Research Report

2012-40

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Optimal Design of a Grid-Connected-to-Rotor Type Doubly Fed Induction Generator for Wind Turbine Systems

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This paper performs a shape optimization of a grid-connected-to-the-rotor type doubly fed induction generator (DFIG) in which the rotor winding is connected to the grid instead of the stator winding. To analyze the characteristics of a DFIG accurately, a time step 2D-FEA is carried out, which is coupled with Simplorer. To maximize the torque per weight as well as to maintain the efficiency, the Kriging model based on latin hypercube sampling and genetic algorithm are utilized. As an optimal design result, the torque per weight on the optimal model has been increased. Finally, the analysis and the optimal design results are confirmed by the experimental results.

***Index Terms*—Doubly fed induction generator (DFIG), finite element analysis (FEA), genetic algorithm (GA), Kriging model, optimal design.**

I. Introduction

DOUBLY FED induction generators (DFIGs) have been used extensively for wind turbine systems due to its variable speed capability, adjustable stator power factor, increased output power, and relatively small size converter compared to squirrel cage induction generators [1]–[3]. Although there are many papers on optimal design of induction machines, it is still valuable to discuss the optimal design of a DFIG for a wind turbine application [4]. There have been some investigation of the shape optimization of a DFIG for wind turbine applications [4], [5]. To minimize the annual power loss of a DFIG, the dimensions of stator core were optimized [4]. Two DFIG models were selected according to air-gap length, and then studied to reduce the total cost including materials, losses, and converter [5].

As the capacity of wind power increases at a rapid pace, research on lightweight wind turbine systems have been actively progressing. While they focus more on the converter and mechanical portions of the system, it is also necessary to investigate the design of lightweight wind generators. It is important to reduce the weight of wind generator, because the greater part of the cost for wind generator is structural material. The cost of structural material is as high as 63% of the total machine cost for a 10 MW generator [6]. In addition, offshore wind farms face the problem of size and weight reduction, which have grown rapidly [7]. Therefore, the torque per weight is an important parameter in wind generator.

A novel concept for a grid-connected-to-rotor type doubly fed induction machine (DFIM) has been proposed which can reduce the size and weight by the authors [8]. A new design process using the loading distribution method (LDM) has been also introduced, which can design a grid-connected-to-rotor type DFIM more efficiently. Considering motoring operation, a proposed grid-connected rotor type and a conventional grid-connected stator type have been analyzed by finite element analysis (FEA), and a proposed type has been previously tested as a motor.

Manuscript received March 02, 2012; revised April 12, 2012; accepted May 08, 2012. Date of current version October 19, 2012. Corresponding author: B.-I. Kwon (e-mail: bikwon@hanyang.ac.kr).

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Digital Object Identifier 10.1109/TMAG.2012.2200667

In this paper, a shape optimization for a grid-connected-to-rotor type DFIG is performed to maximize the torque per weight as well as to maintain the efficiency, which are significant parameters for wind turbine application. To analyze the generation characteristics of a DFIG accurately, a time step 2D-FEA coupled with simplorer is also performed. The Kriging model based on the latin hypercube sampling (LHS) and genetic algorithm (GA) are used for optimization of the DFIG. An optimization process is proposed to consider the inevitable errors between the optimal results by optimization algorithm and verified results by 2D-FEA. To confirm the analysis and the optimal design results, the initial and the optimal model of grid-connected-to-rotor type DFIG have been tested now operating as generators.

II. Finite Element Analysis Coupled With Simplorer

A. Structure and Specifications

The rotor winding of a grid-connected-to-the-rotor type DFIG is directly connected to the power grid, while the stator winding is connected to an adjustable frequency converter, as shown in Fig. 1 [8]. The rotor parameters of the proposed type DFIG can be determined prior to the stator parameters because the rotor winding is the primary winding. Hence, not only the stator but also the rotor of the proposed type DFIG can be designed efficiently. The designed grid-connected-to-rotor type DFIG in [8] was utilized as an initial model, as shown in Table I.

