Design and Evaluation of a 300 kW Dual Mechanical Port Machine Used as Variable Gearbox in Wind Power Generation

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Abstract: Wind power generation systems based on Doubly-Fed Induction Generators (DFIG) require gearboxes to couple the DFIGs to wind turbines. Those gearboxes are heavy, highly cost and generally have fixed gear ratios. This paper presents a Dual-Mechanical-Port (DMP) machine and focuses on its new application as a variable gearbox in wind power generation. The outer rotor (surface PM rotor) is directly driven by the wind turbine and controlled to track the maximum output power operation points in terms of different wind speeds. The inner wound rotor is always operating at a fixed speed to drive another generator to produce the electrical power of a fixed frequency. The design procedures of a 300 kW DMP machine with a variable gear ratio from 5:1 to 12.5:1 are demonstrated in this paper. FEA analysis verifies that the DMP motor is capable of delivering the desired torque.

Key Words: Dual Mechanical Port (DMP) Machine, Variable Gear Box, Variable Gear Ratio, Wind Power Generation.

I. INTRODUCTION

Among many renewable energy sources, wind energy is becoming an increasingly important source due to the high efficiency of electromechanical energy conversion in electric generators and the rapid advancement in semiconductor devices, power electronic circuits, design of electric machines, advanced control theories, etc. In today's wind turbine products, Doubly Fed Induction Generators (DFIG) and Direct-drive synchronous generators are the two most popular types of electrical generators.

A wind turbine based on DFIGs generally consists of the following major parts: a multi-stage gearbox, a DFIG and a back-to-back power converter feeding the rotor winding which has approximately 30% of the rated power of the whole wind turbine [1]. DFIGs, relatively low-cost and easy to maintain, generally operate at a much higher speed than the wind turbines. Therefore, mechanical gearboxes are necessary to convert the low-speed operation on the wind turbine side to the high-speed operation on the generator side. However, those multi-stage gearboxes are bulky and highly cost. Frequent maintenance work is also required for gearboxes to avoid or reduce mechanical failures. In addition, those gearboxes have fixed gear ratios, which requires the electric generators to operate with a wide range of slip frequency.

For direct-drive wind turbines, generators are directly driven by wind turbines. Both synchronous generators with electrical excitation and Permanent Magnet Synchronous Generators (PMSGs) are used in direct-drive wind turbines. Power generated has variable frequencies and needs to be converted to fixed frequency power through power electronic circuits before it is fed to the power grid. Although these kinds of systems require full-scale power electronic circuits, the entire mechanical transmission devices are eliminated and the reliability of the system is increased by a lot. For wind turbines using synchronous generators with electrical excitation, losses in the excitation windings are a major disadvantage. PMSMs-drive wind turbines are much more expensive because of the use of permanent magnets. However, PMSGs-drive systems have received more attention due to the high operational efficiency of PMSGs, decreasing price of permanent magnets and better design technologies of PM machines.

In recent years, a new type of Dual Mechanical Port (DMP) machine has been demonstrated to be a very promising candidate for Electric Variable Transmissions (EVT) [2, 3]. Common speeds of large wind turbines are generally very low which vary from 10 rpm to 25 rpm. Smaller wind turbines may operate at higher speeds up to a couple of hundred rpm. Considering the promising application of DMP machines as an EVT, researchers have proposed to apply DMP machines in wind power generation systems as an electrical variable gearbox [4, 5].

In this paper, we review the dynamic model of the DMP machine first. Then we introduce the configuration of a wind turbine which uses a DMP machine as a variable gearbox and the operational mode of the DMP machine in this specific application. The procedures are demonstrated to design a 300 kW DMP machine working as an EVT in wind power generation. FEA methods are applied to verify the machine is capable of delivering the required torque.

II. DMP MACHINE BASED WIND POWER GENERATION SYSTEM

A. Dynamic modeling of DMP machines

Figure 1 shows the mechanical structure and the electrical connection of a DMP machine. It has two electrical ports and two mechanically rotating parts: the outer PM rotor and inner wound rotor. Currents in the stator winding and inner rotor winding may be controlled independently by two sets of power converters which share the same DC link. The speeds of the two rotors may also be controlled separately.

