DESIGN AND PERFORMANCE ANALYSIS OF A 6 MW MEDIUM-SPEED BRUSHLESS DFIG

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Abstract

The paper presents the design and performance analysis of a 6 MW medium-speed Brushless Doubly-Fed Induction Generation (Brushless DFIG) for a wind turbine drivetrain. Two machines with different frame sizes have been designed to show the flexibility of the design procedure. The medium-speed Brushless DFIG in combination with a two stage gearbox offers a low-cost, low-maintenance and reliable drivetrain for wind turbine applications.

1 Introduction

The Brushless Doubly-Fed Induction Generator (Brushless DFIG), also known as the Brushless Doubly-Fed Machine (BDFM), is an alternative to the well-established DFIG used in wind turbines [1, 2]. The Brushless DFIG retains the benefit of utilising a partially-rated converter, but offers higher reliability, and hence lower cost of ownership, than the DFIG due to the absence of brush gear and slip-rings [3]. The Brushless DFIG is intrinsically a medium-speed machine, enabling the use of a simplified one or two stage gearbox, hence reducing the overall cost and weight of the drivetrain and further improving reliability [4]. A schematic of the Brushless DFIG drivetrain is shown in Fig. 1.

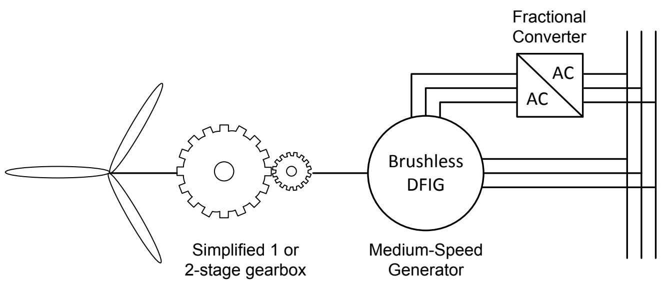

Figure 1: Brushless DFIG drivetrain

The Brushless DFIG has been shown to have superior low voltage ride through (LVRT) ability without the need for additional hardware [5]. The machine has an intrinsically large ‘series’ inductance, and hence experiences a reduced transient current in the machine side inverter compared to an equivalent DIFG [5]. As a result, the system cost can be reduced and the machine side inverter can be utilized to support the supply of reactive current during the entire fault cycle, allowing for fast dynamics.

To date, several groups have reported experimental Brushless DFIGs and there have been attempts to construct larger machines to confirm the machine’s suitability for higher power beginning in Brazil with the 75 kW machine of Runcos et al. [6] and more recently in China with the design of a 200 kW machine by Liu et al [7]. The authors have recently reported the design and testing of a 250 kW Brushless DFIG which is believed to be the largest size reported to date [2]. A 6 MW medium-speed Brushless DFIG has now been designed and the performance of the machine analysed to evaluate whether a multi-megawatt Brushless DFIG can meet the performance requirements of large wind turbines; this paper reports on the design and performance of a 6 MW machine.

Low capital cost:
- Elimination of slip-rings, brush-gear and carbon extraction system in the generator; - Utilization of a simplified 1 or 2-stage gearbox; - Utilization of a fractionally rated converter; - Elimination/simplification of the hardware/software (e.g. crowbar) used for LVRT protection; - Lower drivetrain weight, hence lower structural costs, compared to typical direct-drive drivetrains.
High reliability:
- Elimination of slip-rings and brush-gear in the generator which are known to have the highest failure rate in DFIG’s; - Elimination of the high-speed stage of the gearbox which is known to have the highest failure rate in the gearbox.
Low operation & maintenance (O&M) costs:
- Eliminating the need for regular maintenance and replacement of brush-gear in the generator; - Higher reliability of drivetrain components, reducing the unplanned maintenance costs.
Improved grid compatibility:
- The intrinsically improved LVRT performance of the Brushless DFIG due to its higher rotor inductance by design; - Enhanced reactive current injection capability of the Brushless DFIG during grid faults.

Table 1: Benefits of the medium-speed Brushless DFIG drivetrain

2 Description of the Brushless DFIG

The Brushless DFIG comprises two electrically separate stator windings, one connected directly to the grid, called the power winding (PW), and the other supplied from a fractionally rated variable voltage, variable frequency converter, called the control winding (CW). The pole numbers of the two stator windings are chosen so as to avoid direct coupling and a special rotor design is used to couple between the two stator windings, the nested-loop design being commonly used. The machine therefore contains three magnetomotive forces (MMFs), the first in the stator directly supplied from the mains, the second in the stator supplied from the converter and the third induced in the rotor. The normal mode of operation of the Brushless DFIG is as a synchronous machine where the angular shaft velocity ω_r is determined by the excitation frequency of the PW, f_1, and the CW, f_2 [1]

$$\omega_r = 2\pi \frac{f_1+f_2}{P_1+P_2} \quad (1)$$

3 Generator specification and design

The 6 MW rating of the machine was chosen because this size machine is comparable with the largest DFIG generators currently in use in commercial wind turbines. An 8/16 pole Brushless DFIG was chosen which has a natural speed of 250 rev/min when the control winding is fed with DC [1]. To allow for the range of speeds experienced in a typical wind turbine, the speed range was set to 150-350 rev/min, corresponding to a converter output of +/- 20 Hz. This implies a minimum converter rating of 40 % of the total output, i.e. 2.4 MW for a 6 MW generator [1]. The Brushless DFIG is designed for a wind turbine with specification shown in Table 1. The generator specifications are also shown in Table 1.

