

Direct Drive Wind Turbine Generator with Magnetic Bearing

G. Shrestha, H. Polinder, D.J. Bang, J.A. Ferreira

g.shrestha@tudelft.nl; h.polinder@tudelft.nl; d.j.bang@tudelft.nl; J.A.Ferreira@ewi.tudelft.nl

Electrical Power Processing/ DUWIND, Delft University of Technology,

Mekelweg 4, 2628CD, Delft, Netherlands

Phone: 0031-15-2782955, Fax: 0031-15-2782968

Abstract— Direct drive machines are very heavy and expensive for large wind turbines. The use of magnetic bearing has a possibility of reducing the weight of the direct drive machine. However, the weight and losses in magnetic bearing itself must be considered. A rough design of the magnetic actuator shown here, shows that the weight and losses of magnetic bearing is not prohibitive for use in wind turbines as it can bring weight saving in the generator. However the motivation for using magnetic bearing goes beyond weight saving of the generator. Such construction allows flexibility in the system and will be the topic for further research.

Index Terms—magnetic bearing, direct drive machine, wind turbine, flexibility

1. Introduction

Direct drive wind turbines are now manufactured by various manufacturers. The largest direct drive machine in wind turbine is now rated at 4.5-6MW [5]. The advantage of using direct drive energy converter is that it omits the gearbox in the system, decreases the part count and operates at lower speeds therefore has reduced wear and tear. Hence, this can translate into increased reliability of the wind turbine. Reliability is even more critical for offshore wind turbines where the cost of maintenance is almost double of the onshore ones [14]. Direct drive machines have the highest energy yield compared to other wind energy conversion devices [2], [16]. However, the up-scaling of the direct drive wind turbine is not seen to be economical in the present state-of-art compared to other drive train designs [16]. This is mainly due to the weight of the direct drive machine.

This paper will first look into the problem of upscaling direct drive in large scale wind turbines. Various solutions in literature to address this problem are reviewed. Then a new solution using magnetic bearing is proposed. Then the magnetic bearing solution is compared with conventional bearing of a 1.5MW Harakosan Z72 direct drive wind turbine in terms of weight and losses in the bearings to find out whether this solution is feasible. Then some other possible advantages of such solution to wind turbines are discussed. Then a conclusion is drawn.

2. Problem in Direct Drive Machines

This section discusses the main problem with large direct drive machines and some solutions to this problem in literature are mentioned. The power from the wind that is delivered to the shaft or the rotor of a direct drive generator of a wind turbine is given by

$$P = \frac{1}{2} \rho_{air} C_p (\lambda, \theta) \pi r^2 v_w^3 \quad (1)$$

Where ρ_{air} is the density of air, C_p is the performance coefficient, r is the turbine blade radius and v_w is the wind velocity. As the radius of the blade increases, the power output from the wind turbine increases. However, the rotational speed of the blade is limited by the maximum tip speed of the blade to about 75m/s. This is mainly due to noise restriction of wind turbine. Therefore for increasing radius of the blade the rotational speed of the direct drive machine decreases. The consequence is that the torque rating of the machine needs to be increased for the same power output. The increase in torque in the machine has a consequence for the weight and cost of the machine.

$$P = \omega_g T = 2\pi \omega_g r_g^2 l_g F_d \quad (2)$$

The force density F_d of a machine is mostly a value between 25-50kN/m² [1]. According to equation 2 either the radius of the machine (r_g) or the axial length (l_g) of the machine should be increased to increase the power at constant angular velocity (ω_g). The increase in radius will have a quadratic effect on power; therefore it is beneficial to build direct drive machine as large diameter rings than generators with longer axial length when considering the weight of the active material required. This is because the weight of the active material for the machine can be roughly approximated to be proportional to the airgap surface area of the machine.

