as motor for fraction of second
- II Quadrant: Generates real power and draw reactive power for excitation which is the normal operating mode of WTG for most duration

- III Quadrant: Operating point of WTG during over compensation, which is not recommended due to the possibilities of over compensation and self-excitation

- IV Quadrant: Abnormal mode of operation that can happen during starting of WTG with over compensation

The reactive power characteristic of an induction generator is a function of design and manufacturing tolerances of the air gap. For optimal design, the product of efficiency and power factor is a limiting constant which varies between 0.68 and 0.84. The reactive power required by the induction generator varies between 0.1 p.u. and 0.65 p.u. depending upon the real power generated or the wind velocity.

Also the power transformer used for stepping up the generated voltage (from 415 V to 750 V) to higher levels (11 kV to 66 kV) requires magnetizing current for the operation. This constitutes reactive power consumption from the grid. Depending upon the reactive power compensation methodologies, the power factor will vary between 0.8 and 0.99.

### 3.3.2 Implications of Reactive Power

The reactive power consumption by the WTG from the grid leads to low power factor, increased line losses, poor voltage profile and reduced voltage stability margins, over loading of transmission and distribution equipment and blocked capacity.
As the power factor decreases, the current flowing in the system will increase that result in increased transmission and distribution losses. Due to this additional current, the ability of the equipment to handle real power decreases with its need to handle more reactive power. The voltage profile particularly at the remote line ends will be affected due to the voltage drops.

3.3.3 Reactive Power Compensation Schemes Employed

The need for controlling reactive power in lines has been recognized due to huge lagging reactive power demanded by the induction generators. Reactive power compensation can be done either by drawing a lagging or leading current using suitable components. Permanently connected and switchable shunt capacitors and reactors have been used from the beginning to ensure desirable voltage profile along the transmission and distribution lines and to minimize voltage variation in face of daily power demand changes. To handle dynamic disturbances such as line switching, load rejection, faults, etc., the reactive power control has to be fast in order to provide effective voltage and power flow control and thereby a significant improvement in system stability. In the past, contactors are used for switching the capacitors in and out of the system manually (Mohan Mathur et al 2002).

For leading power factor, shunt inductor can be used and for lagging power factor, shunt capacitor can be used to correct the power factor. Normally the WTG control panels are provided with contactor switched capacitor banks to compensate for 50% of the total reactive power requirement. The balance requirement is obtained from the grid. Since the Tamil Nadu Electricity Board (TNEB) is insisting penalty for the consumption of reactive power from the grid, additional facilities are provided by the manufacturers through additional capacitor banks that are connected to the individual WTG or at the supply point of group of WTG.
Venkatesh et al (2000) detailed the comparison of various compensation schemes are summarized in Table 3.1.

**Table 3.1 Summary of various reactive power compensation schemes in wind farms**

<table>
<thead>
<tr>
<th>Type of Compensation</th>
<th>Advantages</th>
<th>Disadvantages</th>
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| Fixed capacitors     | • Simple and economical  
                      | • Less losses            | • Dynamic compensation is not possible  
                      |                         | • Can lead to over compensation |
| Contactor switched capacitors | • Simple and economical  
                              | • Less losses except when current limiting reactors are used | • Leads to switching transients  
                              |                         | • Contactors are not reliable  
                              |                         | • Capacitance degradation |
| Soft switched capacitors | • Highly reliable  
                           | • No switching transients  
                           | • Frequent switching can be done with less losses | • Costlier than the previous techniques  
                           |                         | • More losses than fixed capacitors |
| Static VAR Compensators  | • Step less control of reactive power  
                           | • Dynamic reactive power compensation | • Expensive  
                           |                         | • More losses than soft switching technique |
| STATCOM / STATCON  | • Step less control of reactive power  
                         | • Dynamic reactive power compensation | • Very expensive  
                         |                         | • High losses  
                         |                         | • Generation of harmonics |
3.3.4 Static VAR Compensators (SVC) for WTG

In recent years, a high quality power is demanded by the market and also better utilization of existing power systems has become imperative. So, the developing market needs have been answered by technology developments. Advances in high power semiconductor and sophisticated electronic control technologies have made the development of fast, thyristor controlled SVC possible. They are characterized by extremely rapid response, unrestricted operation, high reliability and almost unlimited operating flexibility. The SVC demonstrates the two key benefits of power factor correction, which include decreased power costs and increased system capacity.

