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Design and Analysis of a Novel Grid-Connected to Rotor Type Doubly Fed Induction Machine

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This paper proposes a novel grid-connected to rotor type doubly fed induction machine (DFIM) in which the rotor winding is connected to the grid instead of the stator winding. The size and weight of the stator can be reduced on the proposed grid-connected to rotor type DFIM, because the proposed type can use the rotor core more efficiently compared to a conventional grid-connected to stator type DFIM. In order to verify the size and weight reduction of the proposed type, the loading distribution method (LDM) is utilized. As a design result, the outer diameter and weight of the stator on the proposed type have been decreased. Equivalent circuit analysis and finite element analysis (FEA) were performed to verify the design results and to analyze the characteristics of the novel DFIM. Finally, these analysis results are confirmed by experimental results.

***Index Terms*—Doubly fed induction machine, equivalent circuit analysis, finite element analysis, loading distribution method.**

I. Introduction

DOUBLY FED INDUCTION MACHINES (DFIMs) have been widely used for pumps, fans, flywheels, and wind turbine systems due to its variable speed capability, an adjustable stator power factor, and a small size converter [1]–[3]. The stator winding of a conventional grid-connected to stator type DFIM is directly connected to the power grid, while the rotor winding is connected to an adjustable frequency inverter. To design the conventional grid-connected to stator type DFIM, traditional design methods are utilized, such as the D^2L method or the loading distribution method (LDM), also called the shear stress method [4], [5]. The main drawback of the design process for a grid-connected to stator type DFIM is its ineffective rotor design which concentrates on maximizing the inner diameter of the stator to optimize torque production, i.e., D^2L. Because the stator is designed in advance, the outer diameter of the rotor is essentially determined automatically. As a result, the flux density of the rotor core around shaft is much lower than the other parts of the rotor core and the stator core.

This paper proposes a novel grid-connected to the rotor type DFIM wherein the rotor winding is connected to the power grid instead of the stator winding [6]. The stator size and weight of the proposed grid-connected to rotor type DFIM can be reduced because the proposed type can use the rotor core more efficiently compared to the conventional grid-connected to stator type DFIM, which does not well utilize the rotor core as a portion of the flux path. To design the grid-connected to the rotor type DFIM, a novel design process is also proposed, which can design the rotor portion in advance. Equivalent circuit analysis is utilized to analyze characteristics of the designed DFIM as a wind generator, and to consider the end-winding leakage inductance, which is a significant part of the total leakage inductance [7], [8]. To analyze the DFIM accurately, a time step 2D-finite element analysis (FEA) is also performed and these results compared with experimental results.

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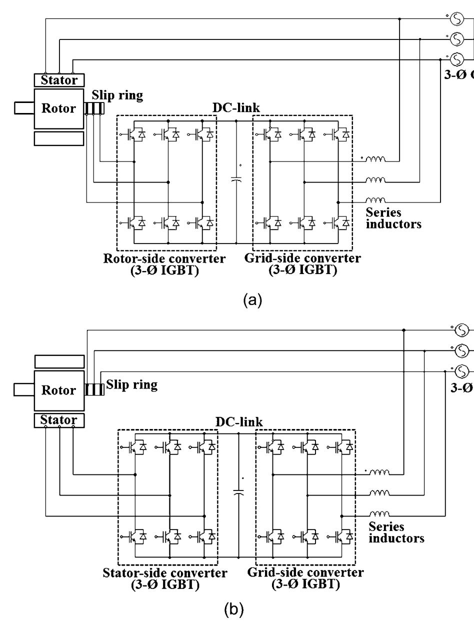

Fig. 1. Schematic diagram of a DFIM. (a) Grid-connected to stator type. (b) Grid-connected to rotor type.

II. Design of a Grid-Connected to Rotor Type DFIM

A. Concept of a Grid-Connected to Rotor Type DFIM

The stator winding of the conventional grid-connected to the rotor type DFIM is directly connected to the grid while the rotor winding is connected to back-to-back AC/DC/AC converters as shown in Fig. 1(a). However, the stator winding and rotor winding of the proposed grid-connected to rotor type DFIM are connected to a converter and grid, respectively, as shown in Fig. 1(b). The rotor parameters of the proposed type DFIM 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 DFIM can be designed efficiently. The operation and control of the converter of the proposed type DFIM is exactly the same as the conventional type since the grid side currents as well as the converter side currents of those are same. The converter rating of the proposed type is also identical with the conventional arrangement.