However, a machine must be held with a small airgap between the rotor and stator for good energy conversion. Literature suggests an air gap is 1/1000th the airgap diameter of the machine [3]. Maintaining the air gap between the stator and the rotor is a big challenge for large diameter machines especially because of the large attractive forces that acts between the stator and the rotor. This requires stiffness in the construction of the generator. A large diameter ring machine requires a lot of structural material (inactive material) to keep the stator and rotor in place. Figure 1 shows the distribution of active and inactive material for 2, 3, 5 and 10MW respectively [4], [15]. This shows that a 10MW machine is about 13 times heavier than a 2 MW machine. [4] also reports that the weight of the rotor for large diameter machine grows more rapidly than the stator as the diameter increases.

This problem with direct drive machine has been identified by various authors leading to novel solutions. Spooner [17] proposes an ironless stator machine with large diameter because an ironless machine has no attractive forces between the stator and the rotor therefore a much lighter construction will be required. However, such concept is mechanically unstable and also decreases aerodynamic efficiency. This is due to large diameters required to compensate the airgap flux density.

Similarly [7] proposes the NewGen concept where the rotor is supported by wheels on the stator. This concept is shown in figure 2. The paper reports massive weight reduction of direct drive machine and the weight of such a machine is comparable with conventional geared wind turbine generator. However this construction requires a large number of wheels and they run at high speeds near the airgap. This may reduce the reliability of such direct drive machine.

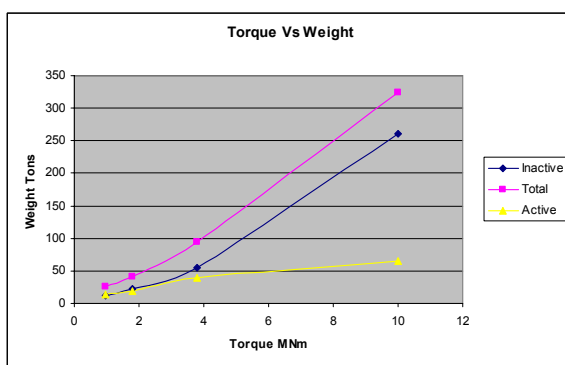


Figure 1: Comparison of weight of 2,3,5 & 10 MW direct drive wind turbine. [4][15]

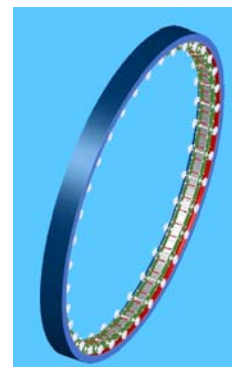


Figure 2: NewGen Concept [7]

3. Direct Drive with Magnetic Bearings

In this section the magnetic bearing solution to the problem of direct drive machine discussed in section 2 is proposed. The advantages and disadvantages of such system are discussed. Then such magnetic bearings solution is compared to the conventional bearing system of a Harakosan Z72 direct drive wind turbine in terms of the weight and losses in the bearing.

Magnetic bearings can be used instead of wheels to have a non contact bearing near the airgap. Such a magnetically levitated machine has the advantage of light weight as the NewGen concept but eliminates the problem of wear and tear of the wheels. It is not unusual to use magnetic bearings in very high dynamic situations with heavy loads. Magnetically levitated trains are one example of such an application. Various literatures exists that show application to a very dynamic situation [9], [10]. Literature also suggests a very high reliability of such a magnetic bearing system in industry [11].

Apart from the advantage of magnetic bearing in direct drive wind turbine for weight reduction, it may also bring additional advantages. They are:

- High reliability as magnetic bearing are non contact type bearing.
- Can add flexibility to the wind turbine, therefore may have the possibility to reduce weight of overall wind turbine as less stiffness in construction is required.
- Can be used for active vibration control.