B. Analysis Conditions

To analyze the generation characteristics of an initial DFIG model accurately, the coil resistance and end-turn leakage inductance derived from the equivalent circuit model have been applied to a time step 2D-FEA, and then 2D-FEA model is coupled with Simplorer, which is a commercial software product for power electronics simulation.

In order to analyze the generation characteristics of a DFIG simply, a three-phase AC voltage has been induced to the stator winding on the converter side while a DFIG rotates at the rated speed. Its electrical output characteristics are then simulated through a three-phase diode bridge with a load resistor and capacitor, which are connected to the rotor winding on the grid side. Considering 220 V and 60 Hz grid connections, which are converted into 310 V DC by a three-phase diode bridge, the

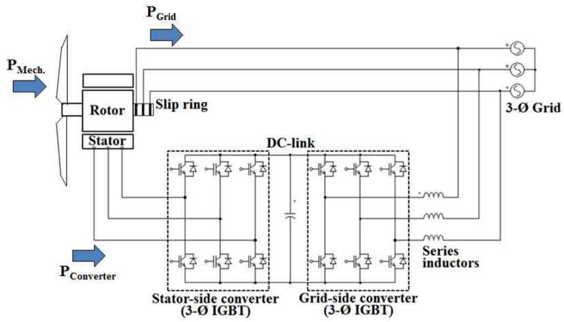

Fig. 1. Schematic diagram of a grid-connected-to-rotor type DFIG.

TABLE I
SPECIFICATIONS OF AN INITIAL MODEL

Items	Unit	Values
Poles	-	4
Rated output power	kW	5
Rated voltage	V	220
Frequency	Hz	60
Rated speed	rpm	1,800
Efficiency	%	92
Outer diameter of stator	mm	197
Inner diameter of stator	mm	136.6
Outer diameter of rotor	mm	136
Inner diameter of rotor	mm	54
Stack length	mm	116
Weight	kg	25.69

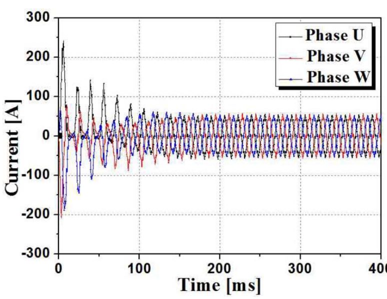

Fig. 2. Input current of the stator winding on the converter side of an initial model.

input voltage of the stator winding on the converter side was decided as 33.93 Vrms at rated speed.

While a time step 2D-FEA is being performed, the core losses in a laminated iron core were calculated. The core losses were computed in the frequency domain, which is 60 Hz, and they consist of hysteresis, eddy-current, and excess losses [9]. Torque of an initial DFIG model is also simulated by 2D-FEA, and consequently, the mechanical input power, efficiency, and torque per weight are calculated.

C. Analysis Results

The total electrical output power of DFIG is computed as

$$P_{\text{elec.}} = P_1 - P_2 - P_{\text{Fe}} \tag{1}$$

where, P_1 is the electrical output power of the grid side, P_2 is the electrical input power of the converter side, and P_{Fe} is the core loss of the stator and rotor.

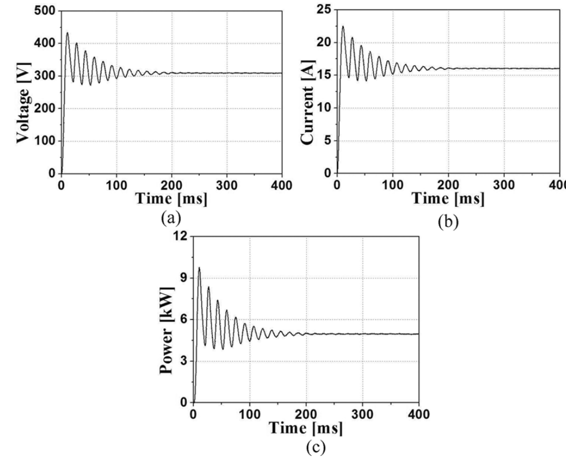

Fig. 3. Electrical output characteristics of the rotor winding on the grid side of an initial model. (a) Voltage of the load resistor (b) Current of the load resistor (c) Electrical output power.