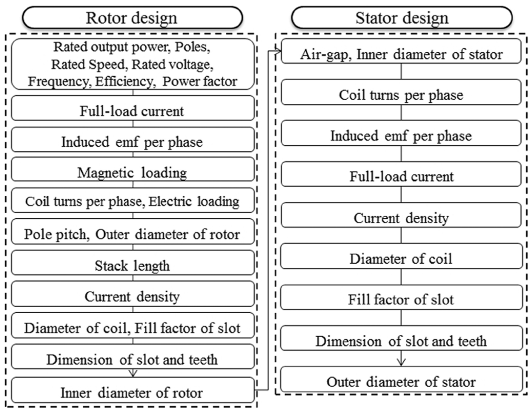

Fig. 2. Design process of a grid-connected to rotor type DFIM using LDM.

B. Design Process Using the Loading Distribution Method

The LDM is a well-known method for designing an electric machine. The capacity per pole of an electric machine can be described in (1) [4]. Therefore, an electric machine can be designed using the electric loading and magnetic loading under a given condition such as the output power, efficiency, and power factor

$$S[VA] = \frac{P_o}{\eta \cos \varphi p} = K_o AC \phi f \tag{1}$$

where, S is the capacity per pole, P_o is the average output power, η is the efficiency, $\cos\varphi$ is the power factor, p is the number of poles, K_o is the coefficient of the emf, AC is the electric loading, ϕ is the magnetic loading, and f is the source frequency of the electric machine.

As mentioned in the introduction, the outer diameter of the rotor of a conventional grid-connected to stator type DFIM is typically decided after determination of the stator parameters [4], [5]. Therefore, the rotor size is unnecessarily large and the rotor core around the shaft cannot be sufficiently utilized. However, the rotor parameters of the proposed grid-connected to rotor type DFIM can be determined prior to the determination of the stator parameters using the proposed design process, as shown in Fig. 2. Therefore, the outer size and weight of the DFIM can be reduced because the rotor can be designed more efficiently.

C. Design Results

The design results of the DFIM using LDM are shown in Table I and Fig. 3. The stator's outer diameter and weight of the grid-connected to rotor type DFIM can be decreased by 11.3% and 14.1%, respectively, for a 5 kW machine compared with the grid-connected to stator type. Although the inner diameter of rotor of the grid-connected to rotor type is 54 mm, which is less than that of the grid-connected to stator type, the dimension is suitable because it is satisfies the IEC standard that the outer diameter of the shaft for a 4 pole, 5.5 kW induction machine has to be above 38 mm.

III. Equivalent Circuit Analysis

A. Analysis Conditions

Although DFIMs have been used for various applications, DFIMs designed for wind turbine generators have been their most frequently used application. To analyze the characteristics of generator type DFIMs with variations of speed, equivalent circuit analysis and maximum power point tracking (MPPT) have been utilized. The equivalent circuit parameters have also been extracted from the model equations.

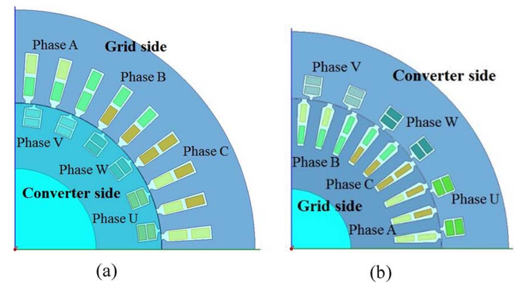

Fig. 3. Designed shape of the DFIM using LDM. (a) Grid-connected to stator type. (b) Grid-connected to rotor type.

TABLE I
Design Results of the DFIM Using LDM

Items		Unit	Grid-connected to stator type	Grid-connected to rotor type
Objective Specifications	Output power	kW	5	
	Rated voltage	V	220	
	Frequency	Hz	60	
	Rated speed	rpm	1,800	
	Efficiency	%	92	
	Power factor	-	0.84	
Stator	Outer diameter	mm	222	197
	Inner diameter	mm	136	136.6
Rotor	Outer diameter	mm	135.4	136
	Inner diameter	mm	75	54
Stack length		mm	116	
Total weight		kg	30.08	25.82

If a wind turbine is rotated at a constant speed, the maximum power can be computed from wind speed [3], [9]. The input mechanical power with MPPT must satisfy

$$P_{\text{mech}} = P_{m\_ref} \left(\frac{\omega_m}{\omega_{\text{ref}}} \right)^3 \tag{2}$$

where, P_{m_ref} is the mechanical power with MPPT at a reference speed, ω_{ref} is the reference speed, and ω_m is the rotor speed.

The electro-magnetic power in the air-gap is:

$$P_{em} = (P_{\text{mech}} - P_f)/(1 - s) \tag{3}$$

where, P_f is the rotor mechanical loss, and s is the slip of a machine.