However there are disadvantages of such system too

- Need of a landing bearing is case of faults.
- Complex design

Magnetic bearings can be differentiated into two major categories, namely the electromagnetic type and the electrodynamic type. Electromagnetic type uses the force created at the airgap between materials of high relative permeability to levitate the system. Electrodynamic type uses the repulsive force created by the induced eddy currents to levitate the system. More on this can be found in [12]. Electrodynamic type operates effectively at relatively high speeds only; therefore it is not of interest for low speed machine. Hence, only the electromagnetic type, active magnetic bearing is discussed here.

However, magnetic bearings itself posses weight and losses due to the current needed to produce the force. It is therefore necessary to quantify the amount of material needed and also the losses in the magnetic bearing system to develop it further as an alternative for conventional bearings.

3.1 Magnetic Bearing Principle

A simple electromagnetic circuit is given in figure 3. Using Ampere's Law and assuming high relative permeability of iron, the flux density at the airgap is given as in equation 3.

$$B = \frac{ni}{2s} \mu_0 \quad (3)$$

The attractive force between the two surfaces can be found using the virtual displacement principle and is given as equation 4.

$$F = \frac{\partial W}{\partial s} = B_g H_g A_g = \frac{B_g^2}{\mu_0} A_g \quad (4)$$

Replacing the value of B,

$$F = k \frac{i^2}{s^2} \quad \text{where } k = \frac{1}{4} \mu_0 n^2 A_g \quad (5)$$

The change in force due to the change in current or the air gap is a quadratic function. This equation can be linearized around a certain operating point of the current and the air gap. A differential mode of operation as shown in figure 4 is used to linearize the system. More on magnetic bearings can be found in [12].

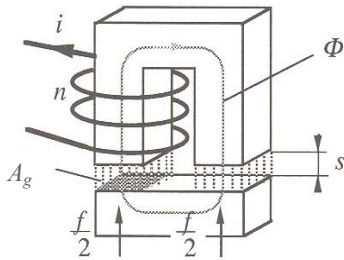


Figure 3: A horse shoe type magnetic circuit

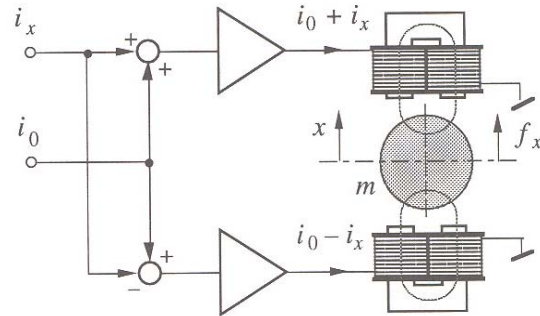


Figure 4: A differential mode of operation

3.2 Design of Magnetic Bearing for Wind Turbines:

A direct drive wind turbine with radial flux PM generator is selected as a reference wind turbine for this preliminary design of the wind turbine with magnetic bearing. This is chosen as a reference because radial flux machines are the mostly widely used type of machines. Even though the electrically excited direct drive machines are mostly found in the market, many new designs are coming up with permanent magnet excitation. A Harakosan Z72 (1.5MW @ 18.5rpm) will be taken as the reference wind turbine as shown in figure 5. The parameters of the wind turbine relevant for the reference turbine is given in table I [6]:

Table I: Harakosan Z72 parameters [6]

Weight of the blades	4600*3 kg
Weight of the hub	19 tons
Weight of the generator stator	25 tons
Weight of generator rotor	12.5 tons
No. of poles	60
Axial length (Active)	1.2 m
Outer diameter	4 m
Weight of bearing	4 tons
Bearing support cone	5 tons

A magnetic bearing should be able to suspend the static loads which are the weight of the blades, hub and the rotor of the generator. These all can be integrated together. The attractive forces due to excitation must also be included in the assessment. Other dynamic loads caused due to the wind properties must also be considered.