In an isolated stand-alone operation for clean alternative renewable energy utilization, the three-phase induction generator operates in the self-excitation power generation mode when a capacitor bank connected in parallel with its stator terminal ports and driven by wind turbine. The three-phase SEIG determines its own generated terminal voltage and its output frequency, which depend on the self-excitation capacitance, the three-phase induction machine parameters, the electrical passive load parameter constants and the turbine speed. This work deals with the design of automatic power factor compensation methodology unlike the existing contactor switched capacitance technique which delivers the lagging reactive power demanded by the induction generator under varying load conditions. The proposed work will reduce the major stress on mechanical components like generator, gear box, tower etc. The block schematic of the proposed work is shown in Figure 3.1.
A SVC is based on thyristor controlled reactors (TCR), thyristor switched capacitors (TSC), and/or fixed capacitors (FC) tuned to filters. A TCR consists of a fixed reactor in series with a bi-directional thyristor valve. A TSC consists of a capacitor bank in series with a bi-directional thyristor valve and a damping reactor, which also acts as a circuit detuner so that parallel resonance with the network is avoided. The thyristor switch connects and disconnects the capacitor bank for an integral number of applied voltage half cycles. As mentioned by Laszlo Gyugyi (1998), the TSC is not phase controlled, i.e., it does not generate any harmonic distortion. A complete SVC based on TCR and TSC may be designed in a variety of ways so that specific criteria and requirements are satisfied. In addition, slow VARs by means of contactor switched capacitors can easily be incorporated into the schemes if required. The three basic configurations of SVC are FC/TCR, TSC and TSC/TCR.
FC/TCR behaves like an infinitely variable reactor. The unit consists of one reactor in each phase, controlled by a thryistor switch. The TCR provides continuously controllable reactive power only in the lagging power factor range. To extend the controllable range to the leading power factor domain, a fixed capacitor bank is connected in shunt with the TCR. The fixed capacitor bank usually connected in star configuration, are split into more than one 3-phase group. Each capacitor contains a small tuning inductor that is connected in series and tunes the branch to act as filter for a specific harmonic order.

TSC provides capacitor based voltage regulation for the distribution system. The major components include capacitors, thryistor switches and a soft start resistor system. During the operation, the capacitors get charged slowly avoiding high inrush currents. After the charging process, the resistor is bypassed by a contactor.

TSC/TCR is the combination of TSC and TCR which gives most optimum solution in majority cases. With this configuration, continuously varying reactive is obtained which provides an optimum performance under dynamic operating conditions. The TSC-TCR compensator shown in Figure 3.2 usually comprises of ‘n’ TSC banks and a single TCR that are connected in parallel. The rating of the TCR is chosen to be 1/n of the total SVC rating. The capacitors can be switched in discrete steps, whereas continuous control within the reactive power span of each step is provided by TCR. Thus the maximum inductive range of SVC corresponds to the rating of the relatively small interpolating TCR.

As the size of TCR is small, the harmonics generation is also reduced. The main motivation in developing TSC-TCRs was for enhancing operational flexibility of the compensator during the large disturbances and for reducing steady state losses. The FC-TSC behaves like a parallel LC
circuit that tends to set up a resonance with the AC system impedance during large disturbances. In this event, a TSC-TCR can quickly operate to disconnect all capacitors from the compensator, to preclude the resonant oscillation. This feature of disconnecting the capacitors in exigencies is not available with FC-TCR configuration.

Figure 3.2 TSC-TCR configuration

3.3.5 Simulation Results and Discussion

The automatic VAR compensator for a wind turbine generator feeding an isolated load as shown in Figure 3.3 is simulated using MATLAB/SIMULINK and analyzed for different loading conditions.

