CHAPTER 4

PROPOSED MODIFICATIONS TO WINDMILLS

4.1 Introduction

Offshore wind power is one of the largest indigenous energy resources in the world with an enormous potential to harness this power in shallow and deep waters. The European wind energy association had set up a target of 40 GW of offshore wind capacity in the EU by 2020 figure 4.1, an average growth of 28 percent. Many other countries are in the process of harnessing offshore wind power, since strong winds exist there. With a growing global market trend in offshore wind farm development figure 4.2, the capacity range from the standard 1.5 MW wind turbine have increased to 5 MW. The reason for the increase in capacity of offshore wind turbines was higher wind resource and fewer foundations that could lead to lower investment cost.

The new generations of offshore wind turbines [1] were dedicated to the harsh environments at offshore. The designs were aimed to address some of the major challenges such as corrosion, reliability, maintainability and online monitoring. However most of this technology was mainly based on incremental improvements from the basic concepts of onshore wind turbine systems and developed later to suit the offshore conditions.

Thus, the main driver for offshore wind technology is economical efficiency rather than technological efficiency. Furthermore, as the accessibility of offshore wind farms for repair and maintenance were lower than onshore, special attention was addressed regarding the turbine reliability. This brings an opportunity to make significance reductions in the cost of energy with the development of innovative concepts with objective to make offshore turbines as simple and robust as possible.
Figure 4.1 Estimated growth of offshore wind energy in European Union by 2020
4.2 Scope

The offshore wind farm projects that were focusing on reducing the cost of offshore wind energy in comparing with the onshore wind energy figure 4.2, brought a radical change in offshore wind turbine technology [1]. The main concept was to centralize electricity generation using pressurized hydraulic oil from the individual wind turbine pumping systems. The idea behind this research was that the high power to weight ratio from hydraulic drive systems would give the opportunity for a reduced nacelle weight and increased reliability of components by eliminating the use of individual gear trains and generators. The first step was taken from the conceptual to the preliminary design, starting with the proper dimensioning of the system and performance evolution. A complete study and review of various existing wind turbine innovations and designs in the commercial market were considered. The possibility of new designs evaluation of the wind mills for transmitting the rotor power from atop the nacelle to the tower floor were:

- By shaft
  - Hydraulic oil system

The overview of the new design concepts was to evaluate the major problems involving and not limited to:

- Nacelle weight
- Capital cost
- Efficiency
- Downtime
- Reliability
- Operating and maintenance
  - Environmental issues
Figure 4.2 Estimated capital cost comparisons onshore and offshore till 2030
The demand for electricity in the country is ever on the rise. Simultaneously, the pressure to reduce the emission of green house gases through excessive burning of fossil fuels is also on the increase. To meet these two conflicting requirements one of the possible ways out is to harness the renewable sources of energy like the wind energy in a big way. But setting up wind farms on land is also beset with problems concerning suitable land acquisition and other related issues. Hence the best alternative is to go to the sea for setting up offshore wind farms. It is a well known fact that the wind regime at sea is far superior to the wind regime on land thus making sea the ideal alternative for locating wind farms. Advanced nations of the world have already gone in for this option with considerable success.

According to the European Union (EU)[2], offshore wind farms of 5000MW capacity will be set up along the European coastline for generating clean electricity by end 2010. India, with a 7500km coastline and coastlines surrounding A&N and Lakshadweep islands is well placed to harness the abundantly available wind energy at sea. Indications are that offshore wind farms are soon going to become a reality around our coast. Because of the higher wind speeds and longer duration of wind availability, higher capacity generation of electricity is possible at sea. But the main problem connected with offshore wind farms is the high operation and maintenance (O&M) costs because of the not too-friendly environmental conditions at sea. According to an estimate the office and maintenance cost of offshore wind farm could be as high as 23% of the total cost.

The principal reason for the high O&M cost is the need for the deployment of special jack-up type crane barges for carrying out O&M work on windmill machinery consisting of, among other things, the induction generator and the main gear box (weighing in tons) which are located in a crammed space inside the nacelle which is at a height of 30m to 40m above the sea level. In order to make the per unit cost of electricity from offshore wind farms comparable to that from an on shore wind farm, the O&M cost needs to be brought down. This can be achieved by redesigning the main machinery lay out in the nacelle. Marine engineers are
familiar with the deep well pumps used on tankers and product tankers. These pumps have deck mounted motors driving the pumps which are located deep inside the tanks using very long vertical shafting. Adopting similar concept the main machinery presently located inside the nacelle at the top of the tower can be moved and installed in an enclosed space on an offshore platform at the base of the windmill tower with a long shafting driving the main machinery i.e. the induction generator and the gear box. This arrangement will considerably reduce the O&M cost of an offshore wind farm.

4.3 Project analysis

The analyses presented are the conceptual idea and a general description of the offshore turbine. It is not the intention of this work to describe in detail each subject, for which more exhaustive and specific literatures are already available. However, it was to describe the main physical principles and basic data that are necessary to integrate for better understanding. The conceptual idea, equations and initial dimensioning of the components were given based on the different design and operational requirements. A baseline of a 1.5MW three bladed wind turbine rotor is used for the general design and explanation of the system. The main sub components of these evaluations were taken from different physical domains such as mechanical, hydraulic and aerodynamics on the basis, to integrate into a single environment.

