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Novel Synchronous Generator for Wind Power Generation

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Abstract– A novel half-wave rectified brushless synchronous generator is proposed for wind power generation. The brushless excitation system for rotor field is based on the half-wave rectified excitation. The method does not require field power source as well as permanent magnet field system. In this paper, the basic characteristics are calculated using the finite element method analysis.

1. Introduction

As demand for clean power generation, some projects of offshore wind power generation have been widely drawn up. Permanent magnet synchronous generator is expected to be suitable for the generation system because of high efficiency and easy maintenance due to its brushless rotor configuration. The generator, however, will be expensive because of sharp increase in the price of rare-earth magnet.

The author (T. Higuchi) and his colleagues previously presented a half-wave rectified brushless synchronous motor as an ac servo motor [1] [2]. The field rotor winding is short-circuited with a diode instead of power supply. The conventional 3-phase winding is introduced to the armature. By superposing excitation current on the 3-phase armature current, the armature winding generates excitation magnetic field with rotating magnetic field. The excitation magnetic field induces current in the field winding. The current in the field winding is rectified by the diode so that constant magnetic flux through the winding is conserved. In this way, the field current in the rotor is induced from the stator. The field flux is controllable by controlling the amplitude of the excitation current superposed on the armature current. The controllability makes it possible to easily perform the field weakening operation at high speed region. The half-wave rectified brushless synchronous motor possesses simple and robust structure and is more inexpensive than permanent magnet motor.

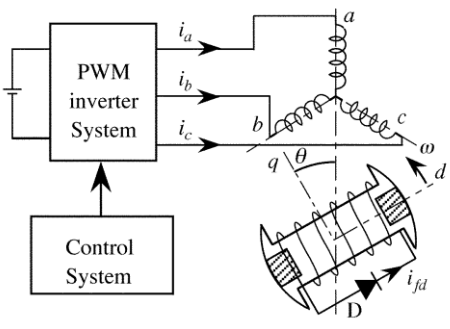


Fig. 1 Motor system configuration

This paper proposes a novel half-wave rectified brushless synchronous generator for wind power generation. The brushless excitation system is based on the above half-wave rectified excitation method. The method needs no power supply for field as well as permanent magnet field system. The basic characteristics of the proposed generator are estimated by the finite element method analysis.

2. Principle of Half-wave Rectified Excitation

2.1. Excitation System

Figure 1 shows the system configuration of the half-wave rectified brushless synchronous motor. The structure of the motor is the same as the conventional salient pole rotor type synchronous motor except the field rotor winding. The winding is short-circuited with a diode instead of power supply. In addition, the rotor does not require any permanent magnets. However magnets generate additional torque.

2.2 Voltage Equation

Figure 2 shows the dq-axis model of the half-wave rectified brushless synchronous motor. The voltage equations for the dq-axis model are

$$\begin{aligned} e_{\mathrm{d}} &= \mathrm{d}\lambda_{\mathrm{d}}/\mathrm{d}t - \omega\lambda_{\mathrm{q}} + r_{\mathrm{a}} i_{\mathrm{d}}, \\ e_{\mathrm{q}} &= \mathrm{d}\lambda_{\mathrm{q}}/\mathrm{d}t + \omega\lambda_{\mathrm{d}} + r_{\mathrm{a}} i_{\mathrm{q}}, \\ e_{\mathrm{fd}} &= \mathrm{d}\lambda_{\mathrm{fd}}/\mathrm{d}t + r_{\mathrm{fd}} i_{\mathrm{fd}}, \end{aligned} \tag{1}$$