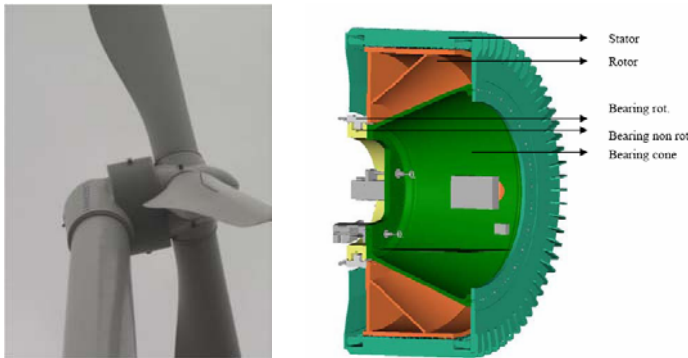


Figure 5:a. A Harakosan Z72 wind turbine b. Generator construction of Harakosan Z72 [6], [18].

3.3 Static Load and Compensation

The total static load in the system is equal to product of mass times gravity. The mass of the rotating body which needs to be levitated are the blades, hub and rotor of the generator which is about 444kN. Static loads can be compensated using either extra permanent magnets or using an eccentric rotor in the permanent magnet machine. Using eccentric rotor, the same permanent magnet used for power generation can be used to support the static loads. However, the attractive force due to eccentricity of rotor should be calculated. An eccentric rotor is shown in figure 6. Change in air-gap due to eccentricity is given by equation 6 [13].

$$\Delta\epsilon(\alpha) = r - e\cos(\alpha) - \sqrt{r^2 - e^2 \cdot \sin^2(\alpha)} \quad (6)$$

When the rotor is in the center the attractive forces of the magnets in opposite sides cancel out. So the net force will be zero. However, when there is a displacement of the rotor, the attractive forces change. For now the contribution of forces due to current in the winding is neglected even though it has some relation to the attractive force in the machine. Not all the parameters of the Harakosan machine are known therefore the parameters for the machine needs to be assumed. First of all the airgap radius is estimated using the sizing equation in [1]. Then the pole pitch, tooth width, magnet dimension are assumed.

Due to eccentricity, the air gap will increase in one side but will decrease on the other side. Firstly, the flux density due to the permanent magnet is calculated. The machine with 1 slot per pole per phase is given in figure 7. The normal force due to permanent magnet is given by the Maxwell's stress equation as given in equation 7.

$$F = \frac{B^2}{2\mu_0} A_g \quad (7)$$

$$B_{g1} = \frac{l_m}{\mu_{rm} g_{eff}} B_r \frac{4}{\pi} \sin\left(\frac{b_p}{\tau_p} \frac{\pi}{2}\right) \quad (8)$$

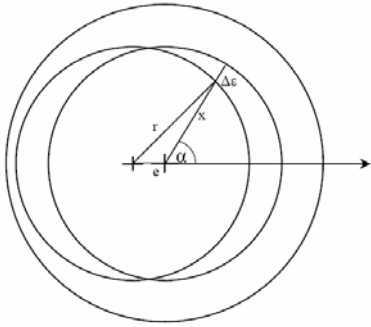


Figure 6: Eccentricity of rotor[13]

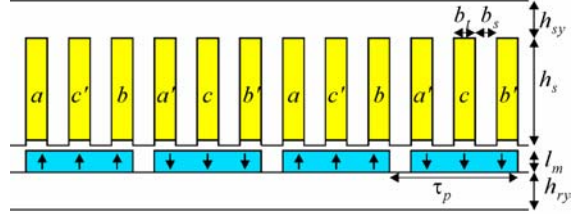


Figure 7: Stator and rotor of PM machine [2]

Table II: Machine parameters

Machine parameter	Dimension
Air gap at centered rotor [6]	3 mm
Axial length [6]	1.2m
No. of pole [6]	60
Outer diameter [6]	4m
Air gap radius	1.6m
Pole pitch	167.5 mm
Tooth width	29 mm
Slot width	26.8 mm
Circumference of at the airgap	10m
Magnet length	15mm

However, the flux density is not the same all over the airgap due to the slots in the stator. This effect of slot can be compensated by an effective airgap (g_{eff}), which is larger than the nominal air gap given. Thus an assumption can be made that the flux density is uniform all over the effective airgap. The flux density in the airgap can therefore be calculated as given in [2]. The rms of the fundamental wave is taken for the calculation.