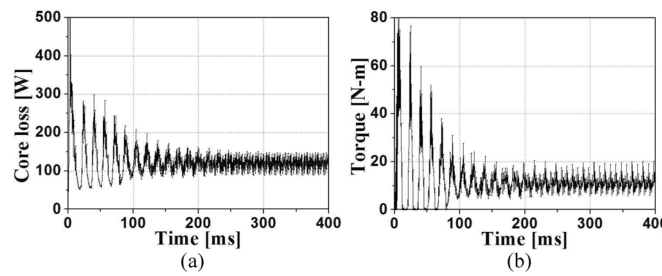

Fig. 4. 2D-FEA results of an initial model. (a) Core loss (b) Toque.

The mechanical input power of DFIG is:

$$P_{\text{mech.}} = T_{\text{mech.}}\omega_s \tag{2}$$

where, $T_{\text{mech.}}$ is the mechanical input torque on the shaft and ω_s is the synchronous speed.

Fig. 2 shows the input current of the stator winding on the converter side of an initial model. The electrical output power of the rotor winding on the grid side of the initial model can be derived from the voltage and current of the load resistor, as shown in Fig. 3. Fig. 4 describes the core loss and torque of an initial model, which are 128.2 W and 10.9996 N-m, respectively. The total electrical output power and mechanical input power are can be calculated by (1) and (2), as shown in Table II. As a result, the efficiency and torque per weight are computed 91.04% and 0.4282 N-m/kg, respectively.

III. OPTIMAL DESIGN

A. Optimal Design Process

Fig. 5 shows an optimal design process to optimize effectively the initial DFIG model. The LHS is applied as a method of the design of experiment (DOE) and the Kriging model is used to approximate the objective and constraints functions. A genetic algorithm is utilized as the optimization algorithm. Although an optimization direct-coupled with the FEA has no errors between the optimization results and FEA results, it is time-consuming. Therefore, the optimization techniques have been widely used using the approximation model, which is based on FEA results according to the DOE. However, the optimization

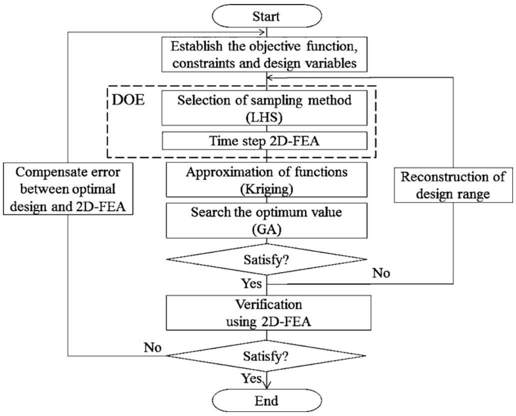

Fig. 5. Optimal design process.

TABLE II
OPTIMAL DESIGN RESULTS OF A GRID-CONNECTED-TO-ROTOR TYPE DFIG

Items		Unit	Initial model	Optimal model (by optimization algorithm)	Optimal model (verified results by FEA)
Design variables	X1	mm	10	11.36	
	X2	mm	12	14.76	
	X3	mm	19.5	22.27	
	X4	mm	6	6.89	
Electrical input power of the converter side		W	2964.2	-	2992.3
Electrical output power of the grid side		W	4980.0	-	4990.3
Core loss		W	128.2	-	132.5
Total electrical output power		W	1887.64	-	1865.46
Torque		N-m	10.9996	-	10.8652
Mechanical input power		W	2073.4	-	2048.1
Generation efficiency		%	91.04	91.21	91.08
Weight		kg	25.69	24.35	24.35
Torque per weight		N-m /kg	0.4282	0.4480	0.4462

techniques using the approximation model has the inevitable errors between the optimization results and FEA results. Therefore, an optimization process is proposed which can consider the errors between them.

