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ABSTRACT
In this paper, the characteristics analysis of a high-speed permanent magnet synchronous generator (PMSG) was performed considering saturation reactance. The equivalent circuit method (EMC) is a method for predicting performance in the design process of a generator. When using EMC, if the inductance of the equivalent circuit is not considering saturation, it is difficult to predict the performance of a generator accurately. Therefore, we applied a reactance that considered saturation to derive more accurate performance prediction through short-circuit analysis. The proposed method was verified using finite element method.

I. INTRODUCTION
High speed permanent magnet synchronous generators (PMSG) that directly drive systems without using reduction gear in turbine power generation systems are gradually increasing. Generators rotating at high speeds can be designed smaller in size for the same output compared to generators rotating at low speeds. In addition, the overall system can be miniaturized, with high energy transfer efficiency, conserving material and space.\(^1,2\)

The characteristics of the generator is calculated using the equivalent circuit method. However, with circuit constants that do not consider saturation, it is difficult to make accurate predictions. Therefore, if magnetic saturation is considered at the core, accurate prediction of output characteristics is possible.\(^3,4\)

For more accuracy, the circuit constant of wound synchronous machine can be derived through the open circuit test and short circuit test. The characteristics of these tests are shown as open-circuit characteristic (OCC) and short-circuit characteristic (SCC). To use the circuit constant derivation method of the wound synchronous generator, the parameters in the OCC and SCC must be changed to match those of the PMSG. In the PMSG, the field current is fixed because a permanent magnet is used instead of a field current to generate magnetic flux. First, we find the back-EMF that can output the rated voltage through no-load analysis, followed by short-circuit analysis performed at the rated speed. Then, the saturation reactance is derived from the output armature current and the back-EMF.\(^5\)

In this paper, we present a method for deriving the saturation reactance using short circuits to analyze the characteristics of the high-speed PMSG. Circuit constant derived from the proposed method applies to EMC for more accurate performance prediction of the high-speed generator. The validity of proposed method is verified by comparing it with the results of finite element analysis.
II. ANALYSIS OF HIGH-SPEED PERMANENT MAGNET SYNCHRONOUS GENERATOR

A. The analysis model

Fig. 1(a) shows the PMSG analysis model while Fig. 1(b) shows the manufactured model. Since it rotates at high speed, there is a sleeve structure to prevent the scattering of magnets. Table I indicates design specifications. Two poles were selected for high-speed rotation. The stator was designed with magnetic saturation below 1.4 T and the outer diameter of the stator was selected according to the design requirement. The winding was selected in the slot fill factor limit and current density limit. The number of turns and coil pitch were selected to minimize the voltage drop due to the inductance of the winding. First, it was confirmed whether the generated voltage could be satisfied by the no-load analysis. The output characteristics were derived using the equivalent circuit method by deriving the saturation reactance using the short circuit in the no-load analysis.

B. The equivalent circuit method

Fig. 2 shows the equivalent circuit of a PMSG. In the initial design of a high-speed permanent magnet synchronous generator, characteristics such as voltage, current, and output can be calculated using the equivalent circuit method. This method assumes the generator’s back-EMF as a sine wave and calculates the output characteristics based on induced voltage, phase resistance, synchronous inductance, and load resistance. Therefore, to obtain more accurate output characteristics, the magnetic circuit related to induced voltage and synchronous inductance must be precisely calculated. The phase resistance is expressed as

\[ R_{ph} = \rho c \frac{L}{A_c} \]  

(1)

\[ L_c = 2L_{stk} + 2r_{coil, end} \times \pi \]  

(2)

The area of the conductor is obtained from the area of the wire and the number of strands. Synchronous inductance is calculated by sum of self and mutual inductance. The inductance is expressed by

\[ L_s = \frac{\lambda a}{I_a}, \quad M = \frac{\lambda_{ab}}{I_a} \]  

(3)

Where \( L_s \) is self-inductance, \( M \) is mutual inductance, \( \lambda a \) is flux linkage in one phase, and \( \lambda_{ab} \) is mutual flux linkage. The back-EMF in one phase is expressed as

\[ E_{ph} = \pi \sqrt{2} f N_{ph} \phi f k_w \]  

(4)

\( N_{ph} \) is the number of turns per one phase, and \( k_w \) is the stator winding coefficient. \( V_t \) is the terminal load voltage, and \( I_{ph} \) is the phase current. In the case when the generator works at an arbitrary operating speed, power factor is constant, and the load is only resistive load output voltage, the current can be explained as follows

\[ I_{ph} = E_{ph} \frac{R^2_{load}}{(R_{ph} + R_{load})^2 + X_s^2} \]  