The entire system consists of following blocks:

- Wind Turbine driven Induction Generator
- Power Factor measurement circuit
- Control and Gating circuit
- Power Electronics Circuit
- Dynamically varying RL and RC load circuit

**Figure 3.3 MATLAB/SIMULINK model of automatic VAR compensator for isolated wind turbine driven induction generator**

The induction generator is driven by a variable speed wind turbine of rating 110 kW, 480 V. The induction generator is self excited by a three phase capacitor bank of 75 kVAR in each phase. The measurement block gives the three phase values of voltages and currents in terms of Volts and Amperes. Three phase instantaneous active and reactive power block is used to compute instantaneous active power (P) and reactive power (Q) associated with periodic set of three phase voltages and currents which is obtained from previous block. The output of three phase active and reactive power block is a vector quantity in the form of (P + jQ). To get the magnitudes of real and reactive power a signal routing component called ‘selector’ is used.
The magnitudes of real and reactive power thus obtained are used to compute the existing power factor. This is done by MATLAB function with real and reactive powers as inputs. The third stage is the simulation of control and gating circuit. This block accepts reactive power demand as an input and generates three phase firing pulses for controlling the capacitor banks. The pulse generator continuously generates pulses at regular intervals of specific amplitude, pulse width and phase delay. The pulses at twice the supply frequency with a phase delay of 90° with respect to each of the three phase voltages are generated. In gating circuit, the error parameter range is continuously monitored and based on the error range suitable capacitor is connected by firing the corresponding thyristors. A MATLAB script is used to perform the function of continuous monitoring of the reactive power demand and controlling the gating pulses applied to thyristors.

The power circuit consists of capacitor banks connected to the three phase lines via anti parallel thyristors. Each capacitor bank consists of three individual capacitors of 75 kVAR connected in star fashion. The gate pulses from the gating and control circuit are applied to corresponding pair of thyristors to control the reactive power supplied by the capacitors. The thyristors are fired at a firing angle of 90° to ensure transient free operation as mentioned earlier.

The value of capacitor is obtained based on the reactive power requirement. The design of capacitance value is obtained as follows:

$$X_C = \frac{1}{2\pi f C}$$  \hspace{1cm} (3.2)

$$Q_{req} = \frac{V^2}{X_C}$$ \hspace{1cm} (3.3)
where $X_C$ is the capacitive reactance in Ohms
$V$ is the phase voltage in Volts
$f$ is the frequency in Hertz
$C$ is the compensation capacitance in Farads
$Q_{req}$ is the required reactive power per phase in VAR

From Equations (3.2) and (3.3),

$$C = \frac{Q_{req}}{2\pi f V^2}$$  \hspace{1cm} (3.4)

The entire system is simulated for dynamic load variations without automatic VAR compensator and the results are depicted in Figure 3.4. As mentioned earlier when the loads consuming reactive power are added to the system the system power factor becomes very poor. Here up to 25th second there is no load and hence the power factor is unity. At 25th second a step change in load results in drop in power factor. As another load consuming more reactive power is added, the system power factor again drops to a very poor value of less than 0.35. The Figure 3.4 shows the system power factor with respect to time which keeps on dropping when loads are added.

![Figure 3.4 Power factor Vs Time (without compensator)](image-url)
Now the automatic compensator is connected and the results are analyzed for the same loading conditions. The results obtained are shown in Figure 3.5. It is seen that almost unity power factor is maintained when the automatic VAR compensation is employed as the reactive power flow in the lines is minimized, because of the reactive power supplied by the capacitors. As a result the reactive power flow in the system will be very less and hence the power factor is maintained above 0.85. This analysis shows the effectiveness of automatic VAR compensator thus designed. Due to automatic VAR compensation the reactive power flow in the system is minimized because of addition of required compensating capacitors in to the system.

![Figure 3.5 Power factor Vs Time (with compensator)](image)

**Figure 3.5 Power factor Vs Time (with compensator)**

### 3.4 CASE STUDY IN A WIND FARM

For fixed speed wind turbines, the generator is directly connected to the load or grid. Since the speed is almost fixed to the grid frequency and most certainly not controllable, it is not possible to store the turbulence of the wind in form of rotational energy. Therefore, for a fixed speed system the
turbulence of the wind will result in power variations and thus affect the power quality of the grid.