The total electrical output power is computed as

$$\begin{aligned} P_{\text{elec}} &= P_1 - P_2 - P_{Fe} \\ &= P_{em} - m_1 I_1^2 R_1 - \left(sP_{em} + m_2 I_2^2 R_2\right) - P_{Fe} \end{aligned} \tag{4}$$

where, P_1 is the electrical output power of the grid side, P_2 is the electrical input power of the converter side, P_{Fe} is the core loss of the stator and rotor, m_1 and m_2 are the number of phases of the grid side winding and the converter side winding, respectively, R_1 and R_2 are the phase resistance of the grid side winding and the converter side winding, respectively.

The mechanical input power is

$$P_{\text{mech}} = T_{\text{mech}} \omega_s = (T_{em} + T_f)\omega_s \tag{5}$$

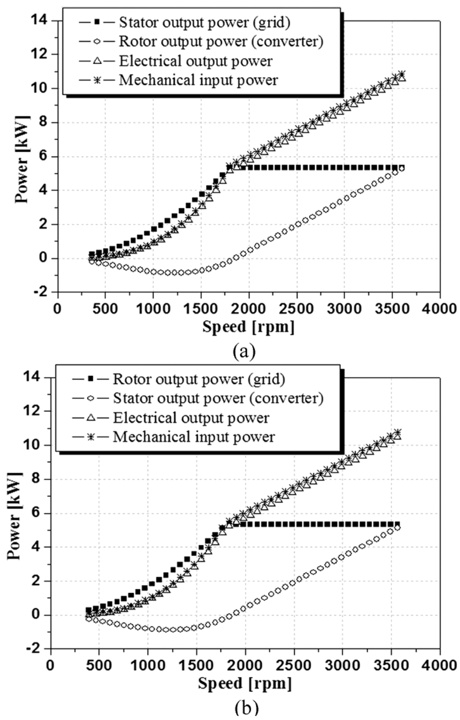

Fig. 4. Input/output power characteristics with variations of speed. (a) Grid-connected to stator type. (b) Grid-connected to rotor type.

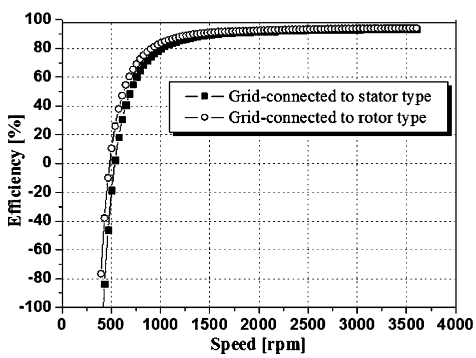

Fig. 5. Efficiency characteristics with variations of speed.

where, T_{mech} is the input mechanical torque on the shaft, ω_s is the synchronous speed, T_{em} is the electromagnetic torque, and T_f is the frictional torque.

B. Analysis Results

Fig. 4 presents the input power and the output power characteristics with variations of the rotor speed. The rotor winding receives power from the converter when the rotor speed is lower than the synchronous speed. However, the rotor winding outputs power to the converter when the rotor speed is higher than the synchronous speed. The electrical output power of the grid connected stator type and the grid connected rotor type are 5.14 kW and 5.13 kW at the synchronous speed, respectively, which satisfies the objective output power of the DFIM. The efficiency of the grid connected stator type and the grid connected rotor type are 91.14% and 92.05% at the synchronous speed, respectively, as shown in Fig. 5.

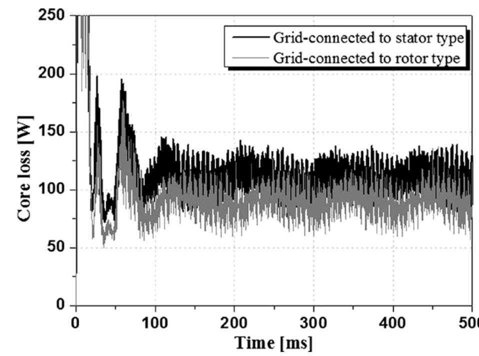

Fig. 6. Core loss of the DFIM using FEA.

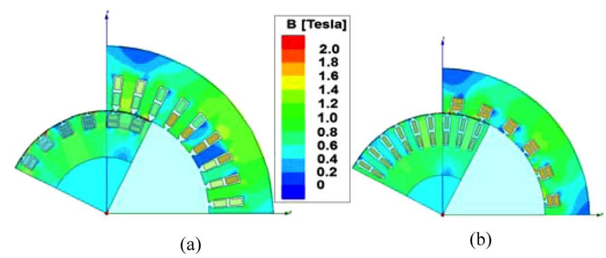

Fig. 7. Flux density distribution of the DFIM using FEA. (a) Grid-connected to stator type. (b) Grid-connected to rotor type.

IV. Finite Element Analysis

A. Analysis Conditions

To analyze the characteristics of DFIMs accurately, the equivalent circuit parameters derived from the model equations have been applied to a time step 2D-FEA, which are coil resistance and end-turn leakage inductance. While FEA was being performed, the resistive winding losses and 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 [10].