Wind Turbine Specifications	
Rotor diameter	130 m
Hub height	140 m
Rotational speed	5.3 – 11.7 rpm
Gearbox ratio	1:30 (2-stage)
Cut in wind speed	3.5 m/s
Rated wind speed	14 m/s
Cut out wind speed	28 m/s
Generator Specifications	
Output power	6 MW
Natural speed	250 rpm
Speed range	150-350 rpm
Nominal voltage	690 V
Grid frequency	50 Hz
Nominal torque	170 kNm
Overall efficiency	> 96 %

Table 2: Wind turbine and generator specifications

The design procedure is shown as a flow diagram in Fig. 2. During the first stage, an analytical approach in conjunction with equivalent circuit analysis [8] was employed to achieve an initial design against machine specifications. Discussion with a machine manufacturer was essential to incorporate construction practicalities in the design. Subsequently, the design was analysed using coupled-circuit analysis as a cross-check to give a more accurate assessment of the nested loop rotor [1]. Finally, the design was verified using finite element analysis. In particular this yields two important outputs, namely the peak flux densities in the iron and a better estimate of magnetizing current. The last stage of design optimisation includes the assessment of system performance, including dynamics, control and stability and LVRT capability which led to final adjustments to the design.

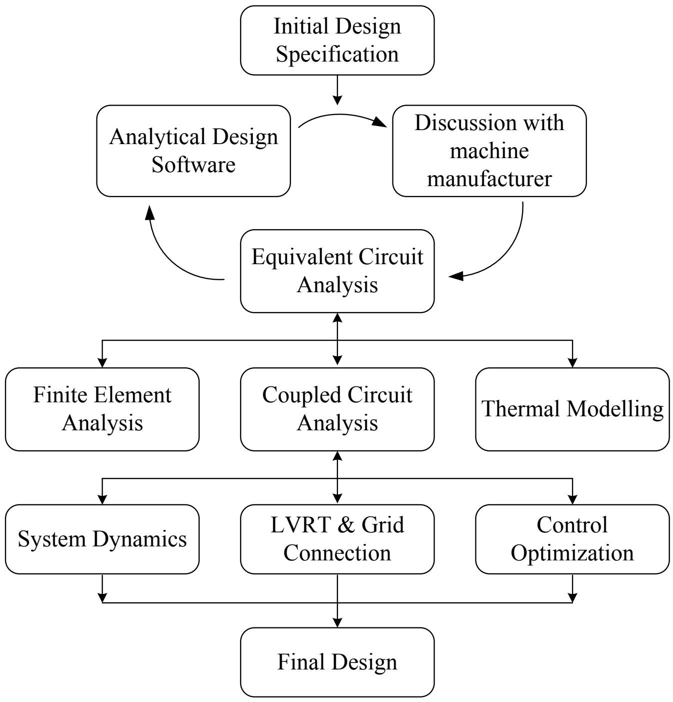

Figure 2: Design procedure for the Brushless DFIG system

Taking into account the specifications shown in Table 2, a design was performed for a 6 MW Brushless DFIG with two different frame sizes: 1000 and 1200. The machine parameters and dimensions are given in Table 3. Our design tools provide flexibility to incorporate practical restrictions such as size and dimensions, so machines can be customised for specific wind turbine designs.

Supply	**Frame 1000**	**Frame 1200**	**Units**
Grid Voltage	690		V
Grid Frequency	50		Hz
Stator			
PW Pole Number	8		
CW Pole Number	16		
Winding Configuration	Delta		
PW Full Load Current	2639	2623	A
CW Full Load Current	1216	1209	A
Outer Diameter	1700	2100	mm
Airgap Diameter	1320	1678	mm
Rotor			
Rotor Type	Nested Loop		
Rotor slots	240		
Number of nests	12		
Loops per nest	10		
Inner Diameter	1098	1413	mm
Shaft Diameter	500		mm
Common			
Airgap	1.5		mm
Stack Length	3074	1894	mm
Electrical Steel Grade	350/0.65		W/kg/mm
Torque	170		kNm
Pin @ 350 rpm	6230	6205	kW
Pout @ 350 rpm	6000	6000	kW
Efficiency @ 350 rpm	96.3	96.7	%
Active Mass	27	24	tonne
Rotor Inertia	7160	11537	kg.m^2

