Losses Calculation of Brushless Doubly-fed Generator with Hybrid Rotor

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Brushless doubly-fed generator (BDFG) has substantial benefits, which make it an attractive alternative as a wind power generator. However, it suffers from lower efficiency and larger vibration noise in comparison with conventional generators. A major part of drawbacks arises from undesirable spatial harmonics of air-gap magnetic field. Losses calculation is an important issue in optimal design researches to improve the performance of BDFG. In this paper, a novel hybrid rotor structure of BDFG which has strong coupling ability is proposed. In addition, the copper loss and core loss calculation methods which take into account the effects of cage bar, harmonic magnetic flux density, alternating and rotating magnetization are investigated. The validity and feasibility of proposed calculation methods are verified by comparing the experimental results of a 25kW prototype BDFG with hybrid rotor.

***Index Terms*—Brushless doubly-fed generator, hybrid rotor, losses calculation, core loss, copper loss**

I. Introduction

BRUSHLESS DOUBLY-FED generator (BDFG) has many advantages, such as no brush or slip rings, robust structure, low operation and maintenance costs as well as requiring a smaller capacity converter. The BDFG has two stator windings with different pole-pair numbers to avoid direct magnetic coupling, which called power winding and control winding. The energy conversion is achieved by the magnetic field modulation of the rotor [1,2]. Due to copper loss and core loss have significant effects on the efficiency and temperature distribution, it is vital to accurately predict these losses component in an optimal design procedure. Paper [3] presents an equivalent circuit including eddy-current core loss resistances and points that the rotor in an axially laminated BDFM produces high rotor core loss. Analytical equations for calculating core loss and stray load loss BDFG is proposed in [4]. The BDFM is investigated in [5] using time-stepping finite element method taking core loss and saturation effects into account.

In this paper, a novel hybrid rotor structure of BDFG is proposed. Furthermore, the copper loss and core loss calculation methods of the proposed BDFG are investigated. In addition, a 25kW prototype of BDFG with hybrid rotor is processed to verify the validity and feasibility of the proposed loss calculation methods.

II. Structure and Parameters of Prototype BDFG

The main dimensions of the prototype BDFG are shown in Table I.

TABLE I
MAIN DIMENSIONS OF PROTOTYPE BDFG

Parameter	Value	Parameter	Value
Rated power	25kW	Stack length	225mm
Pole-pair number of power winding	4	Pole-pair number of control winding	2
Stator outer diameter	400mm	Stator inner diameter	285mm
Stator slots	72	Rotor outer diameter	284mm
Rotor inner diameter	85mm	Magnetic layer number	4

The schematic diagram of the proposed BDFG is shown in Fig. 1. It can be seen that the hybrid rotor is a combination of radial magnetic barrier rotor and cage rotor. Therefore, this rotor not only can increase the magnetic field coupling capability but also can improve the operating performance.

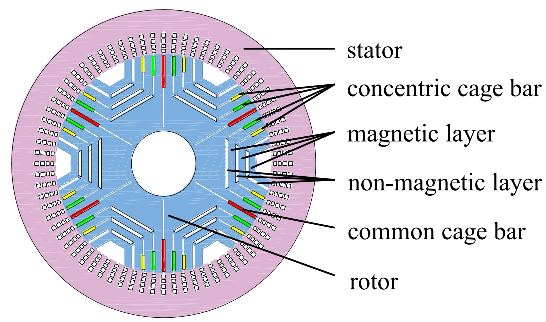

Fig. 1. Schematic diagram of the proposed BDFG.

III. Losses Calculation Model

Due to the particularity of the structure and complexity of the magnetic field, the losses calculation is more complex than conventional generators. In order to calculate the losses of the proposed BDFG accurately, the copper loss and core loss calculation methods are investigated.

A. *Copper loss calculation*

The power winding and control winding are both random coil with small wire diameter, the skin effect can be neglected. Therefore, the copper loss of stator p_{CuS} can be calculated directly as

$$p_{CuS} = 3I_P^2 R_P + 3I_C^2 R_C \quad (1)$$

where, R and I denote the resistance and rms value of current, respectively. In addition, subscript p and c denote the power winding and control winding, respectively.

However, because of the existence of cage bars in the rotor, the copper loss calculation should be considered the rotor copper loss. The equivalent circuit of cage bars in the proposed hybrid rotor is shown in Fig. 2. According to the circuit, the copper loss of rotor p_{CuR} can be expressed as

$$p_{CuR} = \sum_{i=1}^{6}\sum_{j=1}^{2}\left(I_{ij}^2 R_j + I_{i3}^2 R_{l3} + 2I_{ei}^2 R_{e3}\right) \quad (2)$$

where, subscript i and j mean the nest and loop number of cage bar, respectively. Subscript l and e mean "linear part" and end ring, respectively. In addition, $i_{ei} = i_{e,i+1} + i_{i+1,3}$, $R_j = 2\left(R_{nj} + R_{lj}\right)$. In which, subscript n means the nest-loop. So the copper loss of the proposed BDFG can be calculated by