For a variable speed wind turbine the generator is controlled by power electronics equipments, which make it possible to control the rotor speed. Variable speed turbines have many advantages in comparison with constant speed turbines. Variable speed improves the dynamic behaviour of the turbine, alleviating the stresses on the mechanical construction, increases the power production and reduces the noise at low wind speed. In addition, by using a voltage source converter for the variable speed system, grid currents can be controlled to be sinusoidal without low frequency harmonics and the reactive power can be chosen freely.

In spite of the additional cost of power electronics and control circuits, the total energy capture in a variable speed wind turbine system is large, resulting in low life cycle cost. Reactive power is a key element in maintaining voltage and synchronous stability and ensuring proper power system performance. Main aspects of reactive power in today’s power systems are the best design and operating practices and the effect of industry restructuring (Lin et al 2006). A sample wind farm of 8.6 MW capacity located at Udumalpet area of Tamil Nadu with different types of reactive power compensation schemes is taken for a case study. The wind farm is interfaced with Perungudi substation through 11 kV feeders. A 315 kVA transformer connects the generator to the 11 kV feeder. The performance of the WTG with different power factor improvement methodologies are studied for whole year and certain interesting results are obtained.

3.4.1 Survey Objectives

India has some special requirements. The penalty for low power factor is severe, but European designs do not have provision for compensation
to this level. Most of the original designs have contactor switched capacitor bank steps limited to about 33% of the generator capacity which may not do any harm. There will be heavy penalties during low wind period if the same norm is adopted. In Tamil Nadu, the TNEB has introduced the penalty only in late 90’s. As the principals have failed to understand the issue and provide solution, most of the Indian subsidiaries have approached third parties. The cheapest and easiest solution preferred was to add more contactors and more capacitor steps.

Wind resource by its nature is intermittent and fluctuating. Stepped contactor switching cannot meet the compensation requirements as capacitor cannot be re-switched before discharge as at least 60 sec delay is required. As a remedy, the designs provide overcompensation (exceeding 100%) during low wind period. Penalty has been avoided, but the most expensive components like gearbox and generators are being subjected to excess stress. Losses have gone up and active power is also affected. Besides additional capacitor panels in individual wind turbine generators, group compensation with transformer and capacitor panel at the interface point has also been tried in most of the wind farms.

Dynamic control will provide the solution, but is too expensive. As an alternative, static switching has been tried out. This could eliminate overcompensation substantially. There is no systematic study to evaluate losses and scope for improving productivity. This work is an attempt to make realistic evaluation of wind farms provided with different systems in India. The various characteristics of reactive power compensation schemes are:

a) The VAR requirement for wind farms vary from time to time. During high wind periods, the requirement is high and it is very low during low wind periods.
b) As the load is actually a source which is an induction generator, the problems associated with over compensation or self-excitation, especially when the generators are disconnected from the grid.

c) Effect of harmonics and transients.

d) Located in remote sites with low level operators.

The systems available for power factor compensation can be classified into following categories:

a) Traditional systems with capacitor steps switched through contactors controlled by microprocessor based controllers. This system is common for single or dual speed pitch controlled and stall controlled WTG.

b) Group compensation system: In addition to individual compensation in WTG, power factor is further improved by introducing additional low voltage capacitor banks near TNEB metering points. The step of capacitor banks controlled by controllers is connected into the system through transformers.

c) Static switching for capacitor steps in WTG. Hybrid systems are also included, that are partly controlled by contactors.

d) Similar to (c) but with modified transformer configuration. Tertiary winding is introduced for capacitor banks.

e) Dynamic compensation with continuously variable capacitance.
f) Induction generator with slip rings. Rotor output is rectified, inverted and fed back to grid. This system has a limited variable speed option.

g) Variable speed, variable pitch and gearless with synchronous generators.

