

# Characteristic Analysis of 10kw Wind Turbine Generator According to Pole/Slot Number Combination

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## Abstract

**Background/Objectives:** Modern society has become very dependent on renewable energy, due to both the depletion and environmental problems of fossil energy.

**Methods/Statistical analysis:** Permanent magnet generators vary in performance, depending on their pole/slot combinations. Therefore, in this paper, we compared the characteristics of permanent magnet generators, according to their pole/slot combination. The investigation was conducted using a finite element analysis (FEA) method, and the experiment was validated utilizing an improved version of our previously designed generator and pole/slot combination.

**Findings:** In this paper, two configurations of pole/slot combinations are presented, because of their different characteristics, as highlighted by our analysis. The generator, which was manufactured before the improvements, had an output power of 10kW, with 56 poles and 63 slots. To improve this basic generator, the performance was predicted through finite element analysis (FEA). First, we compared the FEA with the no-load results of the basic model, which verified the reliability of the analysis. Next, the pole/slot combination was changed to 48 poles and 54 slots, with the results analyzed for both no-load and load conditions. To reduce the cogging torque, we adjusted the permanent magnet ratio and applied a chamfering effect, then analyzed the balance of the generators by comparing the radial force density. Finally, an improved model was fabricated and compared with the experimental results to demonstrate its validity.

**Improvements/Applications:** As a result of improving the performance of the generator, this paper can be referenced when manufacturing and improving electric devices.

**Keywords:** Chamfering effect, cogging torque, FE analysis, permanent magnet generator, permanent magnet ratio.

## 1. Introduction

Recently, due to global warming and energy depletion caused by the indiscriminate use of fossil fuels, research into renewable energy has increased globally. Dual solar energy systems have a disadvantage due to the large difference in solar radiation between night and day. In addition, systems that use wave energy are difficult to manufacture [1]. Wind generators are usually divided into two types. The disadvantage of the DFIG is that it has a gear box. The PMSG configuration has many advantages [2]. Since the introduction of NdFeB permanent magnets (PMs), their potential for use in electrical machines has been researched. This is because they have various advantages for improving performance, including volume miniaturization and high power density [3]. Wind turbine generators are used to extract wind energy. A wind turbine generator can be split up three sections: blades, generator, and tower. The initial design stage of developing dual-rotor wind turbines is very important, as mistakes here can lead to catastrophic failure and potentially serious accidents.

In this paper, we analyzed the characteristics of wind turbines according to their combination of poles and slots. The pole/slot combinations analyzed were 56 poles/63 slots and 48 poles/54 slots. The 56 pole/63 slot generator used in this analysis was an

existing design. To improve this generator, the design was changed to 48 poles/54 slots, and the characteristics of these two combinations were analyzed and compared. Through all the comparisons, it was possible to confirm the characteristics according to the pole/slot combination, and to prove the reliability of the design improvement process. In particular, the improved generator used an adjusted PM ratio and chamfering effect to reduce bad factors. Further, the weight of the generator was reduced by altering the pole/slot combination [4].

## 2. Verification of the Basic Model Analysis

The two pre-fabricated pole/slot combinations presented in this paper are 56/63 and 48/54, which are the commonly used 8:9 combinations. The 56/63 combination is called the "basic model" in this paper. For an exact comparison of the two combinations, we limited the size of the stator to be equal to (or less than) the stator diameter of the basic model. The basic model is shown in Fig. 1. Figures 1 (a) and 1 (b) show the FE Analysis model and the magnetic flux density distribution, respectively. Table 1 shows the design parameters of the basic model. To ensure the reliability of the optimal design presented in this paper, the FE Analysis was conducted with reference to Table 1.