The hydraulic drive for windmill power generation [3] is an old concept with fewer reliable components and lower power demand. However, many industries around the world are carrying out testing the technology. One such company named Artemis, a Scottish company has developed a hydraulic radial pump with electronically controlled poppet valves with variable speed transmission using a synchronous generators figure 4.3. A similar concept was employed by ChapDrive, a Norwegian company, who has developed a variable speed control system figure 4.4. The modern development in wind energy hydraulic components has attracted the offshore wind mill industry due to high power density and reliability. The hydraulic system does generate good torque with damping impulses and controllability.
Figure 4.3 Artemis variable speed transmission
Figure 4.4 ChapDrive concept for a variable speed transmission
Due to the high demand for renewable energy sources, the development of offshore wind energy farms has made an immense progress during the last few years. Nevertheless, it remains a particular challenge to ensure the reliable operation and high performance throughout the entire period of operation, in order to minimize the investment costs and the maintenance costs [4]. Despite good existing concepts, new solutions that implicate fundamental changes and improvements are developed consistently. A new concept, transferring the power through a hydraulic drive train is expected to combine good efficiency, grid stability with high reliability and to maintain low over all investment costs.

4.4 Wind farms for power generation

In order to protect the environment from pollution [5] caused by the excessive burning of fossil fuels, and to conserve the fast depleting conventional energy resources like oil and coal, many countries have set up wind farms on land for generation of electricity. As of end 2007 seventy four countries have set up wind farms on land taking the total worldwide installed power generation capacity to 93,844.18 Mega Watts (MW) or 94 Giga Watts (GW) approximately. This goes to prove that the wind turbine technology is a proven technology for clean power generation. Further, setting up and operating wind farms on land has its own share of problems. Such problems can include land acquisition in areas with good wind regime, noise pollution, aesthetics, and social and legal issues associated with land acquisition, to name a few. In view of this there is a growing trend among advanced countries to opt for offshore wind farms. table 4.1, illustrates a list of countries that have already ventured into the sea for the purpose of harnessing the abundantly available wind resources there.

According to EU, Europe is expected to reach a target of 5000MW of energy generated from offshore wind farms for power generation. Apart from the benefit of not having to deal with disadvantages that are associated with land based wind farms as described above, offshore wind farms have
Table 4.1 Worldwide offshore wind farm installations

<table>
<thead>
<tr>
<th>Ranking</th>
<th>Country</th>
<th>Total Installed Capacity (kW)</th>
<th>Coastline Length (Kms)</th>
<th>kW/Km</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Denmark</td>
<td>401.55</td>
<td>7,314</td>
<td>55.00</td>
</tr>
<tr>
<td>2</td>
<td>UK</td>
<td>123.80</td>
<td>12,429</td>
<td>9.96</td>
</tr>
<tr>
<td>3</td>
<td>Ireland</td>
<td>25.20</td>
<td>1,448</td>
<td>17.40</td>
</tr>
<tr>
<td>4</td>
<td>Sweden</td>
<td>23.00</td>
<td>3,218</td>
<td>7.15</td>
</tr>
<tr>
<td>5</td>
<td>Netherlands</td>
<td>13.40</td>
<td>451</td>
<td>29.70</td>
</tr>
</tbody>
</table>
superior wind regime like higher wind speeds and longer duration of wind availability. Higher power generation capacity is, therefore, expected at offshore wind farms compared to their onshore counterpart. These developments bear testimony to the fact that the technology for offshore wind power generation has matured into a well proven technology.

4.5 Offshore wind farms related issues

In a windmill, all the machines are located inside an enclosed machinery space called the nacelle. The nacelle is located on top of a tower at a height of 60 to 90 meters above the ground level so as to capture the wind effectively. Due to the inconvenient access to the machines and the cramped space inside the nacelle minor repairs and routine maintenance of the machines, namely the gear box and the generator become issues.

The problem becomes complicated when the machines are required to be moved out of the nacelle for major repair work to be carried out on the machines in a workshop, thus making the operation and maintenance (O&M) cost of windmills relatively, expensive. In the case of offshore wind farms, the issue grows in complexity as the entire O&M operation needs to be carried out at sea using floating cranes, jack-up rigs, barges etc. for the purpose, thus pushing the O&M costs further upwards.

According to one estimate, the O&M cost of an offshore wind farm could be as high as 23% [6] of the total installation cost of the wind farm, mainly because of the not-too-friendly marine environment. Clearly, there is a need to reduce the O&M cost of offshore wind farms in order to make it cost competitive with its onshore counterpart. One possible way of reducing the O&M costs of an offshore wind farm is to shift the major machinery which are normally installed inside the nacelle, to an enclosed space on a fixed platform located at the base of the windmill tower.
The main machinery components that require monitoring and minor repairs are the gear box and the induction generator. By shifting both these machinery components out of the nacelle to the base of the tower, the O&M costs would be considerably reduced. This is because, such a move will obviate the need for hiring floating cranes, jack-up rigs, and similar heavy equipment, which are otherwise necessary for carrying out O&M activities in the nacelle at sea. Further, shifting both the gear box and the generator would require a vertical shafting with a large diameter and the consequent heavy weight of the shaft which again would call for suitable but expensive thrust bearings for bearing the weight of the shaft. It is therefore necessary to opt for shifting one of the two machines i.e. either the gear box or the generator to the base of the tower. As the generator is more susceptible to mal functioning in the marine environment thereby requiring constant attention, it is felt that between the generator and the gear box, preference should be given to the former for shifting to the base of the tower. The design of a suitable vertical shaft for driving the generator located at the base of the windmill is presented in the following sections.

4.6 Vertical shaft design

For the purpose of designing a vertical shaft of suitable diameter for driving the generator, a 1.5MW wind turbine with the following parameters is considered:

Rated power output of the generator =1500 kW/2105 HP, Rated speed of the generator N=1500 rpm, Length of the shaft = 40m and Gear ratio of the main gear located in the nacelle = 1:100.