B. Objective Function, Constraints, and Design Variables

The objective function is to maximize the torque per weight, and the constraints are the efficiency and the outer diameter on the basis of the initial model, as describe in (3). The inner and outer diameter of the rotor and stator are also fixed, as shown in Table I. To satisfy the objective function and the constraints, the design variables are established which are the slot depth and the slot width of the stator core (X1, X2), and the slot depth and the slot width of the rotor core (X3, X4), as shown in (4) and Fig. 6.

$$\begin{aligned} &\bullet\, Objective\ function\\ &Maximize\ the\ torque\ per\ weight\\ &\bullet\, Constraints\\ &Generation\ efficiency \geq 91.04\%\\ &Outer\ diameter\ of\ stator = 197\ mm \end{aligned} \tag{3}$$

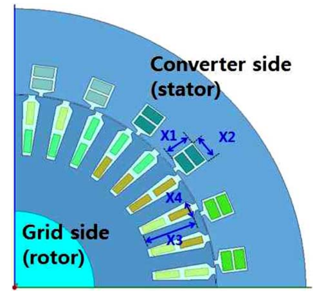

Fig. 6. Optimal design variables of a grid-connected-to-rotor type DFIG.

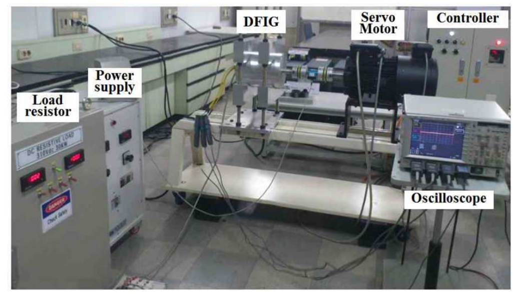

Fig. 7. Experimental set-up for the grid connected to rotor type DFIG.

$$\begin{aligned} &\bullet\, Design\ variables\\ &9.8 \leq X1\,(Slot\ depth\ of\ the\ stator\ core) \leq 14.0\\ &11.8 \leq X2\,(Slot\ width\ of\ the\ stator\ core) \leq 15.0\\ &19.2 \leq X3\,(Slot\ depth\ of\ the\ rotor\ core) \leq 25.0\\ &5.8 \leq X4\,(Slot\ width\ of\ the\ rotor\ core) \leq 7.0 \end{aligned} \tag{4}$$

C. Optimal Design Results

The optimal results using optimization algorithm were almost similar to the optimal results verified by 2D-FEA as shown in Table II. Compared to the initial model, the torque per weight of the optimized grid-connected-to-rotor type DFIG was increased by 4.2%, which is an important parameter for a wind turbine application, while maintaining the same efficiency. The reason that the optimal model has an upper torque per weight is because it has a smaller core weight. Although the slot area of the stator core and the rotor core of the optimal model were increased, magnetic saturation has not yet occurred in the teeth and yoke of the core.

IV. EXPERIMENT

To verify the analysis and the optimal design results, the initial and the optimal model have been tested as generators. An experimental set-up was implemented as shown in Fig. 7. A capacitor and a load resistor were utilized, corresponding to 1 000 μF and 19.293 Ω, respectively.

Fig. 8 shows the experimental results of the initial and the optimal model that Ch. 1 and Ch. 2 are the input currents of two phases of the stator winding, and Ch. 3 and Ch. 4 are the output voltage and the output current of the load resistor, respectively. The electrical input power of the converter side and the electrical output power of the grid side are calculated from those results, as shown in Table III.

