풍력발전 시스템용 회전자 계통연계형 이중여자 권선형 유도발전기

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A Grid-connected to Rotor Type Doubly Fed Induction Generator for Wind Turbine Systems

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Abstract - This paper proposes a grid-connected to rotor type doubly fed induction generator (DFIG) in which the rotor winding is connected to the grid instead of the stator winding. The stator size and weight of the proposed grid-connected to rotor type DFIG can be reduced because the proposed type can use rotor core more efficiently compared to the stator type DFIG. 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 stator outer diameter and weight of the proposed type were decreased. The equivalent circuit analysis and finite element method also performed to verify the design results and to analyze characteristics of the novel DFIG.

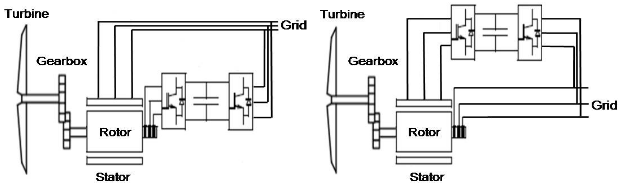
1. Introduction

Doubly fed induction generators (DFIGs) have been widely used for wind turbine systems due to its variable speed capability, adjustable stator power factor, and small size converter compared to squirrel cage induction generators [1]. The stator winding of a conventional grid-connected to stator type DFIG is directly connected to the power grid while the rotor winding of that is connected to adjustable inverter. To design the conventional grid-connected to stator type DFIG, traditional design methods are utilized such as the D^2L method or the loading distribution method (LDM) also called the shear stress method [2],[3]. The demerit of the design process for a grid-connected to stator type DFIG 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.

This paper proposes a novel grid-connected to rotor type DFIG wherein the rotor winding is connected to the power grid instead of the stator winding. The stator size and weight of the proposed grid-connected to rotor type DFIG can be reduced because the proposed type can use rotor core more efficiently compared to the conventional grid-connected to the stator type DFIG which cannot well utilize rotor core as a portion of the flux path. To design the grid-connected to rotor type DFIG, a novel design process is also proposed in section 2, which can design rotor portion in advance. The equivalent circuit analysis is utilized to verify and to analyze characteristics the designed DFIG in section 3. Finally, to analyze DFIG accurately, FEM analysis is also performed in section 4.

2. Design of a grid-connected rotor type DFIG

2.1 Concept of a grid-connected rotor type DFIG



(a) Grid-connected to stator type (b) Grid-connected to rotor type
<Fig 1> Schematic diagram of DFIG

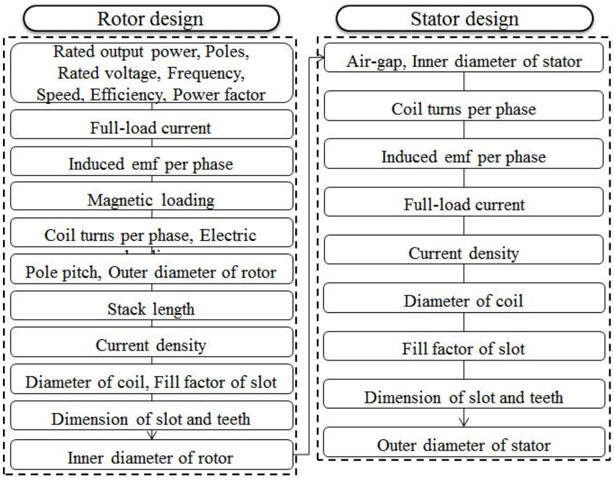
The stator winding of the conventional grid-connected to rotor type DFIG is directly connected to the grid while the rotor winding is connected to back-to-back AC/DC/AC converters as shown in Fig. 1(a). However, the stator winding and the rotor winding of a proposed grid-connected to rotor type DFIG are connected to converter and grid, respectively, as shown in Fig. 1(b).

2.2 Design process and results

The rated output power of DFIG is 5 kW at 1,800 rpm, which is the synchronous speed. The rated voltage and frequency of DFIG are 220 V and 60 Hz, respectively. The efficiency and power factor of DFIG are 92 % and 0.84 at the synchronous speed, respectively. To achieve a goal of specifications for the DFIG, LDM is utilized, which is a well-known method to design an electric machine. The capacity per pole of an electric machine can be described. [2]. 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.

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

The design results of DFIG using LDM are shown in Table 1. As a design result, the outer diameter of the stator and weight of the grid-connected to the rotor type DFIG can be decreased by 11.3 % and 14.1 %, respectively, compared with the grid-connected to the 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 shaft for 4 poles and 5.5 kW induction machine has to be above 38 mm.