The standard formula for determining the diameter (D) of the shaft is:

\[ D = \sqrt{\frac{60 \times \text{HP}}{N}} \]  

(Eq.1)

Using the above formula the diameter of the vertical shaft is determined as:

\[ D = \sqrt{\frac{60 \times 2105}{1500}} = 9.17 \text{inches} = 230\text{mm} \]  

(4.1)
The corresponding shaft torque is calculated as:

\[ T = \frac{(2105 \times 4500)}{(2\pi \times 1500)} = 1005.6 \text{ kgf} \cdot \text{m} \]  
(4.2)

Given that the shaft diameter (D) = 230mm, the shaft length (L) = 40000 mm and the shaft material density (De) = 0.00000785 Kg/mm³, the weight (W) of the shaft can be calculated using the formula:

\[ W = \left[\frac{\pi D^3}{4}\right] \times L \times De \]  
(4.3)

The weight of the vertical shaft is:

\[ W = 3.14 \times 115 \times 115 \times 40000 \times 0.00000785 = 13 \text{MT} \]  
(4.4)

From the expression for determining the diameter of the shaft, it can be seen that the diameter is inversely proportional to the speed of the shaft. Hence if the diameter of the shaft is to be reduced further then the shaft speed needs to be increasing which, by implication means that a generator with higher speed needs to be selected. Further, it can be observed that as the speed of the shaft increases the corresponding torque reduces. Table 4.2 shows the various shaft diameters for different shaft speeds and the corresponding torques. However, for the purpose of illustration a standard 1.5MW wind turbine with the generator speed of 1500 rpm has been selected.

4.7 Further design consideration

Gear box and wind turbine manufacturers are turning to tribology to find ways to increase the life of the gear box failures. These are not due to the operational problems but are due to faulty gear tooth design and faulty methods of lubrication. The slow speed shaft is subjected to very high cyclic stresses by the use of radial thrust bearing and ball bearing. Lubrication of the gear box is an important as well as a complex issue which needs to be looked into to ensure that the gears are
<table>
<thead>
<tr>
<th>Torque (kgf*m)</th>
<th>Horse Power</th>
<th>R.P.M</th>
<th>Diameter (Millimeters)</th>
<th>Weight (MT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1005.6</td>
<td>2105</td>
<td>1500</td>
<td>230.0</td>
<td>13.00</td>
</tr>
<tr>
<td>838.0</td>
<td>2105</td>
<td>1800</td>
<td>212.8</td>
<td>11.16</td>
</tr>
<tr>
<td>754.2</td>
<td>2105</td>
<td>2000</td>
<td>201.9</td>
<td>10.04</td>
</tr>
<tr>
<td>603.3</td>
<td>2105</td>
<td>2500</td>
<td>180.5 mm</td>
<td>8.03 MT</td>
</tr>
</tbody>
</table>

Table 4.2. Torque values for varying dimensions of the shaft
being properly cooled during operation to ensure a longer life cycle. In this case, the primary considerations are the torque loads and the non-torque loads. The bearings which are located in the gear box should be well lubricated to avoid failures. The heat generated by the gears due to high loads and varying external temperatures can easily degrade the lubricating oil thus rendering it useless. This implies that the oil film created between the mating gears has to be maintained at a temperature in the region of 50°C to 60°C, thus enabling the oil to provide a good elasto-hydrodynamic lubrication.[7]

Contamination of lubricants can lead to an increase in noise levels. One such contaminant is water, which is an important as well as an unavoidable factor on offshore platforms and rigs. Water ingress into the gearbox can cause the lubricating oil to foam and lose its ability to create the required film thickness; thereby leading to failures. Defects can also arise due to the presence of debris in the gearbox. Such debris can be traced back to minute particles sheared from the bearings or from gear tooth failures. Good filtration of the lubricating oil is required, particularly for the offshore wind turbines, to avoid gearbox failures, and to maintain proper viscosity during cold start-ups. Lack of proper cooling of the gear box and the resultant high lubricating oil temperatures are considered major factors for failure. Employing large fans and lubricating pumps for keeping the gearboxes within the prescribed temperature limits escalates the initial cost.

The selection of correct lubrication and periodic spectrographic examination will indicate the health of the gearbox at every stage. Finally, installation of good quality oil seals and cover gaskets can prevent fine-dust from entering the lube oil area and the gear box. To summarize, the following key dos and don’ts are required to be followed to ensure that the gear box has an enhanced life-cycle.

- Ensure good filtration.
- Maintain within designed temperature limits.
- Maintain a good cooling system and coolers.
- Prevent oxidation and water ingress.
- Maintain the load within the limits.
- Maintain leak proof and level alarms.
- Monitor oil condition through spectrographic examination every 12 months.
- Renew oil periodically every 3 months
- Monitor noise level.
- Conduct regular inspection to assess gear wear and to detect metal debris.

Even while using synthetic oil, which is a boon for the offshore wind turbine, it is important to follow the steps described above for trouble free service. Synthetic oil is a benefit for wind turbine application as this oil can sustain higher temperature and withstand long running hours in comparison to mineral oil.

Other approaches in our application to reduce the wear on the shaft is to determine the minimum shaft size for the transmitting the torque to the generator, where, the shaft should be strong enough to transmit the required torque without exceeding the maximum allowable torsional shearing stress of the shaft material. Consider the example of the generator, which has been brought down and installed on a fixed platform at the base of the tower for the several benefits which includes the increase in RPM, decrease in the frame size of the generator for the same output power, reduction in the diameter of the shaft, which in turn reduces the weight of the shaft; and the ease of maintenance. In this case, the generator can still suffer from issues such as the alignment problem, which needs attention. For example a 2 mils at 2000 rpm (where ‘mil’ is the measure of deflection) under normal working condition will generate large forces that will be applied directly to the bearing and gears. This will lead to damage in the lip seals, a fact to be borne in mind at the design stage.
4.8 Layout of the re-designed system

As depicted in figure 4.5, the layout of the proposed offshore wind power [8] generation system comprises a fixed foundation platform on which is mounted a container for housing the generator, radiator, monitoring and control panel, switch board with provision for connection to the power grid based ashore etc. The container housing is air-conditioned to ensure circulation of cool dry air for maintaining the temperature of all the equipment at an optimal level so as to ensure for them long life cycle. The container housing the generator etc. is positioned at the base of the tower in such a manner as to enable perfect alignment of the shaft connecting the bevel gears and the generator. This shaft passes through a deck lip seal for preventing ingress of water into the container housing. The 40m vertical shaft installed at the center of the tower is supported by radial thrust bearings with a double ball-bearing supported at mid-center to avoid displacement of its axis. The horizontal high speed shaft in the nacelle operates at an output speed of 1500rpm to 2500rpm and is connected with bevel gears at right angles to a 40 meter long vertical shaft.