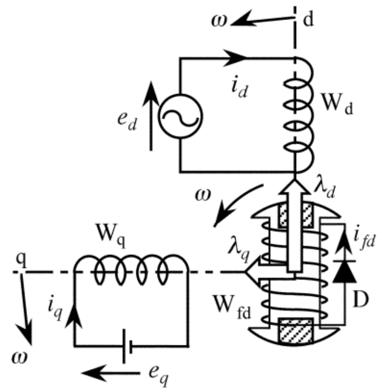


Fig. 2 Motor operation principle on dq-axis

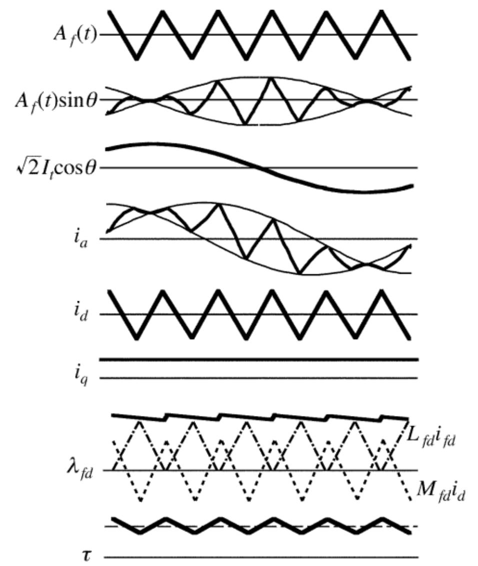


Fig. 3 Waveforms of currents, flux linkage, and torque

where the subscripts d, q, and fd of the variables and the constants represent direct axis, quadrature axis, and field, respectively. For each circuit and each winding indicated by the subscript, voltage e, current i, and flux linkage λ are defined. r_a stands for the resistance of the stator armature winding and r_{fd} that of the field rotor winding.

The flux linkages are expressed in terms of self- and mutual- inductance as follow:

$$\begin{aligned} \lambda_d &= L_d i_d + M_{fd} i_{fd} + (M_{fd}/L_{fd})\lambda_{PM}, \\ \lambda_q &= L_q i_q, \\ \lambda_{fd} &= M_{fd} i_d + L_{fd} i_{fd} + \lambda_{PM}, \end{aligned} \tag{2}$$

where L denotes self-inductance of each winding indicated by the subscript. M_{fd} is the mutual inductance between the direct axis winding and the field winding.

2.3. Principle of Brushless Excitation and Torque Generation

In the proposed excitation method, the field is induced by the excitation current superposed on the 3-phase armature current as illustrated in Fig. 3. The excitation current is included in the armature current as

$$\begin{aligned} i_a &= A_f(t)\sin\theta + \sqrt{2}I_t\cos\theta, \\ i_b &= A_f(t)\sin(\theta - 2\pi/3) + \sqrt{2}I_t\cos(\theta - 2\pi/3), \\ i_c &= A_f(t)\sin(\theta + 4\pi/3) + \sqrt{2}I_t\cos(\theta - 4\pi/3). \end{aligned} \tag{3}$$

The first term on each right-hand side of Eq. (3) represents the excitation current and the second term the conventional 3-phase current. The excitation current is formed by controlling the amplitude of 3-phase current with the function $A_f(t)$. This 3-phase current has phase difference by $-\pi/2$ from the above 3-phase current. The function $A_f(t)$ is a triangular wave with the effective value I_t and the bias frequency ω_b. From Eq. (3), the dq-axis currents are described by

$$\begin{aligned} i_d &= \sqrt{3/2}A_f(t), \\ i_q &= \sqrt{3}I_t. \end{aligned} \tag{4}$$

Two rotating fields λ_d and λ_q are induced by the single phase current i_d and the single phase dc current i_q respectively as shown in Fig. 2. Fig. 3 shows the field flux linkage λ_{fd} produced by the direct axis rotating field. When λ_{fd} through the field winding is increasing, the negatively biased diode turns off in the field circuit. When λ_{fd} decreases, the diode turns on and the field current flows to compensate the decrease of the field flux. If the time constant related with the decreasing flux is large enough, the flux is almost kept constant.

The torque is obtained from the following equation:

$$\tau = \lambda_d i_q - \lambda_q i_d. \tag{5}$$

Though pulsating torque exists in this motor as shown in Fig. 3, it is not serious problem for practical usage by choosing the bias frequency ω_b much higher than the mechanical resonance frequency.