Fig. 9 describes the measured results of the initial and the optimal model that Ch. 1 is the output signal of a torque sensor,

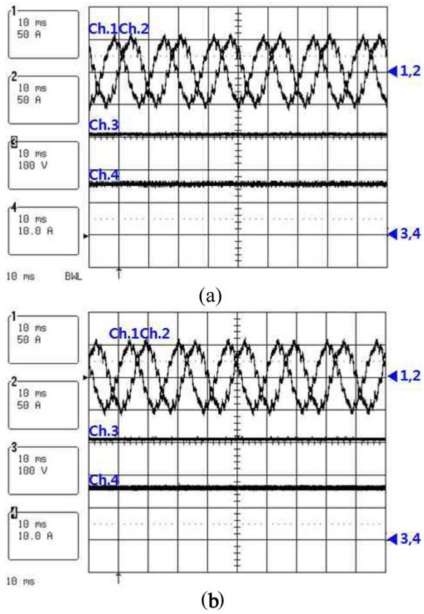

Fig. 8. Experimental results of the currents of stator winding and the voltage and current of the load resistor. (a) Initial model (a) Optimal model.

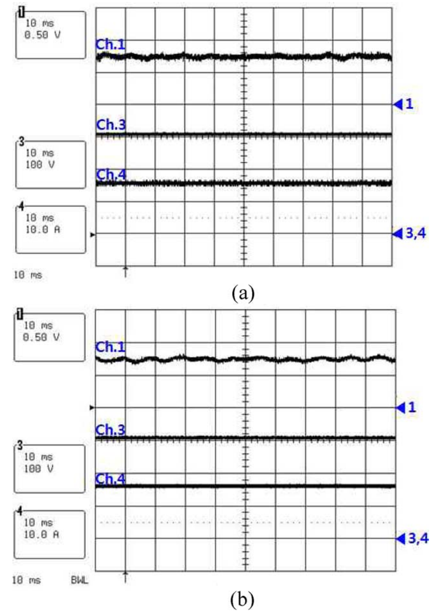

Fig. 9. Experimental results of the torque and the voltage and current of the load resistor. (a) Initial model (b) Optimal model.

TABLE III
ANALYTICAL AND EXPERIMENTAL RESULTS

Items	Unit	Initial model		Optimal model	
		Anal.	Expt.	Anal.	Expt.
Electrical input power of the converter side	W	2964.2	3017.6	2992.3	3058.8
Electrical output power of the grid side	W	4980.0	4992.5	4990.3	5037.5
Total electrical output power	W	1887.6	1846.7	1865.5	1846.2
Torque	N-m	10.9996	10.83	10.8652	10.80
Mechanical input power	W	2073.4	2041.5	2048.1	2035.8
Generation efficiency	%	91.04	90.46	91.08	90.69
Torque per weight	N-m/kg	0.4282	0.4216	0.4462	0.4435

and Ch. 3 and Ch. 4 are the same as Fig. 8. The maximum torque range of the torque sensor is 100 N-m that is converted into 7 V. The mechanical input power, generation efficiency, and torque per weight are derived from the measured torque, as shown in Table III. It shows good agreement between the analytical and the experimental results. The generation efficiency of the optimal model is on a par with the initial model. As an experimental result, the torque per weight of the optimal model has been improved by 5.2% compared to the initial model.

V. CONCLUSION

This paper has performed a shape optimization for a grid-connected-to-rotor type DFIG to maximize the torque per weight as well as to maintain the efficiency. A characteristic analysis of the DFIG has carried out accurately using a time-step 2D-FEA coupled with Simplorer. Optimal design results using optimization algorithm have shown that the torque per weight of the optimal model increased compared with the initial model through weight reduction in the core. The experimental results of the DFIGs have confirmed the analysis and the optimal design results. From these results, a shape optimized grid-connected-to-rotor type DFIG has shown the usefulness of an increase in torque per weight for wind turbine system.

ACKNOWLEDGMENT

This work was supported by the World Class University program through the National Research Foundation of Korea funded by the Ministry of Education, Science and Technology under Grant R33-2008-000-10104-0.

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