The lower end of the long shaft is connected to the generator through bevel gears. The nacelle is mounted on the windmill tower via the yaw motor and a swivel bearing. This bearing is one of the most important parts of the windmill and must be able to withstand dynamic and static loads under all weather conditions. The yaw motor is used to turn the nacelle in the prevailing direction of the wind. The yaw motor system is controlled based on the inputs received from a smart wind speed and direction sensor. Issues arising from sudden gusting wind speeds which could damage the turbine and gear box are prevented by high speed cut off disc brake system. The bevel gears at the top and bottom of the 40m long vertical shaft is lubricated with synthetic lubricating oil which has a poly alpha olefins base. The synthetic oil keeps the gear at a regulated temperature while maintaining a clean environment.
Figure 4.5 Layout of a re-designed shaft driven windmill
The main gear box inside the nacelle is at normal position to the shaft axis. The drive for the self-driven lubricating pump for gear lubrication is taken from the high speed output shaft of the gear box itself. The lubricating pump located inside the nacelle takes suction from a lubricating oil tank located on the platform at the base of the tower and discharges into the main gear box and to the bevel gears. The oil on its return circuit lubricates the lower pair of bevel gears and then flows back into the lubricating tank. A lubricating suction filter is provided to keep the oil clean. Lubrication will be relatively easier and can be safely monitored as a precautionary measure. Heat generated by contacting parts of the system is less as the new arrangement reduces the weight stress.

The system described above is expected to prove beneficial to offshore wind farms in particular[9], where the wind turbine is continuously subjected to several changing parameters, such as, strong wind speeds, suddenly changing weather patterns, corrosion etc. in addition to the complex maintenance issues described earlier in this paper. Reducing the number of machinery items that are normally located in the nacelle of a wind turbine atop the tower will substantially reduce the maintenance cost.

In order to reduce environmental pollution caused by excessive burning of fossil fuels it is necessary to harness clean sources of energy like the wind energy for generation. Many countries including India have set up land based wind farms for power generation but are facing social and legal issues related to land acquisition for wind farms. The sea, because of its superior wind regime, is a better alternative for setting up wind farms. Many advanced countries have already set up offshore wind farms for power generation but are finding the installation as well as O&M costs on the higher side. The O&M cost can be brought down considerably by shifting the generator which is more susceptible to malfunctioning in a marine environment, from its conventional location inside the nacelle atop the windmill tower to a fixed platform at the base of the tower.
4.9 Energy capture from the wind

The main purpose of a wind turbine is to convert the kinetic energy of the wind into useful mechanical energy. For a wind stream flowing through a transversal area, the available power in the wind is expressed as:

\[ P_{wind} = \frac{1}{2} \rho AU^3 \quad (4.5) \]

Where \( \rho \) is the air density, \( A \) is the transversal area and \( U \) is the wind speed.\[10\]

Rotors from conventional wind turbines are designed in such a way that they are able to extract maximum power from the wind. Hence a way of characterizing the ability of a rotor to capture wind energy is the power coefficient, which is defined as the ratio of the extracted power to the available wind power:

\[ C_p = \frac{P_{rotor}}{P_{wind}} = \frac{P_{rotor}}{\frac{1}{2} \rho AU^3 U^3} \quad (4.6) \]

The theoretical maximum value of \( C_p \), known as the Betz limit, is derived from the momentum theory with a maximum value of \( 16/27 = 0.593 \).

The power coefficient is a value inherent to the specific design of the blades, which is typically given as a function of a parameter called the tip speed ratio \( \lambda \), and the pitch angle of the blade. The tip speed ratio represents the ratio of the blade tip speed to the free stream wind velocity.

\[ \lambda = \frac{\omega R}{U} \quad (4.7) \]

To capture maximum power at every wind speed, the rotation speed of the rotor should be changed in order to keep a constant value of the tip speed ratio where the power coefficient is at its maximum.
The total mechanical power extracted by the rotor is expressed in terms of an aerodynamic torque $T_r$, times the rotational speed of the rotor $\omega_r$:

$$P_{\text{rotor}} = T_r \omega_r$$  \hspace{1cm} (4.8)

Since the power extracted by the rotor is proportional to the third power of the wind speed, and taking into account that an optimal aerodynamic efficiency implies a linear increase in the rotational speed of the rotor with respect to wind speed, it is found that the mechanical torque in the rotor is proportional to the second power of the wind speed.