In order to analyze DFIMs using FEA, a three-phase AC voltage has been induced to the grid side windings, rated at 220 V, and 60 Hz. In addition, a no-load condition was applied for one revolution in the rotor, and then a load condition was applied considering the load torque and the moment of inertia. The load torque of the grid-connected to stator type and the grid-connected to rotor type has the same value, 26.526 N-m, because the output power is 5 kW and the rated speed is 1 800 rpm. The moments of inertia of the grid-connected to stator type and the grid-connected to rotor type are 0.0298557 kgm^2 and 0.0303884 kgm^2, respectively.

B. Analysis Results

FEA results have been averaged between 200 ms and 500 ms considering a steady state condition. Fig. 6 shows the core loss of the grid-connected to stator type and the grid-connected to rotor type, which are 109.54 W and 90.11 W, respectively. The reason that the grid-connected to rotor type has a lower core loss is because it has a smaller core volume. In addition, magnetic saturation has not occurred in the core of the grid-connected to rotor type despite the reduction of the stator's outer diameter, as shown in Fig. 7. The flux density of the core of DFIMs is below 1.6 T.

The average torque and rotor speed of DFIMs are almost identical, as shown in Fig. 8 and Table II. Therefore, the mechan-

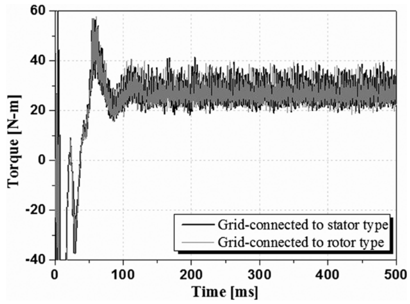

Fig. 8. Torque characteristics of the DFIM using FEA.

TABLE II
ANALYSIS RESULTS OF THE DFIM USING FEA

Items	Unit	Grid-connected to stator type	Grid-connected to rotor type
Copper loss	W	301.59	311.27
Core loss	W	108.78	82.89
Total loss	W	410.37	394.16
Torque	N-m	26.5210	26.5404
Speed	rpm	1760.43	1752.42
Mech. output power	W	4889.20	4870.51
Elec. input power	W	5299.57	5264.67
Efficiency	%	92.26	92.51
Total weight	kg	30.08	25.82
Torque per weight	N-m/kg	0.8817	1.0279

(a) (b)

Fig. 9. Prototype and experimental set-up of the grid connected to rotor type DFIM. (a) Prototype. (b) Experimental set-up.

ical output power of DFIMs is also very similar. The efficiency of the grid-connected to rotor type DFIM is actually higher by 0.25% than the grid-connected to stator type because of its lower core loss, as shown in Table II. The torque per weight of the grid-connected to rotor type DFIM is also 16.6% higher than the grid-connected to stator type, which is an important parameter for wind power application. Therefore, if the weights of both DFIMs are the same, the torque of the grid-connected to rotor type will be 16.6% higher than the grid-connected to rotor type DFIM.

V. EXPERIMENT

To verify the analysis results using FEA, a prototype of the grid connected to rotor type was built and tested, as illustrated in Fig. 9. The experimental results were averaged for 60 sec considering a rated operating conditions and a steady state.

The mechanical output power was measured as 4855.44 W because the average torque and speed were 26.5393 N-m and 1743.5 rpm, respectively, as shown in Fig. 10. The experimental

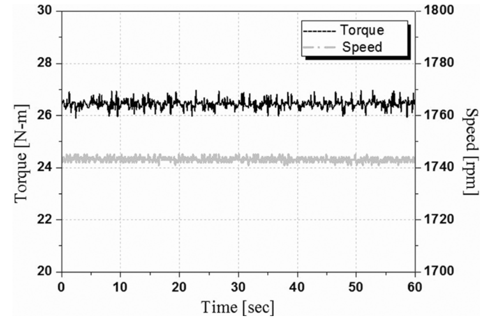

Fig. 10. Experimental results of the grid connected to rotor type DFIM.

efficiency was 90.54%, somewhat lower than the FEA result due to the friction loss and windage loss.

VI. CONCLUSION

This paper has proposed a concept and a design process for a grid-connected to rotor type DFIM which can reduce the outer diameter and weight. Design results using LDM has shown that the outer diameter and weight of the proposed type DFIM decreases compared with the conventional type. The characteristic analysis using equivalent circuit analysis and FEA confirmed the design results. FEA results also showed that the grid-connected to rotor type had higher torque per weight than the grid-connected to stator type DFIM. The measurement results have confirmed the FEA results. From these results, the proposed grid-connected to rotor type DFIM shows the usefulness of a reduction of the size, weight, material cost and an increase in torque compared with the conventional grid-connected to stator type induction machine.

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