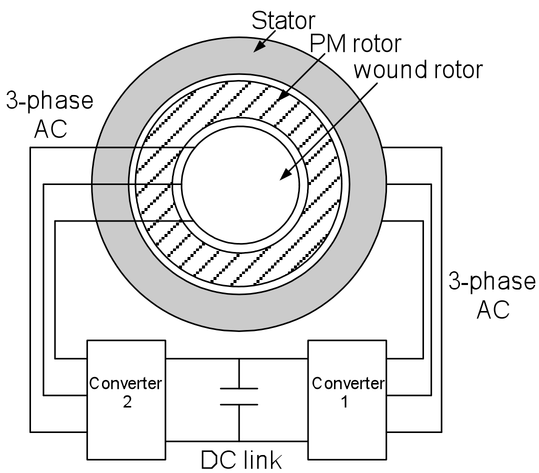

Figure 1. DMP structure, mechanical and electrical connections.

The dynamic model of a DMP machine may be described by Equation (1)-(11). The detailed derivation of the model can be found in previous publication [2]. The voltage equations for the stator and inner rotor windings in the synchronous reference frame can be written as,

$$V_{qs}^e = i_{qs}^e r_s + \frac{d\lambda_{qs}^e}{dt} + \omega\lambda_{ds}^e \quad (1)$$

$$V_{ds}^e = i_{ds}^e r_s + \frac{d\lambda_{ds}^e}{dt} - \omega\lambda_{qs}^e \quad (2)$$

$$V_{qr}^e = i_{qr}^e r_r + \frac{d\lambda_{qr}^e}{dt} + (\omega - \omega_r)\lambda_{dr}^e \quad (3)$$

$$V_{dr}^e = i_{dr}^e r_r + \frac{d\lambda_{dr}^e}{dt} - (\omega - \omega_r)\lambda_{qr}^e \quad (4)$$

where
r_s the resistance of the stator windings,
r_r the resistance of the inner rotor windings,
ω electrical angular velocity of PM rotor,
ω_r electrical angular velocity of wound rotor,

The equations for flux linage of stator and rotor windings are written as,

$$\lambda_{qs}^e = L_s i_{qs}^e + L_m i_{qr}^e \quad (5)$$

$$\lambda_{ds}^e = \lambda_m^e + L_s i_{ds}^e + L_m i_{dr}^e \quad (6)$$

$$\lambda_{qr}^e = L_r i_{qr}^e + L_m i_{qs}^e \quad (7)$$

$$\lambda_{qr}^e = \lambda_m^e + L_r i_{dr}^e + L_m i_{ds}^e \quad (8)$$

where
λ_m flux linkage produced by the PM,
L_s self-inductance of stator windings,
L_r self-inductance of wound rotor windings,
L_m mutual inductance between the stator and wound rotor windings.

Three torque equations associated with the stator, the PM rotor and the inner wound rotor are expressed as following,

$$T_{e,stator} = \frac{3}{2}\frac{P}{2}(\lambda_{dr} i_{qs} - \lambda_{qr} i_{ds}) \quad (9)$$

$$T_{e,pm-rotor} = \frac{3}{2}\frac{P}{2}\lambda_m(i_{qs} + i_{qr}) \quad (10)$$

$$T_{e,wd-rotor} = \frac{3}{2}\frac{P}{2}(\lambda_{ds} i_{qr} - \lambda_{qs} i_{dr}) \quad (11)$$

Equation (10) shows that both the stator current and inner rotor current interact with the permanent magnet and contribute to the torque on the PM rotor.

B. Configuration of wind power generation system having DMP machine as variable gearbox

Figure 2 demonstrates the configuration of a wind turbine using the DMP machine as an electrical variable gearbox. The outer PM rotor is directly driven by the wind turbine without using any mechanical gearbox. All disadvantages coming with mechanical gearboxes such as bulky size, high cost, low reliability and requirement of regular mechanical maintenance are eliminated. The inner wound rotor is controlled to always operate at the synchronous speed to drive Generator II, which may be synchronous machines with electrical excitation or PMSGs. Generator II can feed electric power of a fixed-frequency to the grid directly without using any power electronic circuits regardless of the wind speeds. The magnitudes of the voltage and current of Generator II may vary with different wind speeds.