4.10 Hydraulic drives

Hydraulic pumps and motors are used to convert mechanical energy into hydraulic energy and vice versa, respectively. The hydraulic power obtained from a pump is given by the product of the volumetric flow $Q$ and the pressure difference across the pump $\Delta p$

$$P_{\text{hyd}} = \Delta p \cdot Q$$  \hspace{1cm} (4.9)

Pumps are normally characterized by the flow obtained at a certain shaft speed, and the ratio of these two parameters is known as the volumetric displacement $V_p$. This value is typically expressed in terms of a volume of fluid per revolution.

$$V_p = \frac{Q}{\omega_p}$$  \hspace{1cm} (4.10)

Hence, for an ideal pump analysis, the hydraulic parameters are obtained in terms of the mechanical parameters, such that:

$$\Delta p = \frac{T_r}{V_p}$$  \hspace{1cm} (4.11)

$$Q = V_p \omega_p$$  \hspace{1cm} (4.12)
A hydraulic pump is not an ideal machine, there are some considerations that should be taken into account like friction, pressure losses and leakage losses among others, so in order to obtain an optimal efficiency of the system there should be certain relationship between its parameters.

4.11 **Steady state performance**

A pilot model is proposed based on well established theory of positive displacement pumps, where some of the terms involve constant loss coefficients, and although some discussion has been addressed due to their validity for a narrow range of operation, for the purpose of this work it gives enough insight of the pump performance in terms of the desired parameters like fluid viscosity, and bulk modulus. The steady-state continuity equations for a piston hydraulic pump can be derived for the following assumptions:

- Fluid inertia neglected.

- The effect of the pressure and temperature on the properties of the fluid is not considered.

- Leakages other than those from the pump are ignored.

- Laminar leakage flow.

- Return pressure neglected (for interest of uniformity of data presentation and simplicity of analysis).

Although there are many assumptions, none of them is unduly restrictive. The analysis that will be described is centered in pumps; however an analogous description is made for motors.

4.12 **Generated flow**
The net generated flow obtained from the pump is expressed as:

\[ Q = V_p \omega_p - Q_s \]  

(4.14)

Where \( Q_s \) represents the slip flow due to leakages, this flow is usually laminar and therefore inversely proportional to the viscosity of the fluid \( \mu \). The slip flow is also presented as a function of a dimensionless coefficient of slip \( C_s \):

\[ Q_s = \left( C_s \frac{V_p}{\mu} \right) \Delta p \]  

(4.15)

\[ C_s = \frac{\mu}{V_p} \left( C_{int} + C_{ext} \right) \]  

(4.16)

\( C_{int} \) is the internal or cross-leakage coefficient and \( C_{ext} \) is the external leakage coefficient. The net flow is then expressed as:

\[ Q = V_p \omega_p - \left( C_s \frac{V_p}{\mu} \right) \Delta p \]  

(4.17)

### 4.13 Generated pressure

In the same way as the generated flow, not all the torque obtained from the rotor is converted into pressure [12]. There is a torque that is needed to shear the fluid in the small clearances between mechanical elements in relative motion, and a torque loss due to the bearing friction; both torques' are expressed in terms of a dimensionless damping coefficient \( C_{damp} \) and a dimensionless friction coefficient \( C_f \) respectively.

\[ V_p A_p = T_r - T_{damp} - T_{friction} \]  

(4.18)

\[ V_p A_p = T_r - (C_{damp} V_p \mu \omega_p) - (C_f V_p A_p) \]  

(4.19)

Hence, the pressure difference obtained from the rotor torque is expressed as:
\[ \Delta p = \frac{1}{1 - C_f} \left( \frac{T_r}{V_p} - C_{damp} V_p \mu \omega_p \right) \] \hspace{0.5cm} (4.20)

### 4.14 Pump efficiencies

**Volumetric efficiency**

It is defined as the ratio of flow obtained from the pump to the flow in pump speed (ideal flow). The volumetric efficiency describes internal and external leakages and the losses through the compression work

\[ \eta_{vol} = \frac{Q}{V_p \omega_p} \] \hspace{0.5cm} (4.21)

Replacing from eq 3.13, the volumetric efficiency becomes:

\[ \eta_{vol} = 1 - \frac{C_s p}{\mu \omega_p} \] \hspace{0.5cm} (4.22)

**Mechanical-hydraulic efficiency**

It is defined as the ratio of the net torque useful to generate pressure, to the mechanical torque supplied to the pump. The hydraulic mechanical efficiency describes the friction and pressure losses.

\[ \eta_{mech} = \frac{V_p \Delta p}{T_r} \] \hspace{0.5cm} (4.23)

By substituting eq 4.15, the torque efficiency becomes:

\[ \eta_{mech} = \frac{1}{1 + C_{damp} \frac{\mu \omega_p}{\Delta p} + C_f} \] \hspace{0.5cm} (4.24)

Total pump efficiency
The overall or total pump efficiency is defined as the ratio of hydraulic power obtained to the mechanical power supplied:[12]

\[
\eta_{tot} = \frac{P_{hyd}}{P_{mech}} = \frac{Q \Delta p}{\omega_p T_r}
\]

(4.25)

\[
\eta_{tot} = \left( \frac{Q}{V_p \omega_p} \right) \left( \frac{V_p \Delta p}{T_r} \right) = \eta_{vol} \eta_{mech}
\]

(4.26)

Thus the overall efficiency is simply the product of the volumetric and mechanical efficiencies. Using eq 4.18 and eq 4.20, the overall efficiency becomes

\[
\eta_{tot} = \frac{1}{\frac{C_s \Delta p}{\mu \omega_p} - \frac{C_f \Delta p}{\mu \omega_p}}
\]

(4.27)

\[
1 + C_{damp} \Delta p + C_f
\]

Therefore, the static performance of a pump is defined by the dimensionless parameters \( C_s, C_{damp}, C_f \); the properties of the fluid \( \mu \) and the operational conditions \( p \) and \( \omega_p \). A graph of the performance of a pump with constant volumetric displacement is observed in figure 4.6 and figure 4.7.
Figure 4.6 Efficiency curves for a fixed displacement pump
Figure 4.7 Pump performances for variable displacement conditions
4.15 **Hydraulic offshore wind turbine system**

**Introduction**

Hydraulic components have figured in drive train design for some time in motors, brakes, fluid coupling or torque limiting systems. Hydraulic drives comprising pumps and motors for main power transmission were employed in the unsuccessful 3MW prototype in the early 1980s, but this design route was not pursued further. The key problems were inadequate capacity, efficiency, reliability and life of existing commercial hydraulic component and lack of components specifically designed for the needs of efficient wind power generation. However, with the increase in size of commercial wind turbines and the current development in the fluid power industry, the idea of using hydraulics as an alternative solution for power transmissions has become particularly attractive because of their high power density and increased reliability of components. Other advantages comprise the possibility of damping torque impulses and the good controllability with outstanding dynamic performance.

