An 18 slot, 8-pole Permanent Magnet Synchronous Generator for Small-Scale Wind Turbine Energy Conversion: Design, Fabrication, and Experiments

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Abstract. Compact permanent magnet synchronous generators (PMSGs) for renewable energy conversion are required for remote areas. In this work, an 18-slot, 8-pole PMSG (18S8P PMSG) was designed and fabricated for small-scale wind turbine energy conversion. Finite element analysis was conducted to assess the magnetic flux density distribution of the 18S8P PMSG prototype. The simulation results showed that most of the magnetic flux values were within 0.4–1.5 T, which was well below the saturation level for 35JN360 material. The magnetic flux intensities of the stator and rotor cores were within the optimal magnetic permeability range of the 35JN360 material. There were seven steps involved in fabricating the 18S8P PMSG prototype: (1) material cutting, (2) burring, (3) stacking, (4) welding, (5) coil winding, (6) configuration wiring, and (7) assembling. The electromagnetic performance results showed that the back electromotive force voltage of the 18S8P PMSG prototype seemed to be proportional to the rotor speed, where $K_E$ was 0.52 V⋅s/rad. The no load torque maximum of 18S8P PMSG is 1.7 N.m at 5000 rpm. The mechanical performance results showed that the highest power output (2500 W) was obtained for the 18S8P PMSG prototype at a rotor speed of 5000 rpm using the 20-Ω load model. The maximum efficiency of this prototype was 85.4%.

1. Introduction

The limited fossil fuel reserves and the growing awareness for clean energy resources has spurred the development of renewable energy technologies over the years. Small-scale wind turbines are the best solution for remote areas (which are located far from the power grid) as well as archipelagos such as Indonesia. In wind turbines, the wind power is converted into mechanical power through the aerodynamic effect of the rotor blades. Many studies have been carried out to optimize the structure and performance of permanent magnet synchronous generators (PMSGs).

Verde, Lastres [2018] Yousefian and Meshgin Kelk [2018]. To design a good PMSG, the following criteria need to be fulfilled: (1) the power output, torque, and efficiency need to be maximized and (2) the cogging torque needs to be minimized [3]. In this work, an 18-slot, 8-pole PMSG (18S8P PMSG) prototype was designed and fabricated. Two-dimensional FEA was conducted to assess the magnetic
flux distribution of the 18S8P PMSG internal structure. Finally, experiments were carried out to evaluate
the electromagnetic and mechanical performance of the 18S8P PMSG prototype.

2. Methodology

The methodology adopted in this work consisted of the following phases: (1) design of the 18S8P
PMSG prototype, (2) design, (2) FEA (which is a numerical method used to solve linear and nonlinear
partial differential equations [4]) to assess the magnetic flux density distribution of the 18S8P PMSG
internal structure, (3) fabrication, and (4) experimental testing to evaluate the electromagnetic and
mechanical performance. The 18S8P PMSG prototype was designed based on the specifications listed
in Table 1. The schematic of the 18S8P PMSG internal structure is shown in Fig. 1(a). The two-
dimensional finite element model of the 18S8P PMSG internal structure was meshed, as shown in Fig.
1(b). The 18S8P PMSG assembly model is shown in Fig. 2. The 18S8P PMSG prototype was fabricated
according to the following steps. First, the core material was cut using a laser cutting machine. Second,
the housing was fabricated using a computer numerical controlled (CNC) machine. Third, the rotor shaft
was formed using a lathe machine. Lastly, the 18S8P PMSG prototype was assembled manually. The
performance of the 18S8P PMSG prototype (i.e., electromagnetic and mechanical performance) was
tested using the experimental setup shown in Fig. 3. The instruments and equipment used for the
performance testing are presented in Table 2. The electromagnetic performance was assessed in terms
of the back electromotive force (BEMF) constant and torque constant at a rotor speed of 500–5000 rpm.
The BEMF constants was calculated using Eq. (1) [5]. The mechanical performance was assessed in
terms of the power output and efficiency.

\[ K_E = \frac{e}{\omega_n} \]  

Here, \( K_E \) is the BEMF constant, \( e \) is the BEMF, \( \omega_n \) is the rotor speed

| Table 1. Design specifications of the 18S8P PMSG prototype. |
|----------------------------------|
| Slots/Poles | 18/8 |
| Stator: outer diameter/inner diameter (mm) | 150/102 |
| Rotor: Outer diameter (mm) | 100 |
| Air gap (mm) | 1 |
| Stack length (mm) | 35 |
| Coil specifications (diameter/number of turns) | 1.0mm/36 |
| Coil connection | Y-3Ser2Par |
| Core material | 35JN360 |
| Magnet material | Neodymium NMX-48SH |

**Figure. 1** (a) Schematic of the 18S8P PMSG internal structure. (b) Meshing of 18S8P PMSG model in FEA.
Figure. 2 Schematic of the 18S8P PMSG assembly model.

Figure. 3 Schematic of experimental setup used to test the performance of the 18S8P PMSG prototype.
Table 2. List of instruments and equipment used to test the performance of the 18S8P PMSG prototype.

| No. | Measurement output | Instrument/Equipment                          | Brand                                      |
|-----|--------------------|-----------------------------------------------|--------------------------------------------|
| 1   | Voltage spectrum   | Signal oscilloscope and data acquisition recorder | Scope corder DL850EV, Yokogawa Test and measurement Corporation |
| 2   | Torque and speed   | Torque sensor and speed sensor                 | Magtrol SA Type:TM 310/011 |
| 3   | Current            | Ammeter                                       | Fluxe                                      |
| 4   | Voltage            | Voltmeter                                     | Fluxe                                      |
| 5   | Resistive load     | Ohmmeter                                      | Fluxe                                      |

3. Results and discussion

3.1. Finite element analysis

Fig. 4 shows the magnetic flux density distribution of the 18S8P PMSG prototype, where the red and white colors indicate the maximal and minimal magnetic flux densities, respectively. In general, the magnetic flux density was within a range of 0–2 T, and the maximal magnetic flux density was observed around the rotor tip. However, most of the magnetic flux densities of the 18S8P PMSG were within a range of 0.4–1.5 T. It is essential to analyze the magnetic flux density distribution to ensure that the prototype design was within the design capability of the materials.