(5)

\[ V_t = E_{ph} \frac{R^2_{load}}{(R_{ph} + R_{load})^2 + X_s^2} \]  

(6)

Therefore, output power can be expressed as follows

\[ P_{out} = 3V_t I_{ph} \]  

(7)

C. Derivation of saturation reactance through no-load analysis and short circuit analysis

The method of deriving the circuit constant through the short circuit is used in the wound synchronous machine as described in

### Table I. Specification of analysis model.

| Parameter          | Value       | Parameter          | Value       |
|--------------------|-------------|--------------------|-------------|
| Rotor diameter     | 68 [mm]     | Current density    | 10 [A/mm²/m²]|
| Rated voltage      | 380 [V]     | Rated speed        | 36000 [rpm] |
| Rated power        | 124 [kW]    | Cooling            | Water       |
| Stator diameter    | 200 [mm]    | Sleeve             | 4 [mm]      |
| Turns              | 3           | Pole               | 2           |
| Slot               | 24          | Coil pitch         | 11          |
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FIG. 2. Equivalent circuit of a PMSG.

The existing method calculates the inductance at the no-load condition by applying a current of 1 A to one phase given by equation (4). Figs. 3(a) and (b) depict the magnetic flux density distribution at no-load and short-circuit condition. The stator has a high magnetic saturation at no load. However, the stator has a low magnetic saturation due to the armature reaction during load analysis. Therefore, the inductance during load analysis increases rather than at no-load. To obtain more accurate output characteristics, inductance considering magnetic saturation in stator core is applied. Fig. 3(c) shows the short current at rated speed, whereas Fig. 3(d) shows the line to line back EMF and short current according to rotational speed. The saturation reactance is calculated by back EMF and short current. The phase resistance and inductance components for the windings remain circuit constants at short circuit condition. Here, the phase resistance is smaller than saturation reactance,

FIG. 3. Results of short circuit analysis and no-load analysis: (a) magnetic flux density distribution at no-load condition, (b) Magnetic flux density distribution at short circuit condition, (c) Short circuit current, and (d) Back-EMF and short circuit current according to rotational speed.

the introduction. The open-circuit characteristic provides a relationship between the spatial fundamental wave component of the air gap magnetic flux and the back-EMF of the magnetic circuit when the field current is the only source of magnetism. Open-circuit characteristics are usually obtained experimentally, with the armature terminal open, mechanically driving the synchronous machine at a synchronous speed, and measuring the terminal voltage according to various DC excitation currents. The short circuit test drives the machine at rated synchronous speed and measures the armature short-circuit current for various DC field powers. The variation of the short circuit armature current according to the field current is called the short circuit characteristic. To use this method, the characteristic variation was not confirmed by the field current but by the rotational speed. This method is described as improved method.
therefore the phase resistance could be neglected. The saturation reactance component at rated speed is represented by the following as

$$X_s = \frac{E_{ph}}{I_{short}}$$  \hspace{1cm} (8)

The back-EMF of one phase was derived to be $278.8 \text{Vrms}$ from no-load analysis and the short current was $321.26 \text{A rms}$. Substituting this result into Equation (8), we can derive the saturation reactance considering magnetic saturation. Therefore, the saturation reactance is $0.8678 \text{ohm}$, which can be calculated to estimate inductance considering saturation according to the operating frequency. The inductance derived using the existing method is $214.9 \mu\text{H}$, while that derived by the improved method is $230 \mu\text{H}$.

D. Load analysis

The generator equivalent circuit was constructed using the circuit constants derived from the existing and improved methods to perform the load analysis. Fig. 4 shows the output characteristic curve of the generator. Fig. 4(a) describes the output voltage-output current curve and Fig. 4(b) shows the output power-output voltage curve. Table II summarizes the error when the output characteristics derived from the existing and improved methods are compared with the FEM results according to the load resistance. The positive and negative errors indicated that the calculation results of the method used are greater and smaller than the FEM results, respectively. It can be seen that the FEM results agree well with the results of the equivalent circuit composed of the circuit constants derived using the improved method than existing method.

III. CONCLUSION

In this study, we present an improved analysis method for more accurate PMSG performance prediction. In order to apply the circuit parameter derivation method used in the wound synchronous machine to PMSG, the analysis was performed based on the rotational speed and not the field current. The equivalent circuit was constructed using the saturation reactance derived from the short circuit analysis. The validity of the proposed method was verified by comparing the output characteristics derived from the existing and improved methods with the FEM results. The improved method presented in this paper is very convenient for predicting the output characteristics more accurately in the initial design of the PMSG.

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