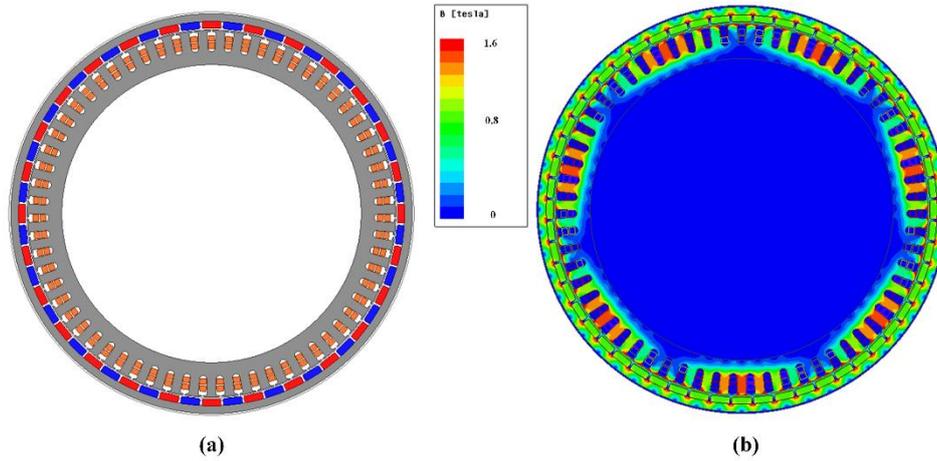


Figure 1: FE Analysis model of the PMSG: (a) basic model, (b) magnetic flux density

Table 1: Specification of basic model design

Parameter	Value	Parameter	Value
Rate Speed	150 rpm	Phase / layer	3/2
Stack Length	225 mm	Winding Distribution	ABB'BCC'CAA'
Number of Slots	63	Number of poles	56
Winding specification	2.45 mm	PM	N35SH

### 2.1. FEA Analysis of no-Load Basic Model

As mentioned above, the FE Analysis was conducted using the information in Table 1. First, the line voltage as a function of speed [rpm] of the basic model is shown in Figure 2. Here, the permanent magnet was N35SH, and the  $B_r$  value was 1.17 [T]. Figure 2 shows that the analytical results are in similar as the two method results. Figure 3 shows the experimental and FE Analysis results for counter-electromotive force and line-to-line voltage, respectively. Table 2 shows the FE Analysis results at the rated speed. Therefore, we can confirm that the no-load results of the basic model.

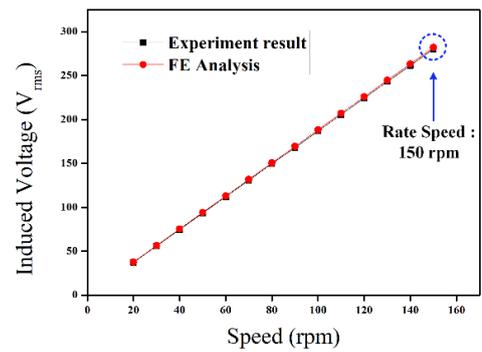


Figure 2: Comparison of experimental results and FE Analysis results according to the speed of the basic model