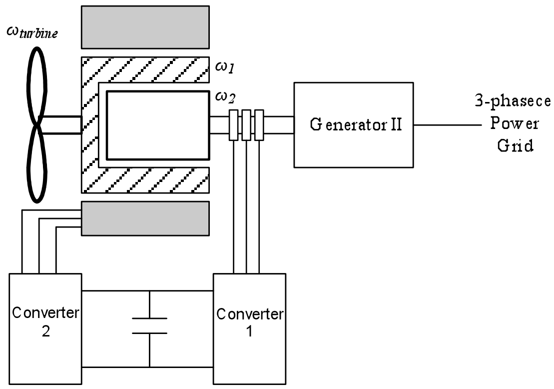

Figure 2 Configuration of DMP machine based wind power generation system

III. MACHINE DESIGN AND EVALUATION

The DMP machine can be regarded as a combination of a PM machine and an induction machine with wound rotor. Therefore, design techniques and methods for PM machines and wound-rotor induction machines can also be applied to the design of a DMP machine. Additional considerations should be given to the operational mode of DMP machines in certain applications since the balance in torque and power is more complicated than that in other machines which only have one rotating part.

The input mechanical power from the wind turbine is split into two parts: 1) the electrical power generated by the stator which is sent to the DC link through power electronic circuits; 2) the electromagnetic torque which is passed to the inner wound rotor through the inner air-gap between the PM rotor and the wound rotor.

Assuming the mechanical torque on the wind turbine shaft to be T_{m1}, the input mechanical power from the wind turbine can be written as,

$$P_{turbine} = \omega_{m1} T_{m1} \quad (12)$$

The output mechanical power of the inner wound rotor is expressed as,

$$P_{m2} = \omega_{m2} T_{m2} \quad (13)$$

where T_{m2} is the mechanical torque on the inner wound rotor, which is also balanced with the electromagnetic torque on the rotor shaft.

The electrical power generated by the stator is written as,

$$P_e = \omega_{m1} T_{e1} \quad (14)$$

where T_{e1} is the electromagnetic torque generated in the air-gap between the stator and the PM rotor.

The power passed to the inner wound rotor directly through the inner air-gap is expressed as,

$$P_d = P_{turbine} - P_e = \omega_{m1}(T_{m1} - T_{e1}) = \omega_{m1} T_{m2} \quad (15)$$

Due to the two mechanical ports and two electrical ports, a DMP machine has many possible operational modes [2]. Its major operational mode as a variable gearbox in wind power generation application is demonstrated in Figure 3. A constant power curve is shown in Figure 3. We assume that the DMP machine and the two power converters are lossless so the outer PM rotor and inner wound rotor run at the same power level.

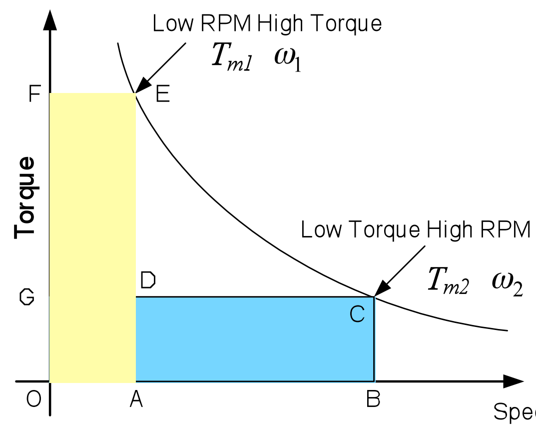

Figure 3 Operational mode of DMP as variable gearbox

The PM rotor is driven by the wind turbine and operates at a low-speed and large-torque operation point on the constant power curve. The area enclosed by OAEF represents the power of the PM rotor. While the inner wound rotor operates at a low-torque but high-speed operation point. The area enclosed by OBCG represents the output power of the inner rotor. The overlapped area OADG is the power that the PM rotor passes to the inner rotor directly through the inner air-gap. Area ABCD is the power that the PM rotor passes to the inner rotor through the stator and power converters.

The rated power of the DMP machine presented in this paper is 300 kW. Some key ratings and dimensions of the DMP machine are shown in TABLE I. The gear ratio which the DMP machine can achieve is from 5:1 to 12.5:1. The maximum mechanical torque on the wind turbine is proportional to the square of the rotating speed of the shaft. Therefore, the PM rotor is required to deliver the maximum torque at the top speed of the wind turbine which is 150 rpm. The inner wound rotor also

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delivers the maximum torque at the top speed of the wind turbine. The number of poles of the PM rotor is designed so that the power converter for the stator winding operates between 20 Hz and 50 Hz.