Fig. 5 shows the comparison between the magnetic flux intensity values of the 18S8P PMSG stator and rotor cores and the magnetic flux density curve of the 35JN360 material. The magnetic flux intensities of the 18S8P PMSG stator and rotor cores were within the optimal flux density range (0.1–1.5 T) of the 35JN360 material. The magnetic flux intensities of the 18S8P PMSG stator and rotor cores were well below the magnetic saturation level of the 35JN360 material. The saturation level of the ferromagnetic material resulted in a lower magnetic flux density even when the rotor speed of the 18S8P PMSG prototype was increased. According to Clegg, Beckley [2003] materials with lower saturation flux density requires a larger core cross-sectional area to carry the magnetic flux. Fig. 6 shows the comparison between the magnetic flux intensities of the 18S8P PMSG stator and rotor cores and the relative permeability curve of the 35JN360 material. Magnetic permeability is a measure of the ease with which magnetic flux flows through a material [7]. The magnetic flux intensities of the 18S8P PMSG stator and rotor cores were within the optimal relative permeability range of the 35JN360 material.
Comparison between the magnetic flux intensity values of the 18S8P PMSG stator and rotor cores and the magnetic flux density curve of the 35JN360 material.

Comparison between the magnetic flux intensity values of the 18S8P PMSG stator and rotor cores and the magnetic permeability of the 35JN360 material.

Fabrication of the 18S8P PMSG prototype

Fig. 7 shows the fabrication process of the 18S8P PMSG prototype. There were seven steps involved in fabricating the 18S8P PMSG prototype: (1) material cutting, (2) burring, (3) stacking, (4) welding, (5) coil winding, (6) configuration wiring, and (7) assembling. First, the 35JN360 material sheets (used for the stator and rotor cores) were cut using a laser cutting machine. The material sheets for the rotor and stator were stacked and welded so that the 18S8P PMSG components can be tightened at the designated points.

Steps involved in fabricating the 18S8P PMSG prototype.

Analysis of the 18S8P PMSG prototype performance

Fig. 8 and 9 show the BEMF voltage and torque of the 18S8P PMSG prototype, respectively. Based on the results, both the BEMF voltage and torque appeared to be proportional to the rotor speed. BEMF is generated from changes in the magnetic flux and it can be expressed by the product of the BEMF constant and rotor speed. BEMF is the difference between the terminal voltage and the neutral voltage.
of the non-energized phase because there is no current flow in the non-energized phase [5]. The BEMF constant, $K_E$ was determined to be 0.52 V⋅s/rad. The no load torque maximum of 18S8P PMSG is 1.7 N.m at 5000 rpm. This torque is resulted by mechanical losses, cogging and core losses.

![Figure 8](image1)

**Figure. 8** BEMF voltage of the 18S8P PMSG prototype at different rotor speeds (500–5000 rpm).

![Figure 9](image2)

**Figure. 9** Torque of the 18S8P PMSG prototype at different rotor speeds (500–5000 rpm).

Fig. 10 shows the power output of the 18S8P PMSG prototype at different rotor speeds. In general, the power output of the 18S8P PMSG increased as the rotor speed increased. For the lowest resistive load model (10 Ω), the highest power output was attained at 3500 rpm, with a value of 2000 W. The maximum power output (2500 W) was achieved for the 20-Ω load resistive model at a rotor speed of 5000 rpm. Owing to the wire current capacity limitation, the lowest resistive load model (10 Ω) was not tested at rotor speeds of more than 3500 rpm.

![Figure 10](image3)

**Figure. 10** Power output of the 18S8P PMSG prototype at different rotor speeds.

Fig. 11 shows the efficiency of the 18S8P PMSG prototype. Overall, the efficiency increased with an increase in the rotor speed. The efficiency of the 18S8P PMSG prototype was highest for the 20-Ω resistive load model whereas the lowest efficiency was obtained for the 100-Ω resistive load model. The highest efficiency of the 18S8P PMSG prototype was 85.4%.
4. Conclusion

In this work, an 18S8P PMSG prototype was designed and fabricated for small-scale wind turbine energy conversion, and experiments were conducted to analyze its performance. Based on the FEA results, the magnetic flux density of the 18S8P PMSG prototype was within 0.4–1.5 T, which was well below the magnetic saturation level for 35JN360 material. The magnetic flux intensities of the 18S8P PMSG stator and rotor cores were within the optimal magnetic permeability of the 35JN360 material. There were seven steps involved in fabricating the 18S8P PMSG prototype: (1) material cutting, (2) burring, (3) stacking, (4) welding, (5) coil winding, (6) configuration wiring, and (7) assembling. The electromagnetic performance results revealed that the BEMF voltage and torque of the 18S8P PMSG prototype seemed proportional to the rotor speed, where $K_E$ was found to be 0.52 V⋅s/rad. The mechanical performance results showed that the power output of the 18S8P PMSG prototype was highest (2500 W) at a rotor speed of 5000 rpm for the 20-Ω resistive load model. The maximum efficiency of the 18S8P PMSG prototype was 85.4%.

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