To facilitate a comparative study, it is necessary that the power production is calculated on a common basis and performance evaluation carried out considering following aspects for the entire year in monthly basis:

a) Power production: For analysis, specific power production is calculated in kWhr per square metre of blade swept area. It has been recognized by the experts in the industry that evaluation based on this concept is more reliable than capacity factor for the WTG, as there are no norms for specifying WTG capacity.

b) Wind farm losses: The losses are calculated based upon the power produced and power transferred to the grid. It is obtained from the WTG control panel and TNEB meter readings.

c) Meter readings:

I. kWhr Export: In practice, it has been found that when there is heavy overcompensation (confirmed by high percentage of kVARhr Export / kWhr Export), active power is less. Comparison of active power of identical WTG having different compensation systems in the same wind farm (influenced by same wind regime) will confirm the observation.
II. kWhr Import: kWh Import/MW is considered to compare under a common basis. The value will be higher during low wind speeds and may exceed norms if kVARhr import / export is very high. Asynchronous and synchronous generators may have different characteristics.

III. kVARhr Import: To avoid penalty, kVARhr is maintained below 5%.

IV. kVARhr Export: This is very important parameter to assess performance of reactive power compensation system. Abnormally high kVAR represents hazardous situation.

d) Component failure records: Data to be collected for major components like generator, gear box, transformer and blades. Gear box is one of the costlier components and the normal life should be 20 years if maintained properly. There are premature failures of gear boxes.

3.4.2 Illustration

The 8.6 MW wind farm with same type of WTG employing different schemes of reactive power compensation techniques taken for comparison during the period January 2008 to December 2008 located at Udumalpet area in Tamil Nadu, India are:

a) Group A (10 x 400 kW): WTG provided with individual reactive compensation capacitor in steps.
b) Group B (4 x 400 kW): WTG provided with additional group controlled capacitors for reactive power compensation.

c) Group C (4 x 750 kW): WTG provided with static switched capacitor panel in tertiary winding in addition to conventional panel.

Figure 3.6 shows Productivity in kWhr/sq.m of swept area of blade month wise for the above groups. The average yearly power production for the above service connections during January 2008 – December 2008 are as follows:

a) WTG in Group A provided with individual compensation contactor in steps is 764.3 kW.

b) WTG in Group B provided with additional group control is 799.0 kW.

c) WTG in Group C with static switched reactive power compensation in tertiary winding is 887.8 kW.

![Figure 3.6 Month wise productivity in kWhr/sq.m of swept area of rotor](image)
The productivity graphs appear to be normal and reasonable. Annual power yield are also realistic. The power production is higher in Group C (WTG having larger power rating) being an advanced version with technology improvements. Production in Group B WTG is higher by 16.16% compared with Group A WTG without compensation for increase in hub height. Considering 0.14 as power law index, hub height will contribute to 6.11%. Net power increase for Group C is 10.05% approximately, as all the three wind farms are in the same wind regime.

Further analysis as per Figure 3.7 indicates that increase in power production is determined more by the low wind performance. The duration from May to December is taken as high wind period and from January to April as low wind period. Group C has recorded almost 100% increase in power production during low wind period compared with Group B. Group A provided with group control system for reactive power compensation, shows lowest performance for low wind period, about 20% lower compared with Group B.

![Figure 3.7 Wind period wise productivity in kWhr/sq.m of swept area of rotor](image-url)
By analyzing the power yield during low and medium wind periods, low production can be attributed to the following factors:

a) Poor power factor: Since the induction generators draw reactive power and generate real power, the power factor decreases and the current flowing in the system increases. Due to this, the following conditions occur:

- Increased losses in the generator, transformer and transmission line.
- Over loading and blocking capacity in all the power equipment. The ability of all the power equipment to deliver / handle real power decreases as it needs to handle more reactive power that results in loss of revenue due to the inability to deliver useful power.
- Temperature rise in the equipment especially in transformers.
- Reduced voltage stability margins due to the voltage drops in the line. The poor voltage profile causes increased losses in the rotating machinery.

b) Overcompensation: The effect of overcompensation due to high leading power factor will be similar to (a), though the penalty for low power factor can be avoided. Active power will be lower. There are other hazards which may lead to failure of not only electrical components but also gear box.

c) Losses due to mechanical contactor based stepped switching of capacitors: The mechanical switches have the problem of
producing switching inrush currents and associated capacitor over voltages. This results in poor reliability of capacitors.

d) Blade efficiency: Due to varying grid frequency, the rotor speed of the induction generator and thus the aerodynamic performance of the wind turbine will be modified.