<Fig 2> Design process of Grid-connected to rotor type DFIG

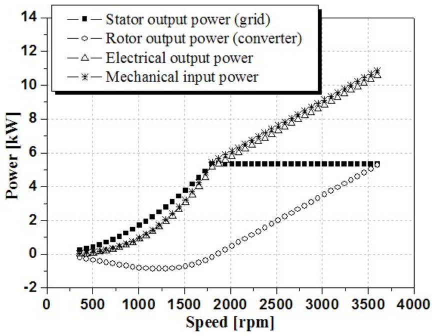
<Table 1> Design results of DFIG using LDM

Items		Unit	Grid-connected to stator type	Grid-connected to rotor type
Stator	Outer diameter	mm	222	197
	Inner diameter	mm	136	136.6
	Coil size	mm	ϕ2.1 (round)	4*4 (flat)
	Turns per slot	turns	14	4
Rotor	Outer diameter	mm	135.4	136
	Inner diameter	mm	75	54
	Coil size	mm	4*4 (flat)	ϕ2.1 (round)
	Turns per slot	turns	4	14
Air gap		mm	0.3	
Stack length		mm	116	
Total weight		kg	30.08	25.82

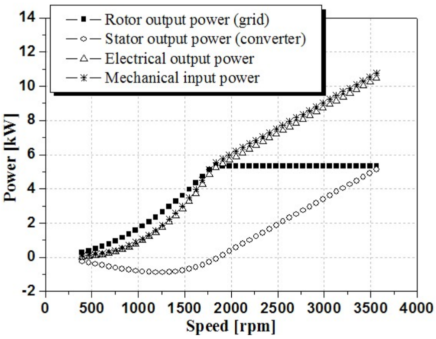
3. Equivalent circuit analysis

To analyze characteristics of the designed DFIG with variation of the speed, the equivalent circuit method and the maximum power point tracking (MPPT) are utilized.

Fig. 3 presents the input power and the output power characteristics with variation of the rotor 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 DFIG. 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. 4.

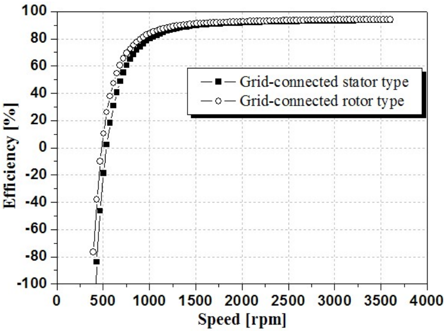


(a) Grid-connected to stator type



(b) Grid-connected to rotor type

<Fig 3> Input/output power characteristics with variation of speed



<Fig 4> Efficiency characteristics with variation of speed

4. Finite element method

To analyze characteristics of the designed DFIGs correctly, the FEM analysis has been utilized. The FEM analysis coupled with a control circuit is time consuming and complicate. Therefore to examine characteristics of DFIG easily and accurately, a three-phase AC voltage is induced to the grid side windings, which is 220 V, 60 Hz. While FEM analysis has been performed, the core loss of stator core and rotor core has been considered. In addition, a no-load condition has been applied during one revolution in rotor, and then a load condition has been applied considering the load torque and the moment of inertia. The load torque of the grid-connected stator type and the grid-connected 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 moment of inertia of the grid-connected stator type and the grid-connected rotor type are 0.0298557 kgm^2 and 0.0303884 kgm^2, respectively.

The magnetic flux density in the stator core of the grid-connected to rotor type DFIG is below 1.6 T, which is acceptable value and similar to that of the grid-connected to stator type. The efficiency of the grid-connected to the rotor type DFIG is actually higher by 0.5 % than the grid-connected to stator type because of the lower copper loss and core loss, as shown in Table 2. The efficiency of the grid connected stator type and the grid connected rotor type using FEM and ECA (Equivalent circuit analysis) have analytical errors, which are 1.35 % and 0.93 %, respectively. The torque per volume of the grid-connected to rotor type DFIG is also higher 27 % than the grid-connected to stator type. Therefore, if the volumes of both DFIGs are same, the torque of the grid-connected to the rotor type will be higher 27 % than the grid-connected to the rotor type DFIG.

<Table 2> Analysis results of DFIG using FEM

Items		Unit	Grid-connected to stator type	Grid-connected to rotor type
Copper loss		W	286.51	277.39
Core loss		W	109.54	90.11
Total loss		W	396.05	367.50
Elec. input power		W	5274.14	5235.31
Torque		N-m	26.5386	26.5325
Speed		rpm	1755.28	1751.97
Mech. output power		W	4878.13	4867.82
Efficiency	FEM	%	92.49	92.98
	ECA	%	91.14	92.05
Volume		cm^3	4,490	3,536
Torque per volume		mN-m/cm^3	5.91	7.50

5. Conclusions

This paper has proposed a concept and a design process for a grid-connected rotor type DFIG which can reduce the outer diameter and weight. In order to compare the conventional grid-connected stator type and the proposed grid-connected rotor type, each DFIG was designed using LDM. Design results showed that the outer diameter and weight of the proposed type DFIG were decreased compared with the conventional type. The characteristic analysis using equivalent circuit analysis and FEM analysis confirmed the design results. FEM analysis results also showed that the grid-connected rotor type had higher torque per volume than the grid-connected stator type DFIG. From these results, the proposed grid-connected to rotor type DFIG shows the usefulness of a reduction of the size, weight, material cost and an increase in torque compared with the conventional grid-connected stator type induction generator.

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[참 고 문 헌]

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