TABLE I. KEY PARAMETERS AND DIMENSIONS FOR 300 KW DMP MACHINE

Rated output power P_R	300 kW
Turbine speed $\omega_{turbine}$	60 to 150 rpm
Inner rotor speed ω_{wound}	750 rpm
Rated torque $T_{pm.rated}$	19.1 kNm
Rated torque T_{wound}	3.82 kNm
Rated DC bus voltage V_R	1000 V
Rated phase current $I_{S.rated}$	700 A
Rated phase current $I_{R.rated}$	350 A
Number of poles	40
Stator outer radius	880 mm
Stator inner radius	720 mm
PM rotor outer radius	718.9 mm
PM rotor inner radius	705 mm
Length of air-gap 2	1.2 mm
Wound rotor outer radius	650 mm
Active stack length	365 mm

To verify the torque capability of the designed DMP machine, FEA is used to simulate the torque production. Figure 4 shows the cross section of FEA model of the DMP motor. The permanent magnets (black) are mounted on the surface of the outer rotor. The thickness of the permanent magnets is increased in this figure so that readers may understand the outer rotor structure easily.

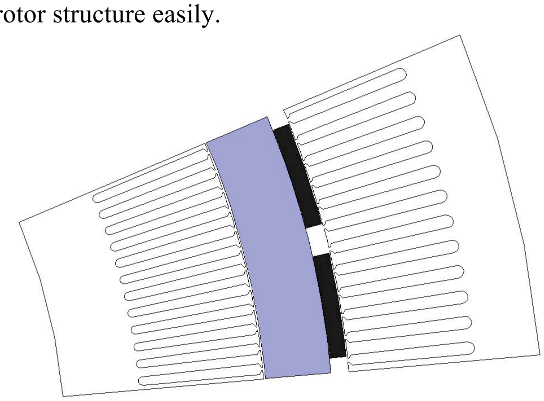

Figure 4 Cross-section FEA model of two poles of 300 kW DMP machine

Figure 5 (a) and (b) provide the FEA-calculated torque-vs-current characteristics of the DMP machine. The stator winding and inner rotor winding are separately excited in FEA calculation. In Figure 5(a), the torque produced by the PM rotor varies from 3 kNm to 19.2 kNm when the phase current of stator winding changes from 100 Amps to 700 Amps. Figure 5 (b) shows the torque production capability on the inner wound rotor. The torque varies from around 0.6 kNm to 3.75 kNm when the rotor current changes from 50 Amps to 350 Amps. The results of FEA-calculated torque show that the designed DMP can deliver the desired torque very well.

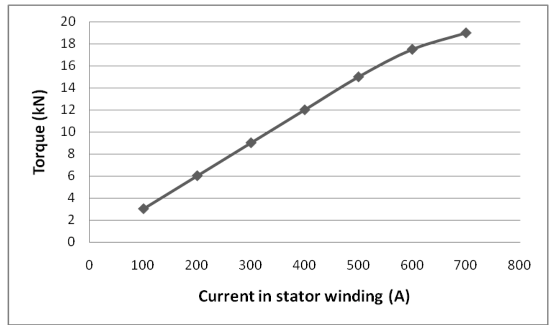

Figure 5 (a) Toruqe vs. phase current of stator winding (PM rotor at 150 rpm)

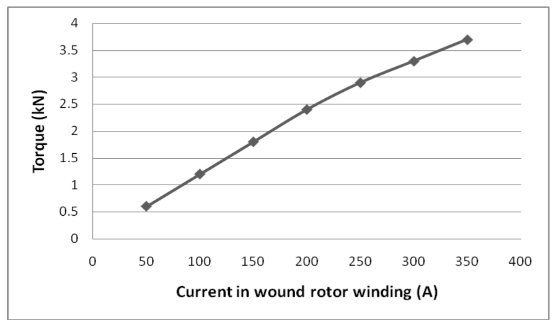

Figure 5 (b) Toruqe vs. phase current of nner wound rotor winding (wound rotor at 750 rpm)

IV. CONCLUSIONS

In this paper, we review the advantages and disadvantages of the two most popular generators used in wind turbines. Gearboxes in wind turbines based on DFIGs are heavy, highly cost and not reliable and needs regular maintenance. For wind turbines based on electrically excited synchronous machines, losses on the excitation windings are not favored. Due to decreasing price of permanent magnets and better design techniques of PM machines, more and more wind turbine manufacturers begin to apply PMGs in products. We introduce a brand new type of machine, DMP machine, and apply it to wind power generation system as a variable gearbox, which can eliminate mechanical gearboxes. An overview is given to the dynamic model of a DMP machine. Then we analyze the operational mode of a DMP machine functioning as a variable gearbox in wind power generation systems. The procedures of designing a 300 kW DMP machine as an EVT are demonstrated. Finally, we use FEA methods to verify that the designed machine is capable of delivering the desired torque.

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