The development of offshore wind turbines in recent years has made great progress and the reason was the high demand for renewable energy source. There are many countries involved in offshore wind power research in design concepts of transmission system and components for 1 to 10 MW range. It was a well known fact that the power density of hydraulic machines is three times higher than the advanced electric motors. The majority of wind turbines currently under development rely on mechanical gearboxes to convert the low speed, high-torque rotary motion of the rotor to a high-speed rotation suitable for electricity generation. The mechanical gearboxes have the advantages of being a readily available mature technology with a significant disadvantage offering only one speed ratio, increasing failures and downtime. The recent development in wind turbine transmission system was a hydraulic driven variable speed gearbox, allowing direct connection to a synchronous generator output shaft and doing away with the electrical power converter. The designer claims 20% decrease in nacelle weight with this innovation.

The system uses a hydrodynamics torque converter providing a variable speed relationship to the output shaft. It was a mechanical solution for variable speed operation,
combining the use of a planetary gear system and torque converter. The torque converter was well matched to the wind turbine rotor in a hydraulic system and arranged to decouple the input/output shafts by absorbing the input torque and damping the vibrations. The cost of this system was substantially decreased with advantages of lowering the cost of this system was substantially decreased with advantages of lowering the nacelle weight and losses in electrical power converter.

The variations in the wind stream velocity have to be accounted for by using variable speed generator system and/or variable pitch control on the rotor blades. A hydraulics transmission system typically consists of a low-speed pump, connected directly to the shaft of the rotor, a high-pressure hydraulics circuit with power electronics, which may include a storage accumulator and a high speed motor that drives the electrical generator. As per the theory, either the pump or the motor has variable displacement capability, thus hydraulic transmission offer an infinite speed ratio range. In practice, overall performance is optimized, if both are variable displacement machines.

4.15.2 Functional principles of the concept

The new concepts are developed constantly, bringing the fundamental changes. A new approach in this paper is the power transfer through hydrostatic transmission [12]. Such a transmission utilizes radial piston pumps driven by the wind rotor directly, to convert the mechanical power derived from the wind to a high oil pressure. This depends on the operating point of the system to the hydraulic motor and transferred to a constant speed generator. The variable displacement of the motor allows a continuous change of the transmission ratio of the hydrostatic transmission and can be used to impart a desired speed of the rotor. The main advantage of this design concept in connecting the system to the mains with a constant generator speed is to do away with the frequency converter. The other advantages that the system could be flexibly adapted to different wind conditions, to obtain the benefit of good damping properties.

In the scope of developing a wind turbine generator using a hydrostatic transmission for wind energy plants, a 1.5 MW power class wind turbine is considered. The main intention is to do away with the commonly used gearbox and the frequency converter. The idea is to utilize a
slow turning radial piston pump that is directly connected to the turbine shaft to transfer the wind power into a hydraulic pressure of high intensity. This high pressure is used to power a hydrostatic motor which could convert back into mechanical power to drive the constant speed generator. The high transmission ratio that is needed in a turbine could easily be achieved by the displacement ratio of pump and motor. Figure 4.8 clarifies the functional principle of the hydrostatics transmission.

A hydrostatic transmission allows merging the functions of a mechanical transmission with those of a frequency converter. This means the varying, low rotation speed of the turbine is transferred into a constant rotation speed at the generator. The needed continuous variable ratio is realized by changing the displacement of the hydraulic pumps or motors. The varying wind conditions, gusts of wind and the tower structure effects the transmission with load intense torque fluctuation. The outstanding damping and control characteristics of the hydraulic drive trains can be used to conserve the drive train as well as the structure of the turbine including the electric power and at partial load of a turbine. The combination of overall efficiency and cost of the system could return the entire turbine investment in a shorter span. In this research, the efficiency at different operating points has to be weighed according to the probability of occurrence of the corresponding wind speed. According to the long lifecycle of a wind turbine the selected components should be robust, easy to maintain in order to lower the operating and maintenance costs. All possible errors to be detected at an early stage with the stringent trail test at manufacturer’s facility in order to prevent any risk of damaging the system component during the turbine operating life.
Figure 4.8 New hydraulic drive concepts for wind turbine generator
The initiation of this project was the experience gained during operation and maintenance of the hydraulic transmission steering system on a large merchant ship. The concepts were analyzed and scaled to the requirements to a wind energy turbine, e.g. the possibility to vary the hydraulic transmission load of the ship’s rudder at different angles. This required a closed loop operating system with variable pressure and displacement swash plate pumps controlled by fuzzy logics circuit figure 4.9. The idea was to split hydraulic power mechanically to different drive path. A full-hydrostatic drive combining various configurations of the pump and controls provides high torque to move the ship’s ruder and thus the torque is converted back to mechanical work in operating the ship’s steering and in the same manner, the torque is converted back to mechanical work in wind turbine by generated hydraulic power and combining mechanically back to a constant speed generator.