3. Principle of Half-wave Rectified Brushless Synchronous Generator

The half-wave rectified excitation method generates field of the conventional synchronous motors. This implies that the proposed method is applicable to field excitation of synchronous generators. Fig. 4 shows a 4-pole, 3-phase, and 2 kW generator model with the proposed excitation system. In the generator, the excitation winding is separated from the armature winding. The two groups of the winding coils are arranged in the short pitch distributed winding with the same stator slots. The field winding is short-

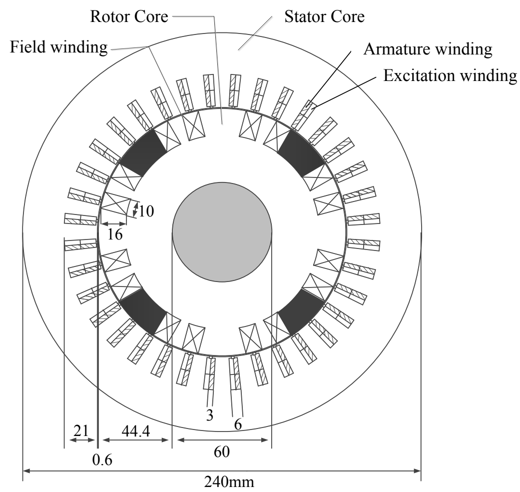


Fig. 4 Generator model

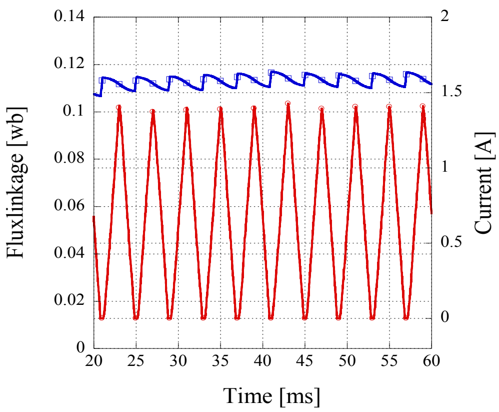


Fig. 6 Flux linkage and excitation current

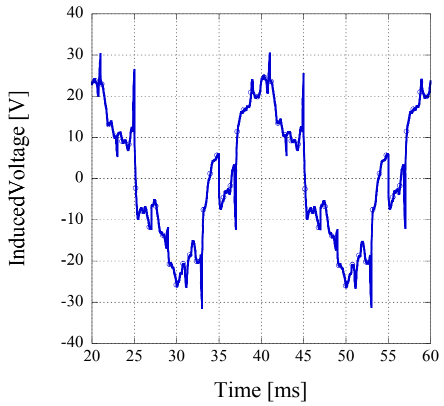


Fig. 7 Induced voltage and phase a winding for triangular modulation function

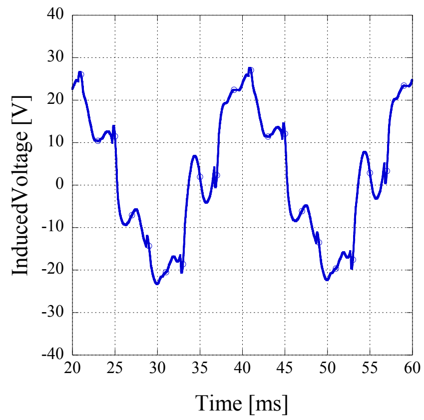


Fig. 8 Induced voltage and phase a winding for sinusoidal modulation function

circuited with only a diode. The generator achieves a maintenance free, simple and robust brushless structure without any permanent magnets.

The excitation current is formed by controlling the amplitude of 3-phase current with a function $A_{\mathrm{f}}(t)$ as follows:

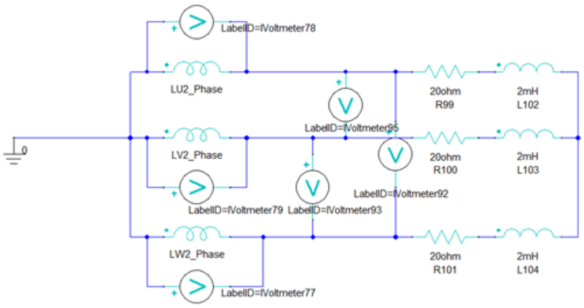


Fig. 9 Circuit model

$$
\begin{aligned}
i_{\mathrm{a}} &= A_{\mathrm{f}}(t)\sin\theta, \\
i_{\mathrm{b}} &= A_{\mathrm{f}}(t)\sin(\theta - 2\pi/3), \\
i_{\mathrm{c}} &= A_{\mathrm{f}}(t)\sin(\theta - 4\pi/3).
\end{aligned} \tag{6}
$$

The current of Eq. (6) in the excitation winding corresponds to the direct axis current i_{d} described by

$$
i_{\mathrm{d}} = \sqrt{3/2}A_{\mathrm{f}}(t). \tag{7}
$$

The magneto-motive force alternating with the bias frequency ω_{b} is generated on the d-axis of the rotor.