$$p_{Cu} = p_{CuS} + p_{CuR} \tag{3}$$

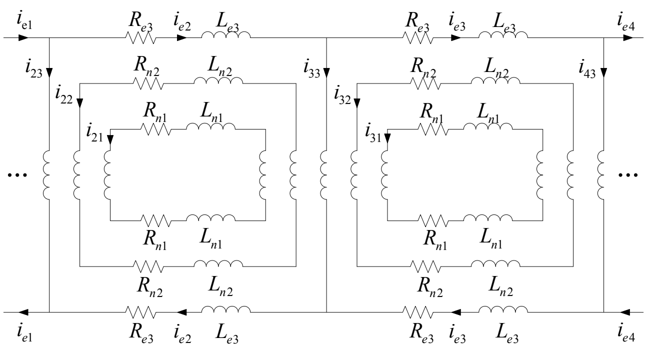

Fig. 2. Equivalent circuit of hybrid rotor cage bars.

B. Core loss calculation

Fig. 3 shows the composition of the air-gap magnetic flux density. It can be seen that the harmonic contents of BDFG are more than that of the conventional generators, so it needs to consider the effect of harmonics on the core loss.

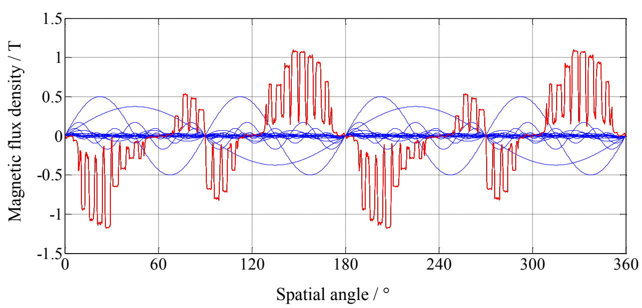

Fig. 3. Composition of the air-gap magnetic flux density.

Furthermore, the magnetic field in the iron core varies with the time and space, the effect of alternating magnetization and rotating magnetization should be considered. Therefore, the core loss of the proposed BDFG can be calculated as

$$p_{Fe} = p_h + p_c + p_e = K_h f \sum_{k=0}^{\infty} k\left(B_{k\max}^{\alpha} + B_{k\min}^{\alpha}\right) + K_c f^2 \sum_{k=0}^{\infty} k^2\left(B_{k\max}^{2} + B_{k\min}^{2}\right) + \frac{K_e}{(2\pi)^{3/2}} \frac{1}{T} \int_0^T \left(\left|\frac{dB_r(t)}{dt}\right|^{1.5} + \left|\frac{dB_\theta(t)}{dt}\right|^{1.5}\right) dt \tag{4}$$

In which, K_h, K_c and K_e indicate the coefficient of hysteresis loss, eddy-current loss and added loss, respectively. f denote the frequency of magnetic flux density. B_{kmax} and B_{kmin} are long axis and short axis of k sequence oval harmonic magnetic flux density, respectively. $B_r(t)$ and $B_\theta(t)$ are radial component and tangential component of magnetic flux density, respectively.

IV. Experimental Results and Discussion

Two experimental conditions have been tested in order to verify the validity and feasibility of the proposed losses calculation methods. The experimental platform is shown in Fig. 4. Because the core loss and rotor copper loss can't be measured through experiment directly, so the efficiency is used to evaluate the total loss. In the test, the load is selected 10kW under the sub-synchronous (300r/min) and super-synchronous (700r/min) conditions. The torque transducer and encoder are used for testing the input power and the voltage and current sensors are used for measuring the output power.

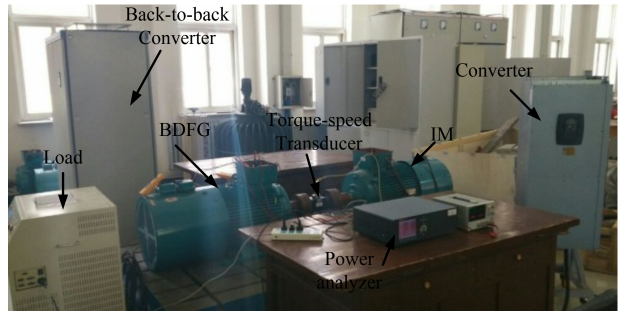

Fig. 4. Experimental platform of the proposed BDFG.

The efficiencies of calculation and experiment are listed in Table II. From the results, it can be known that the calculation value is little higher than experimental value because of the add loss and mechanical loss are neglected in the calculation condition. So the comparison results can verify the validity and feasibility of the proposed losses calculation method.

TABLE II
Types Sizes For Camera-Ready Papers

	Calculation value %	Experimental Value %
300 rpm	80.3	79.8
700 rpm	85.1	84.6

V. Conclusion

This paper has presented a novel BDFG with hybrid rotor. The structural characteristics of the proposed BDFG are presented. In addition, the losses calculation methods are proposed for the novel BDFG. The copper loss of rotor cage bars is considered in the proposed method. Furthermore, the effects of harmonic magnetic flux density, alternating magnetization and rotating magnetization on the core loss are also considered in the proposed calculation method. The validity and feasibility of the calculation method are verified by a 25kW prototype BDFG with hybrid rotor. According to the results, it is concluded that the proposed calculation method can be used to calculate the BDFG losses accurately.

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