The flux density is given by equation 8 [2]. The rms flux density of the fundamental is given by

$$B_{gms} = \frac{B_{g1}}{\sqrt{2}} \quad (9)$$

The calculation of effective airgap g_{eff} is done following [2]. Similarly the forces act perpendicular to the surface of the magnet. It has a component in the horizontal and vertical axis. Therefore to calculate the force in the vertical direction, the component referring to that direction must be taken. The radius of the machine is sub divided into various small segments, as the change in airgap due to eccentricity is different at different position along the radius. So the force is calculated by equation 10.

$$F = \int_0^{2\pi} \frac{B_{gms}^2 (\cos \alpha)}{2\mu_0} A_{g1} d\alpha \quad (10)$$

Here A_{g1} is an area of a small segment of the circumference. The force produced due to eccentricity is given in figure 8 and shows the linear relation between eccentricity and the force produced. An eccentricity of more than 2 mm is required to compensate the static load of the rotating body. This is not possible because the air gap length is 3 mm. A larger eccentricity has consequence such as saturation of tooth and voltage imbalance. Therefore, the static force can be compensated with a combination of eccentricity and additional permanent magnet. However the static loads are not the main concern for magnetic bearing. It is therefore assumed that the static loads are compensated using eccentricity and additional permanent magnets so that the power production from the wind turbine is not affected. A magnetic bearing should be designed to compensate the dynamic loads of the system. It will be discussed in the following subsection.

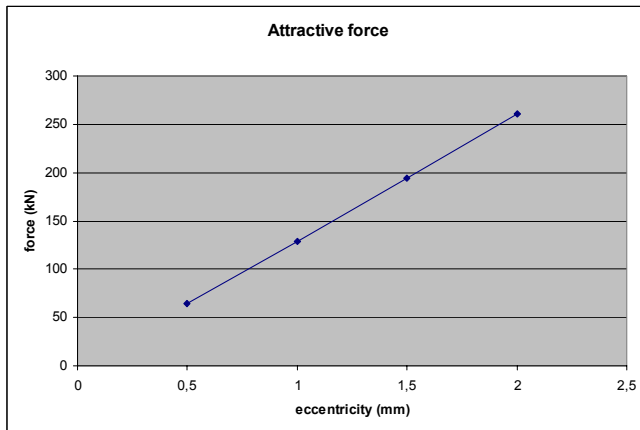


Figure 8: The relationship between eccentricity and force produced

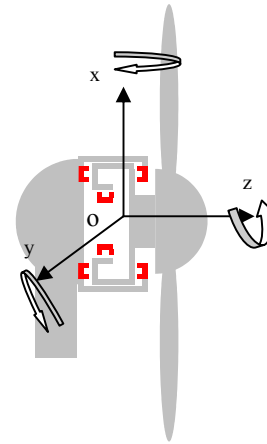


Figure 9: Placement of magnetic bearing actuators in wind turbine.

3.4 Dynamic Loads

A detailed calculation of all the dynamic loads is beyond the scope of this paper. The dynamic loads that the wind turbine should withstand are forces and moments in a normal operating condition. The reference dynamic loads that the magnetic bearing should withstand in a normal operation (i.e. wind speeds of 0-25m/s) for a reference turbine can be estimated by commercial software like Bladed and are given below. At other wind conditions it is assumed the rotor is supported by the landing bearing (backup bearing).

Radial force (rms) = 100kN

Axial force (rms) = 200kN

Bending moment (around x&y axis, rms) = 800kNm

The values given here are the rms value; the peak value will be much higher than the given value.