### 3.4.3 Results and Discussion

The reactive power produced and consumed from TNEB is illustrated in Figures 3.8 and 3.9 respectively for the three types of groups. Also the wind farm losses in percentage for a period of one year are depicted in Figure 3.10. The following inferences are obtained from the said characteristics:

a) Group C has specific production (kWhr/sqm. of swept area of blade) higher than about 10%, compared with Group B.

b) In Group B, the production at lower wind speeds are lowest. It is also seen that there is heavy overcompensation, even exceeding 100% that results in higher loss. Overcompensation at metering point will also cause higher voltage compared to generated voltage of the WTG, which may lower the power output. It is also noted that kVARhr Import is not very good for higher production. This may due to inability of mechanical switching to optimize the kVARhr compensation.

c) Group A provided with additional mechanically switched capacitor has shown clear sub-optimal performance, as kVARhr Import was higher for first half of the months (from January to April) and kVARhr Export higher for last three months (from October to December).
Figure 3.8 Export kVARhr characteristics of different groups

Figure 3.9 Import kVARhr characteristics of different groups
d) Thus the primary objective of the reactive power compensation is not to maintain unity power factor, but to reduce the line currents and hence the line losses.

e) Considering the dynamic variations in power factor in a WTG, special controllers are required to suite all operating conditions. Apart from the controllers, the compensation scheme needs fast switches for connection and disconnection of capacitors. Use of mechanical switches might cause damage to the induction generators. Due to the time delay of these mechanical switches, the inclusion of additional capacitors may lead to over voltage on the system.

f) An optimum power factor for minimum total losses is to be maintained by providing suitable reactive power compensation scheme.

Thus a detailed study has been made from the survey obtained from different types of WTG with various power factor improvement methodologies, located in the same wind regime of Udumalpet area. The case
study has given beneficial outputs about the practical systems. It is observed that the wind farm with group compensation of capacitors has productivity higher by about 10% which appears to be reasonable. It is to be noted that performance during low wind has substantially contributed to the enhanced power production. The losses for all the WTG are observed to be less than 3.5%.

3.5 INVESTIGATIONS IN PERFORMANCE ENHANCEMENT

3.5.1 Yaw Error Problems

On further investigations in a 10.02 MW wind farm at Aralvaimozhy pass Muppandal area in Tamil Nadu, India, having various models and capacities of WTG, the following issues were identified in a specific group of 250 kW, Danish machines. These WTG are equipped with hydraulic yawing unit with negative fail safe braking system. The yaw mechanism which is used to turn the WTG rotor and nacelle against the wind is operated electrically and controlled by the controller based on the information from wind vane. It consists of a yaw mounting plate of cast steel, a ball bearing slew ring with inside cogging, a two stage electrical yaw gear unit with gear ratio of 1:1218.875 and equipped with three phase induction motor of 0.37 kW rating and a friction to dampen yaw movements. The yaw movement is dampened by five yaw brakes out of which, three are hydraulically activated and two mechanically operated.

If the rotor is not perpendicular to the wind direction, yaw error occurs. It implies that the wind energy harnessed by the rotor area is lesser. Hence appropriate yaw control is required to control the power input to the wind turbine rotor. The part of the rotor which is closest to the wind direction will be subjected to a larger force than the rest of the rotor. Hence the rotor will have a tendency to yaw against the wind automatically. As the wind gusts are severe in this regime, the yaw brakes allow some restricted yaw movements to avoid peak loads in the yaw drive system. Thus the yaw gear
unit failure is more frequent and yaw hydraulic brakes are not sufficient to control the orientation of nacelle assembly towards predominant wind direction. Hence the power capturing capacity is reduced.

