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ABSTRACT
This paper presents the magnetic field characteristics of a synchronous generator with a salient pole structure using a simple magnetic equivalent circuit (MEC) method. This method aims to reduce the analysis time considering nonlinearity. By using the MEC, a solution for the magnetic flux density is obtained. The linkage flux is derived using the magnetic flux density of the air gap and the armature voltage is obtained. Additionally, results obtained using the finite-element method and MEC are validated against experimental data.

I. INTRODUCTION
Global energy consumption has increased rapidly in recent decades. Improving energy efficiency using distributed energy resources (DERs) is a key area of study. The use of hydroelectric power in DER systems is also increasing.1 There are typically two types of hydropower generators: induction generators and synchronous generators. The wound-rotor synchronous generator (WRSG) can maintain the rated voltage according to the load fluctuation; it is optimal for hydropower generators as it can cope with the change in operation characteristics.2 The finite element method (FEM), which is high accuracy of analysis is a high accuracy method, is used to analyze the electromagnetic characteristics of a WRS; however, it has a disadvantage in that it takes a long time to improve the accuracy of the analysis. The magnetic equivalent circuit (MEC) method is an alternative to the FEM because it reduces analysis time and allows for a free design based on the design variables.3 This paper presents an MEC model for a 900-kW-class WRS considering nonlinearity. The MEC method can be used to obtain the magnetic flux density and the back electromagnetic flux (EMF). These results are compared to those obtained via the FEM and those obtained experimentally.

II. NONLINEAR MAGNETIC EQUIVALENT CIRCUIT MODEL OF WRS

Fig. 1 shows the analysis and experimental models of the rotor core considered in this paper. The model has an 8-pole 96-slot shape and consists of a shaft, rotor and stator. The stator core and rotor core are made of 50PN400 and SS400, respectively. DC current is applied to the rotor coil to make the electromagnet, and the rotor rotation by the turbine rotation induces the voltage in the stator winding. The specifications of the generator are summarized in Table I.

In order to analyze its electromagnetic characteristics, a nonlinear MEC model of WRS is established. Considering the periodicity, 2T poles and 24T slot combinations are used, where T is the number of periods, as shown in Fig. 2(a). For a simple nonlinear analysis, the stator structure is assumed to be slotless and the damper windings of the rotor pole tip are neglected. The
The reluctances considering the fringing effect are calculated as follows:

\[
R_{g1} = \frac{1}{\mu_o \left( \frac{2}{\pi} \ln \left( 1 + \frac{(r_f/2)(g/2)}{g} \right) \right) L_{stk}} + \frac{(g/2)}{\mu_o (w_{ph}/2) L_{stk}} \\
R_{g2} = \frac{1}{\mu_o \left( \frac{2}{\pi} \ln \left( 1 + \frac{(w_{ph}/2)(g/2)}{g} \right) \right) L_{stk}} + \frac{1}{\mu_o (w_{ph}/2) L_{stk}}
\]

where \( w_s \) is the length of the stator teeth, \( r_f \) is the radius of the air-gap and \( \theta_s \) is angle of the slot pitch. \( R_{g1} \) is the reluctance that includes the straight magnetic flux path and the magnetic flux path considering the fringing effect. \( R_{g2} \) is the reluctance that includes two magnetic flux paths considering the fringing effect. The magnetomotive force (MMF) of each rotor teeth can be expressed as follows:

\[
F_{rt} = N_{rt} I_{f} [F_{rt}] = [F_{r1}], [F_{r2}]^T
\]

To solve the nonlinear MEC, Kirchoff’s voltage law is applied to each closed loop to determine the magnetic flux of the closed loop. The system has the following form:

\[
[\phi]^T = [P][F]^T
\]

where \( P \) is the matrix of permeance, \( F \) is the matrix of the rotor MMF, and \( \phi \) is the matrix of the closed loop magnetic flux. The matrix of permeance is updated using the Newton–Raphson method to determine the relative permeability. Next, the Carter’s factor is calculated to take into account the slotting effect of the stator as follows:

\[
k_{cs} = \frac{2}{\pi} \left( \tan^{-1}(\frac{w_s}{2g}) - \frac{g}{w_s} (\log(1 + \frac{w_s}{2g})) \right), k_{car} = \frac{1}{1 - k_{cs} w_s / w_{ph}}
\]

The algorithm for this process is shown in Fig. 3.

### III. VERIFICATION OF MEC ANALYSIS

#### A. Electromagnetic characteristic analysis according to pole/slot combination

To verify the validity of this MEC method, in addition to the 8-pole 96-slot, the two-dimensional (2-D) FEM and MEC methods were compared using an 8-pole 48-slot, 12-pole 96-slot. Based on pole-pair and slot combination, a comparison of the air-gap flux density obtained using MEC and FEM is shown in Fig. 4(a). As the magnitude of the field current applied to the rotor windings increased, reasonable results were obtained when compared with the FEM results. The air-gap flux density waveforms obtained using the Carter’s factor and FEM are shown in Fig. 4(b), (c), and (d). As the air-gap length is multiplied by the Carter’s factor, the air-gap increases, reducing the magnitude of the maximum air-gap flux density. In particular, as the slot opening length increases, the Carter’s factor increases and the magnitude of the air-gap flux density considering the Carter’s factor decreases, as shown in Fig. 4(c).

### TABLE I. Specification of the 900kW-class WRSG.

| Parameter            | Value   |
|----------------------|---------|
| Pole/Slot            | 8/96    |
| Output Power         | 900kW   |
| Rated Speed          | 900 RPM |
| Terminal voltage     | 3300V   |
| Rated Current        | 185A    |
| Air-gap              | 7mm     |
B. Experimental results

By analyzing the air-gap flux density, the linkage flux to the windings of one phase can be derived as the fundamental wave. The linkage flux can be calculated as follows:

$$\lambda_a = k_w \cdot N_{ph} \cdot \Phi_{\text{air-gap}} \cdot \cos(\theta_{em})$$ (8)

where $k_w$ is the winding factor, $N_{ph}$ is the number of series turns per phase, and $\theta_{em}$ is the electrical angle. The armature voltage can be derived by differentiation of the linkage flux per phase according to...
the electrical rotation period, as follows:

\[ e_a = \frac{d\lambda_a}{dt} \]  

(9)

where \( t \) is the electrical rotation period (mm). Fig. 5(a) shows the basic waveform of the linkage flux derived from the air-gap flux density considering Carter’s factor. Fig. 5(b) shows a comparison of the magnitude of the armature voltage obtained from the result of the linkage flux. It can be seen that the error rate of the maximum line-to-line armature voltage between the 2-D FEM and the MEC results is low. Additionally, compared with experimental results, the FEM and MEC results show the same trend.
IV. CONCLUSION

This study analyzes the nonlinear electromagnetic characteristics of a wound-rotor synchronous generator using the MEC. To analyze a nonlinear MEC, reluctance calculations considering a mesh-based MEC configuration and a nonlinear analysis using the Newton–Rapson method were performed. The magnitude of the air-gap flux density according to the DC current magnitude was compared with the results of a 2-D FEM analysis. The magnitude of the armature voltage derived from the MEC was verified by 2D-FEM and experimental results. The comparisons show that the results obtained by the MEC, 2D-FEM, and experiments match reasonably well according to the DC current. Thus, the MEC method proposed in this paper is considered to be useful for the initial design of WRSGs.

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