3.5 Placement of Magnetic Bearing Actuator:

It is assumed that the rotor and the stator are stiff structures. The magnetic bearing actuators are placed in a configuration as shown in figure 9. In total 5 degree of freedom must be controlled to levitate the rotating part of the wind turbine. As shown in the figure 9, the radial axes x&y are controlled using 1 pair of actuators in differential operating mode for each axis respectively. Similarly 4 pairs of actuators are placed to control the displacement in the z axis and also the rotational moments around the x & y axis. Such placement of actuator is suitable for machines of large diameter and short axial length. The actuators are placed in homopolar configuration i.e. the flux path is perpendicular to the rotational direction [8]. Using homopolar configuration, the hysteresis and eddy current losses can be reduced [8].

3.6 Actuator Design

The moment around the x and y axis in figure 9 is 800kNm each. The moment M is given as

$$M = F_1 r + F_2 r \quad (11)$$

Here r is the radius at which the magnetic actuator is placed. Therefore the distance between two actuators is 3m. The point 'o' is the centre of mass in figure 9. The moment is given by equation 11. Therefore the axial actuators should be able to provide a force of 270 kN each in order to counteract the moment due to the loads in the wind turbine. The same actuator is used for the axial force control. On the radial side, the maximum force that will occur is given to be about 100 kN, therefore smaller actuators are enough for the radial side.

The force required will also depend on the level of flexibility in the magnetic bearing. If larger rotor displacements in the airgap are required then the actuator should be designed for more force. This is because the larger displacement on one side will require an actuator with enough pulling force on the other direction. This becomes even more necessary in permanent magnet machines, as the rotor is subjected to more force in case of displacement from the centre position. The maximum displacement is however limited by the airgap length of the generator. A smaller airgap length is good for the generator, however from the magnetic bearing point of view, a larger airgap length means more space for displacement of the rotor in case of wind loads.

The flux density can be higher but for now a flux density of 1.2T is used, the airgap length is taken similar to the machine airgap length i.e.3mm. Using this low flux density, a higher peak force can be produced in extreme cases. Assuming that the flux density in the iron can go upto 1.8T linearly, a peak force of 2.25 times the value can be obtained using flux density of 1.2T. However if a higher peak value is necessary, then the operating flux density should be decreased with larger surface area.

The pole shoe area A_1 required can be provided by various actuator geometries. A thin but long tooth is better in terms of weight of the actuator. However a square actuator is better from loss point of view as it uses less copper. The axial length of 1m was chosen as the maximum because bigger axial length will have more curvature and the error will be larger for the forces calculated by the assumption of a flat surface. By choosing an axial length of 1m, and assuming a straight actuator without a curvature will produce an error of about 4-5% maximum and also the losses are not so high.

The actuator parameters are given in table III. Some values like current density, height of the slot, fill factor in the design of the actuators are assumed in accordance with values seen in machine literature [2], [3].

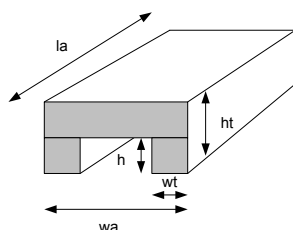


Figure 10: Parameters of a magnetic actuator

Table III: Magnetic bearing parameters

Design Parameters		
Flux density (B)	1.2T	
Airgap length (s)	3mm	
Current density (J)	4A/mm ²	
Height of the tooth (h)	70mm	
Flux density in the yoke (B_{yoke})	1.2T	
Copper fill factor (k_{fill})	0.4 (round conductor used)	
Number of turns (n)	100	
Axial length of the actuator (l_a)	1m	
Magnetic Actuator Design		
	Axial	Radial
Force required (F)	270kN	100kN
Mmf required (ni)	5.73kAT	5.73kAT
Current required (i)	57.3A	57.3A
Area of the pole shoe (A_1)	0.235m ²	0.0873m ²