### 3.5.1.1 Remedial Measures

To overcome this problem, an electromagnetic brake replacing yaw hydraulic brake is suggested. The main requirements to be considered are high reliability, low maintenance and a low braking torque tolerance. In the existing system, the hydraulic yaw brake and the mechanical brake are provided on the high speed shaft of the yaw system located on the slew ring.

By detailed investigations, it is proposed to have an additional electromagnetic braking on the high speed shaft and the hydraulic yaw brake is operated as mechanical yaw brakes on the low speed shaft. The hydraulic unit has three controls for parking brake, aerodynamic brake and yaw brake respectively. The solenoid coil corresponding to the existing yaw brake is used for electromagnetic braking. Also, the cooling fan of the yaw motor is removed and the electromagnetic brake is mounted on the shaft with some mechanical arrangements. As the yawing is not so frequent in a day, the motor is not operational continuously. Hence the cooling fan is not required in this application. Also as the nacelle is highly ventilated and the yaw system is located about 30 m from the ground level, natural cooling of yaw motor is sufficient.

### 3.5.1.2 Design of Electromagnetic Yaw Braking System

The electromagnetic yaw brake consists of field, armature and hub. The magnetic field is bolted to the yaw motor shaft. When the armature is attracted to the field, the stopping torque is transferred into the field system and hence into the yaw shaft decelerating the load. Similarly when the supply to the coil is cut-off, the magnetic flux falls rapidly and the armature gets separated. Eight springs hold the armature away from the disc surface at a predetermined air gap.
Figure 3.11 Design of new electromagnetic yaw braking system

The new braking system will keep the nacelle to face the predominant wind direction. In the event of a fault, the brakes will act as a
friction clutch to enable the nacelle to move with the wind. The design details of proposed electromagnetic yaw braking arrangement are shown in Figure 3.11. The entire system is designed based on the available measurements in the yaw component. As the cooling fan is removed, the space is adequate to fix the discs on the yaw gear shaft.

Figure 3.12 illustrates the snap shots of the proposed system incorporated in the existing WTG which is under satisfied operation for the last two years.

Figure 3.12(a, b) Snap shots of new electromagnetic yaw braking system
3.5.1.3 Performance Analysis

On implementation in a WTG, the performance analysis is made for two years duration before and after installation. The performance measures considered for the study are generated units in kWh, capacity factor and generated units per running hour for the years 2008 and 2009. The yaw brake was installed during the end of January 2009 and hence the monthly data are collected and recorded for the duration from February 2008 to January 2010. An interesting fact that was observed from the collected data is the running hours and the generated units for the similar months in the two consecutive years are not comparable. For instance, the running hours during February 2008 was 109 hours and during February 2009 was 510 hours. As the grid availability was not proper during 2008, there was a decrease in running hours. Hence the performance details of another Danish model of neighboring machine of same 250 kW capacity is also taken for analysis.

![Performance Characteristics Before Installing New Electromagnetic Yaw Braking System](image)

Figure 3.13 Performance characteristics before installing new electromagnetic yaw braking system
Figure 3.13 and Figure 3.14 show the performance characteristics of the proposed WTG and the nearby WTG of different make and same capacity for duration of two years. From the characteristics in Figure 3.13, it is observed that the generation is affected during peak wind periods i.e. from June to October and hence the generated units from the proposed WTG are 35% lesser when compared to the nearby WTG. Whereas the generation during low and medium wind periods is also lower about 10%.

After installing the electromagnetic yaw braking system, the performance characteristics in Figure 3.14 illustrate a significant improvement in the generation of the proposed WTG. During the same peak wind period, the difference in the generation between the proposed WTG and nearby WTG is only 12%.