Due to a variable rotation, speed of the frequency converter is needed to connect each turbine to the grid. Furthermore, reliability problem with mechanical gear boxes have occurred and the weight of the directly driven generator is becoming a problem when, increasing turbine sizes. The continuous development of wind turbine gear boxes are still facing, increasing operation and maintenance costs. The most important value is to compare the turbine’s effectiveness is the cost of energy, since all resulting production costs including operation and maintenance are opposed to the produced energy.

A new concept figure 4.10, transferring the power via a hydrostatic drive train is considered to combine good efficiency, grid stability with high reliability and low costs. The high transmission ratio that is needed in a turbine can easily be achieved by the displacement ratio of hydraulic pumps and hydraulic motors figure 4.11. By using a variable displacement motor the transmission ratio can be varied so that the generator can run at constant speed directly connected to the grid. The optimal power production of a wind turbine is achieved by optimizing the drive train to the important points of the operation and control strategy simultaneously. Therefore a compromise between steady state operation and controllability has to be
Figure 4.9 Typical layout of an electro-hydraulic ship’s steering gear system
Figure 4.10 Hydraulic operated wind turbine connection to grid
Figure 4.11 Proposed hydraulic operated wind turbine layout
found. In general, it can be foreseen that the success of an offshore hydraulic turbine will not be dictated by the individual power performance but by the potential cost reduction and increased reliability of the overall system in order to reduce operational and maintenance costs.

4.16 Basic design concept

A rotor is designed for the conversion of the harnessed wind energy into useful mechanical energy. The closed-loop system fulfils the function of transferring the mechanical energy from the nacelle to the base of the turbine; in order to do this a hydraulic pump and motor are used in a hydrostatic transmission figure 4.12. At the base of the turbine a servo-controlled constant speed motor is coupled to the generator at constant pressure. Finally, the generator will convert hydraulic power from the motor into useful in the form high voltage electricity.

The pump and the motor deal with very different rotary speeds and therefore were of different designs. The pump requires an extremely large displacement per revolution to achieve a high power rating at very low shaft speeds. This is achieved by using low speed high torque pump coupled to the rotor shaft in the nacelle. The specifications of the transmission are mainly dictated by the control strategy of the turbine. The turbine is rated as 1.5MW with the rotor speed of 8 revolutions per minute. This means that the hydraulic pump has to deal with varying large input torque, hence its large volumetric capacity. The sizing of the motor is optimized to supply just 1.5MW of the mechanical power to the electrical generator. The motor operates at a much higher revolutions per minute with that compared with the hydraulic pump in the nacelle and its volumetric capacity is much smaller. The specifications of the transmission components are given in table 4.4. The conventional hydraulic machines have good efficiency at full displacement but their performance drops significantly at partial displacement. This means that losses in the transmission are proportionally higher when the input power from the turbine rotor is lower. As the transmission must be sized for much larger powers the average operating level, part-load efficiency is of supreme importance.
Figure 4.12 Proposed hydraulic circuit for wind turbine generator
In order to understand the concept as well as its advantages in terms of efficiency, it is useful to first give a brief overview of energy losses in reciprocating piston hydraulic machines. The sources of energy dissipation in a mechanical system are numerous. The main losses associated with hydraulics are:

1. Shear losses are when a thin film of oil between two moving metal parts ensures that there is no metal to metal contact; energy is still dissipated as the oil film is subjected to shear. This type of loss can typically be found at the interface between piston pads and swash plates or crankshafts.

2. Leakage losses are those shear losses to form in small gaps or clearances between the moving parts must be allowed. These gaps lead to some oil leaking internally out of the high pressure cylinder.

3. Compressibility losses are that fluids with a finite stiffness, such that they compress and store energy as pressure rises. In a hydraulic machine, each chamber must be compressed decompressed at the end stroke. Commutating valves throttle this energy into heat.

4. Flow losses are caused due to viscosity effects and vortex shedding when the flow passes around an obstruction

A pump or motor consist of a shaft which turns causing working chambers, such as pistons and cylinders to oscillate in the fluid volume. It also needs a flow control port or valves to control the filling and emptying of the chambers. The cylinders must be alternately connected to either the low pressure tank or the high-pressure manifold in order to transfer work between the fluids and the shaft.

4.16.1 Rotor power transmission

The rotor is the mechanical device that converts the kinetic energy[13] from the wind into useful mechanical energy. In this design concept, a horizontal axis of low revolutions associated with increased torque needed in the transmission. It is a three bladed configuration of
the rotor and it is downwind or upwind, will depend on a detailed structural analysis in which the final blade stiffness should be enough to allow a safe tower clearance in the case of an upwind configuration. On the other hand, if a downwind configuration is used, special attention should be addressed for the tower structure obstruction (variations in the airflow velocity component due to the presence of the tower).

4.16.2 Closed loop hydraulic system

This subsystem works as the driven train in a conventional turbine; it consists of a hydraulic transmission whose main function is to transfer the mechanical power from the rotor shaft to the base of the turbine. Directly coupled to the rotor shaft, a hydraulic pump transforms the mechanical energy of the rotor into hydraulic energy by pressurizing a hydraulic fluid, and converts it back into mechanical energy with a hydraulic motor located at the base of the turbine. A pump with a radial piston design unit is the most suitable pump for the kind of applications required for this system. With the use of this first closed-loop, the need for a mechanical gearbox and power electronics used in conventional wind turbine is eliminated from the nacelle; furthermore the total weight of the nacelle is reduced by using fewer components. The use of high pressure in this subsystem allows having a high power density however main energy losses will occur due to the mechanical and volumetric efficiencies of the hydraulic drive system. Volumetric efficiencies are associated to the fluid leakages from the pump and motor, which have to be connected through drainage line to a fluid reservoir. The reservoir not only has the function to store the hydraulic fluid, but also helps to dissipate the heat produced by the internal friction of the hydraulic drives (associated to their mechanical efficiency). An auxiliary pump is used to add an extra pressure to the return line, and at the same time provide cooling fluid. This extra boost pressure prevents cavitations in the pump casing a smooth functioning of the system and avoiding downtime.