Width of the actuator tooth (wt)	23.5cm	8.73cm
Width between two teeth (wa-2wt)	8.3cm	8.3cm
Width of the yoke (ht-h)	23.2cm	8.73cm
Radius of the wire	2.1mm	2.1mm
Length of the conductor	247m	217m
Volume of iron	0.1635m ³	0.0347m ³
Volume of copper	0.0035m ³	0.0031m ³
Weight of the actuator	1.29 tons	295 kg
Loss in the actuator (Bias) (100 ^o C)	255W	224W
Maximum loss (100 ^o C)	1kW	897W
Total Magnetic Bearing		
No. of radial actuator	4	
No. of axial actuator	8	
Total weight of the Magnetic bearing	11.4 tons	
Total maximum loss in the system	5.7kW	

Now the radius of wire can be calculated by

$$A_{\text{wire}} = \pi r_{\text{cu}}^2 = \frac{I}{J} \quad \text{F (12)}$$

A low current density J is taken so that the circuit does not heat up rapidly. The density of copper and iron are taken as 8900kg/m³ and 7700 kg/m³ respectively. The final actuator dimension on the axial and the radial side, the corresponding weight and losses are given in table III. It should be kept in mind that, using lower flux densities, the weight of the magnetic actuator increases as larger magnetic actuators are needed to produce the same force. Using a flux density of 0.8T instead of 1.2T will increase the weight of the axial actuator to 5.5tons each from 1.29 tons. So the magnetic bearing system will then weigh about 50 tons.

3.7 Losses in the Magnetic Bearing System

There are mainly two types of losses in a magnetic bearing, copper loss and iron loss. The iron loss in this magnetic bearing is neglected. This is because the hysteresis and eddy current component which occurs due to the change in magnetization is not present or very negligible because the bearing is of homopolar type and the speed of rotation is very low. The main losses are the copper losses.

Magnetic bearings use a differential mode of operation as mentioned in section 3.1. The current is divided into bias current and control current to produce the bias flux and control flux respectively. This control flux can be either added or subtracted to a differential side as required to produce a force between 0– F_{max} with a bias of 50%. The bias current is always present in the circuit even when the system is in balance; however the control current will depend on the different disturbance loads on the wind turbine. Therefore the bias current will give a continuous loss, however the control current loss will be load dependent average loss. When a disturbance occurs in a magnetic bearing, current increases on one actuator and the same amount of current decreases on the opposite actuator. Therefore when the current given to one actuator is maximum, the current on the other side is zero. Therefore only 4 axial actuators and 2 radial actuators can contribute to a maximum loss at one time. The losses in individual actuator and the losses in the magnetic bearing system are given in table III.

4. Discussion

It is seen that the weight of the conventional bearing and the supporting cone is 9 tons for the Z72 direct drive machine. The weight of the magnetic bearing for such system is about 22 % more than the conventional bearing. The loss in the magnetic bearing is below 0.5% of the rated power which is also the magnitude of loss for conventional bearings. It should be noted that the use of magnetic bearings can save a lot of support structure in the construction apart from the weight of the bearing itself. However one of the main motivation for using magnetic bearing can be that it enables

flexibility in the construction of the machine. Flexibility has been used in construction of blades, tower of the wind turbine to reduce cost and weight. Similarly the flexibility of the drive train of wind turbine could also provide such savings. This needs to be investigated further.

5. Conclusion

This paper presents a novel solution to the problem of large scale direct drive generator. The magnetic bearing solution presented here shows that the use of magnetic bearing is not prohibitive for such large diameter machines in terms of weight and losses. Even though the weight of such bearings may be bit higher than conventional bearings, it will save considerable weight of structural material needed in direct drive generators. Such magnetic bearing also enables flexibility in the drive train of wind turbine. The motivation for using magnetic bearing goes beyond the mass saving in the generator of the wind turbine. It gives the possibility to use flexible structure. This will also be investigated in the future during this project.

6. Acknowledgement

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