Figure 3.14 Performance characteristics after installing new electromagnetic yaw braking system
The performance analysis based on the generated units and capacity factor before and after installing the new electromagnetic yaw braking system are depicted in Figure 3.15 and 3.16. From the characteristics, it is obvious that during 2009, there is an average increase of about 15% in capacity factor. As the running hours of similar months in the two consecutive years are not comparable, the generated units in kWhr per running hour is computed for the said period and comparison characteristics are drawn as shown in Figure 3.17. On an average, a 10% increase is observed from the performance particulars.
It is observed that the effectiveness of the yaw system is enhanced. This improves the life of yaw gear unit and avoids oil spills in the yaw brakes, thus increasing the power generation capacity. The management of the wind farm owns an industry in south Tamil Nadu. The power produced from the WTG is adjusted with the power consumed from TNEB in their industry. The present tariff of power consumed @ Rs. 4.00 per kWhr yielded an increase of Rs. 2.27 Lacks during the year 2009. Thus the minimal modifications in the existing system with optimum design of electromagnetic braking have increased the efficiency of the WTG and also the revenue for the wind farm owner is consistently improved. As the results are encouraging, the entire similar model WTG in the wind farm are presently equipped with new electromagnetic yaw braking system.

3.5.2 Rotor Hydraulic Unit Problems

In another Indian model of 250 kW WTG, frequent failures of hub power pack and rotor hydraulic brake systems constantly occurred. This particular model uses two hydraulic systems for aerodynamic brakes and
parking brakes respectively. In the hub power pack, the hydraulic motor frequently failed to operate. The failure rate was more and hence the machine down time rapidly increased. This decreased the capacity factor of the WTG.

### 3.5.2.1 Suggested Solution

An in depth analysis has been made and the major reason for down time is found to be the overheating of hydraulic motor due to its continuous operation as the pressure to be build up in the accumulator is inadequate. The pre-charging of $\text{N}_2$ gas pressure in the accumulator was found to be insufficient. For satisfied operation a hydraulic pressure between 80 bar and 90 bar is required keep the rotor blade tips in alignment with the blade. The existing hydraulic power pack was modified such that the motor is made to run with the aid of an extra 555 timer circuit and a 9 A contactor. The average time for building up the required hydraulic pressure was studied and found to be less than one minute. Hence a 555 timer is connected to operate the motor for about one minute so that the motor will stop after this time irrespective of the pressure developed. This has been installed in a WTG during May 2011 and tested. The snap shot of the electronic circuitry installed in a hub power pack is shown in Figure 3.18.

![Figure 3.18 Snap shot of hydraulic power pack with proposed design](image)
3.5.2.2 Performance Analysis

The performance analysis of the proposed design is made and the comparison characteristics are drawn. The generated units in kWhr is compared with the nearby WTG of same model and as illustrated in Figure 3.19, a 2% increase in generation for the period after installing the timer circuit is produced.

Figure 3.19 Generated Units in kWhr before and after installing proposed circuit

Figure 3.20 Generation hours before and after installation
The generation period is also increased by 24 hours as the machine break down hours due to failure in hub power pack in the nearby machine is 27 hours. Hence the technical availability of the WTG after modification is 96.28% when compared to 92.28% before installing the timer circuit. These are illustrated in the Figures 3.20 - 3.22. Thus the failure rate of hydraulic hub power pack is drastically reduced so that the operation and maintenance cost is minimized.
3.6 CONCLUSION

The practical aspects of the commercial wind farms related to reactive power management and other manufacturing design modifications to suite Indian atmospheric and grid conditions to enhance the power production are presented in detail with the aid of case studies. The induction generators employed in wind turbines require reactive power from the grid for excitation. The loads on the power systems in India also consume a significant reactive power, mainly due to agricultural pumps. The resulting reactive power demand causes losses in the transmission. In Tamil Nadu, the reactive power consumption results in poor power factor, which reduces the capacity of the power stations. This is a critical issue, because the available power station capacity is insufficient to supply the peak demand. Also, excessive reactive power consumption can be critical for the stability of the power system. From the results, it is obvious to note that the wind farm with group compensation of capacitors has increased the productivity and the losses for all the compensation methodologies are observed to be in the limit.

Also some remedial measures to reduce the down time of the WTG due to few critical issues such as yaw errors and failure of hub power packs are proposed and implemented in the existing systems. The results are encouraging in terms of power production, machine stoppage and reduced operation and maintenance costs as certified by the wind farm owners and the same are being implemented in other WTG of similar models.