4.16.3 Hydraulic power transmission
This subsystem has the main function of transforming the mechanical power from the closed-loop and rotor through a hydraulic motor as a medium to transfer energy from the nacelle to the generator at the tower base. A variable axial piston pump is needed in order to have a variable transmission able to match the aerodynamic torque requirement of the load at varying wind speeds. This variable transmission of the closed loop will allow a variable speed operation of the rotor and a constant speed motor coupled to the generator. A constant pressure in the system is required in order to connect the turbine rotor pump transmitting all the hydraulic power from the wind to the manifold at the tower base. This would pressurize the manifold at constant pressure at all times and the synchronous generators could run at constant speed assisted by the solenoid operated hydraulic valves. Thus the frequency converter is eliminated lowering the capital and the maintenance cost. The specific lay-out for the piping connection for a single turbine and generator system figure 4.11. The friction losses are of particular interest due to the large pipe distance from the tower to the base of the each turbine or to the central offshore generator platform, nevertheless for the operational conditions of the high pressure and low volumetric flows can be minimized with proper pipeline design.

4.16.4 Common offshore generator platform concept

The main concept is to convert the pressurized hydraulic oil from individual offshore wind turbine pumping system into a common dedicated high pressure hydraulic tank on a common generator platform. In this platform, the pressurized hydraulic oil could operate several hydraulic motors / generators at the same time. One of the main characteristics is the idea of a centralized offshore electricity generation. As the power scales of offshore wind approaches the output rating of conventional power plants it won’t became unusual to think in the possibility of having just one or two central generators instead of the several individual generators from all the turbines in a wind farm (i.e. for a 150 MW wind farm, 10 generator of 1.5 MW are required)[14]. A few central generators will facilitate compliance with typical grid connection requirements for wind power plants (i.e. behavior during disturbance in the grid and control of the power quality). Furthermore, it is known that depending on the ambient conditions and the lay-out of the wind farm, power losses will occur due to pipe distances. These represent typically a power loss in the range of 2 to 7 % of the power output. From a centralized generation point of view, this means that if the central generator is possible, leading not only to economical benefits but to higher
capacity factors of the entire wind farm. Thus the operational and maintenance cost are reduced due to a fewer generators and hydraulic motors. A common offshore generator platform also represents an opportunity for increased availability could be done. This idea of a platform for offshore wind farms are in the planning stage of some offshore wind companies.

A suitable hydraulic motor for the proposed 1500 MW offshore wind mill was calculated and using the hydraulic motor speed and torque table 4.3 the Rexworth Bosch model AA2FM-1000 was identified table 4.4.

\[
T_m = \frac{V_g \times \Delta p \times \eta_m}{20 \times \pi} = \frac{1000 \times 350 \times 0.95}{20 \times 3.14} = 5295 \text{ Nm} \quad (4.28)
\]

\[
Q_m = \frac{V_g \times n_m}{1000 \times \eta_{vol}} = \frac{1000 \times 1500}{1000 \times 0.95} = 1578 \text{ l/min} \quad (4.29)
\]

\[
V_p = \frac{Q_m \times 1000}{n_p \times \eta_p} = \frac{789.5 \times 1000}{20 \times 0.97} = 79753 \text{ cm}^3/\text{rev} \quad (4.30)
\]

From the above equations a hydraulic pump was selected based on the hydraulic motor displacement and the nearest is a Hagglunds model MB 1600 with a displacement of 86392 cm³/rev. The reason being it delivers high torque at very low speeds. The complete specifications of a suitable pump table 4.5 taken from haggland specification table 4.6 is given below.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td>Maximum hydraulic motor speed</td>
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<tr>
<td>Max flow rate</td>
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<tr>
<td>Displacement per rev $V_R$</td>
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<td>Differential pressure $\Delta p$</td>
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<td>Volumetric efficiency of motor $\eta_m$</td>
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<tr>
<td>Flow rate required by motor $Q_m$</td>
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<tr>
<td>Motor operating speed $n_m$</td>
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<tr>
<td>Volumetric efficiency of pump $\eta_p$</td>
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<td>Pump operating speed $n_p$</td>
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<tr>
<td>Pump displacement $V_p$</td>
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<td>Torque of motor $T_m$</td>
<td>5295 Nm</td>
</tr>
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Table 4.3 Hydraulic motor specifications for 1500 MW offshore wind turbine generator
Table 4.4 Rexworth Bosch hydraulic motor AA2FM-1000 specification

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<thead>
<tr>
<th>Size</th>
<th>$V_d$</th>
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<th>in$^3$</th>
<th>$n_{full}$</th>
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<th>$n_{max}$</th>
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<th>$\rho$</th>
<th>gpm</th>
<th>L/min</th>
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<td>1722</td>
<td>1722</td>
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Legend: $\alpha$ - angle of rotation, $\rho$ - flow rate, $\Delta p$ - pressure difference, $T$ - torque, $N_m$ - moment of inertia.
<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
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<td>Pump displacement</td>
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<tr>
<td>Specific torque</td>
<td>1375 Nm/bar</td>
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<td>Rated speed</td>
<td>30 rpm</td>
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<tr>
<td>Maximum speed</td>
<td>43 rpm</td>
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<tr>
<td>Maximum pressure</td>
<td>350 bar</td>
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<tr>
<td>Maximum torque</td>
<td>447 KNm</td>
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Table 4.5 Specification of the hydraulic pump for the proposed windmill
Table 4.6 Hagglunds pump specification

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<tr>
<th>Motor-type</th>
<th>Displacement (cm³/rev)</th>
<th>Specific torque (Nm/bar)</th>
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