Table 3: High level design output for of a 6 MW brushless DFIG

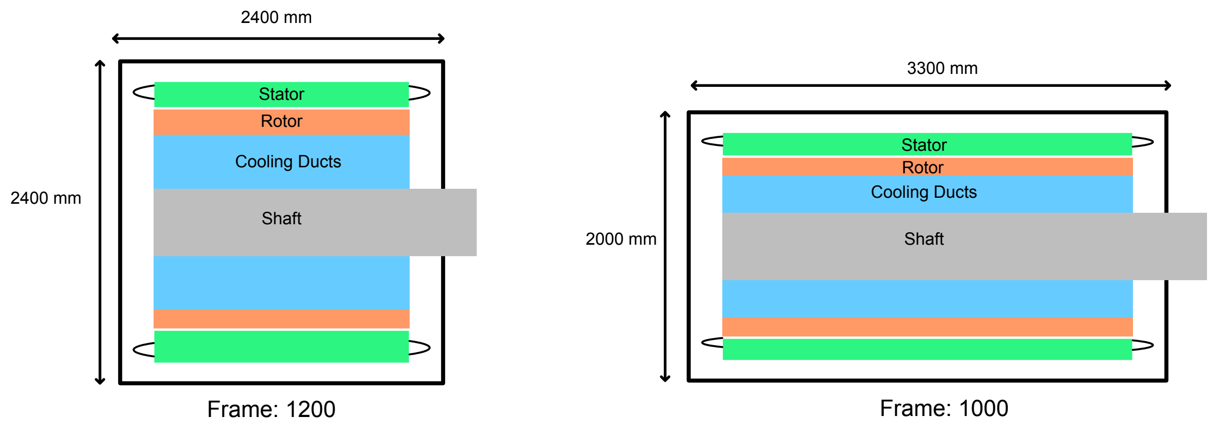

Figure 3: Physical dimensions of 6 MW Brushless DFIG with different frame sizes

4 Performance Analysis

4.1 Equivalent circuit model

The equivalent circuit model is a simple method of representing the steady-state performance of the Brushless DFIG [8] and offers a straightforward way of calculating the efficiency, power factor and other steady-state measures of the machine to a practical accuracy. One form of the equivalent circuit for the Brushless DFIG is shown in Fig. 4 where all the parameters are referred to the stator power winding [8]. The calculated parameters of the equivalent circuit model are shown in Table 4.

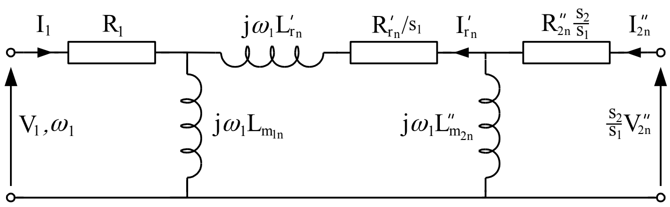

Figure 4: Per-phase equivalent circuit for the Brushless DFIG

Parameter	Frame: 1000	Frame: 1200
R_1 (mΩ)	1.31	1.23
R_2'' (mΩ)	1.63	1.44
R_r' (mΩ)	7.3	6.2
L_{m2}'' (mH)	3.18	3.9
L_{m1} (mH)	5.98	7.34
L_r' (mH)	0.58	0.61

Table 4: Parameter values for the equivalent circuit

4.2 Efficiency of Brushless DFIG

Fig. 5 shows the efficiency versus load of the 1200 frame sized, Brushless DFIG. The machine has an efficiency of 96.7 % when operating at rated power and a maximum efficiency of 97.3 % at 0.6 pu of full load. The decline in efficiency at partial load is inevitable in induction machines such as the Brushless DFIG because of the magnetizing current required to establish the magnetic fields. The efficiency of the Brushless DFIG can be lifted by utilising more iron and copper in the machine design, however this will result in higher weight and cost.

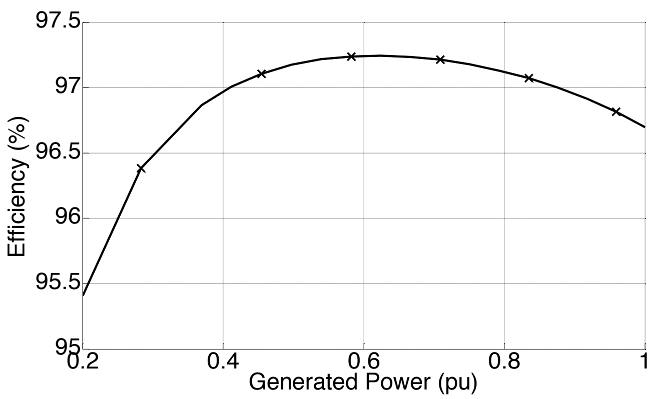

Figure 5: Efficiency versus load for 6 MW Brushless DFIG (Frame: 1200)

3 Conclusions

A 6 MW medium-speed Brushless DFIG has been designed to meet current wind turbine specifications for similar power rating. Analytical modelling and equivalent circuit analysis have been used during the design process to ensure that the machine meets the specified requirements.

The paper shows that a medium-speed Brushless DFIG is practical and scalable to larger (multi-megawatt) powers and is suitable for wind turbine applications. The Brushless DFIG offers brushless operation, reduced converter rating and does not require expensive magnetic material. Hence, a significant reduction on capital and operational costs is possible using the generator for wind turbine applications which will feed through to a lower cost of energy.

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