For the increase of the flux linkage with the field winding, the diode is biased reversely by the electromotive force generated in the rotor winding and is turned off. When the flux linkage decreases, the diode turns on. In other words, the field current i_{fd} flows through the field winding to keep the flux linkage constant. The field is easily controllable by varying the effective value of $A_{\mathrm{f}}(t)$.

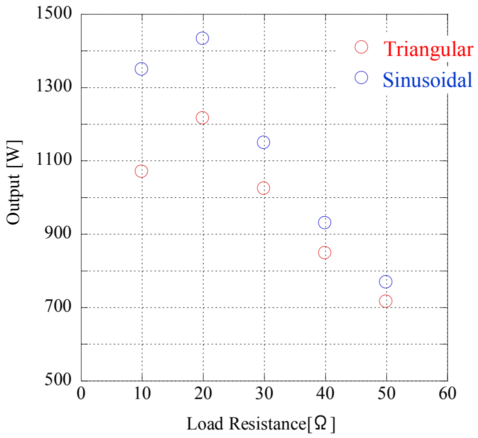
4. Analytical Results

4.1. Induced Voltage

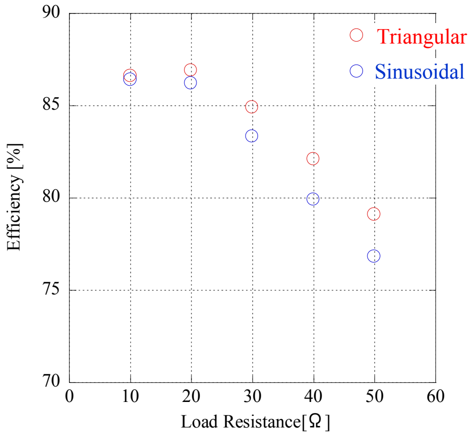
Fig. 6 shows an excitation current and a produced flux linkage. Fig. 7 shows the induced voltage of the phase-a armature winding for the triangular modulation function. It is shown that the flux linkage is almost constant, but the induced voltage includes many harmonics. Fig. 8 shows the induced voltage of the phase-a armature winding for the sinusoidal modulation function. The harmonics are suppressed rather than that of the triangular waveform shown in Fig. 7.

4.2. Output Characteristics

Fig. 9 shows a circuit model to simulate the output characteristics. The simulation results are shown in Fig. 10. The maximum output for the sinusoidal modulation function is larger than that of the triangular modulation function. However the efficiency of the sinusoidal modulation function is smaller than that of the triangular waveform.



(a) Output power



(b) Efficiency

Fig. 10 Output characteristics

4.3. Design Analysis

Design analysis is carried out for higher output power and efficiency. Here three designs are investigated. Design 1 is the basic model shown in Fig. 4. The rotor radius is set at 74.4 mm. Fig. 11 (a) shows Design 2 model. The rotor radius is decreased to 69.4 mm and the electric loading increases 1.17 times as large as Design 1. Fig. 11 (b) shows the Design 3 model. It has dimensions similar to Design 2. However the field coils are arranged into one block. Table 1 describes the characteristics of these designs: induced voltage, output power and efficiency. Design of the electric loading and the field parts is possible to improve the power generating operation.

5. Conclusions

A novel synchronous generator is proposed for wind power generation. The generator does not require field power source as well as permanent magnets. A test machine is designed and the basic characteristics are presented using the finite element method analysis. In the future work, the experimental performances will be shown.

Table 1. Characteristics of Designs 1-3.

Design	Induced Voltage [V]	Output power [W]	Efficiency [%]
Design 1	103.01	1215	86.9
Design 2	116.01	1530	87.4
Design 3	134.26	2064	90.7

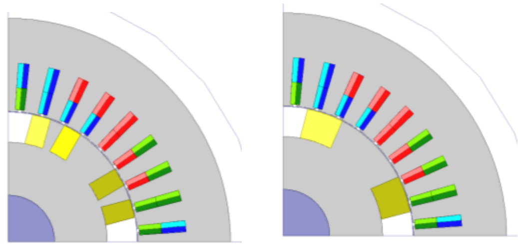

(a) Design 2　　(b) Design 3

Fig. 11 Design models

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