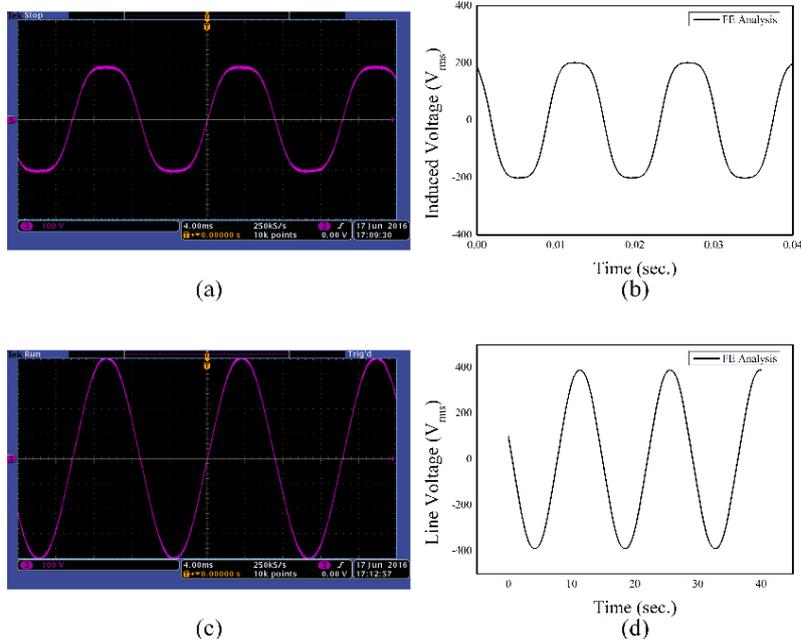


Figure 3: No-load back-EMF of the basic model: (a) experiment result [ $V_{rms}$ ], (b) FE Analysis [ $V_{rms}$ ], (c) experiment result [ $V_{line\_line}$ ], (d) FE Analysis [ $V_{line\_line}$ ]

**Table 2: No-load FE Analysis result of basic model**

Parameter	Value
Emf [V <sub>max</sub> ]	200.696
Emf [V <sub>rms</sub> ]	166.212
Emf [V <sub>rms</sub> ]	282.187
Cogging Torque [Nm]	2.753
Inductance [mH]	3.77E-0

## 2.2. Verification of FEA Analysis for the Basic Model with an AC Load

To obtain an FE Analysis result for the basic model under load, the phase resistance value must be calculated. The phase resistance can be predicted by using Equation (1):

$$R_{phase} = \rho_0 \frac{l_w}{A_c} \quad (1)$$

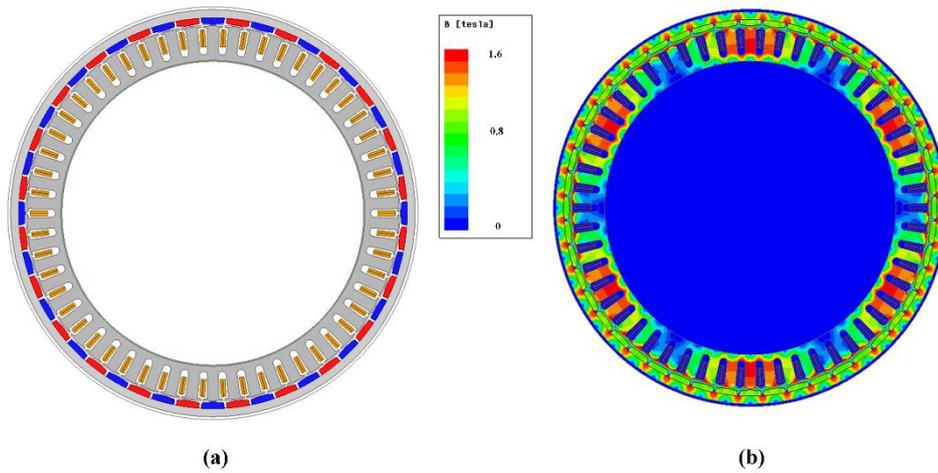
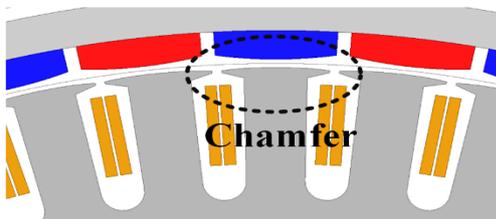
Where  $\rho_0$  is the resistivity of coil (copper),  $l_w$  is the total length of the windings, and  $A_c$  is the cross-sectional area of the windings. Table 3 shows the FE Analysis results with an ac load. The results indicated that the efficiency was very low and the mass was very high. All these results demonstrated the reliability of our method of interpretation, which meant that the improved design could be implemented, as described in the following section.

**Table 3: Velocity and force error result according to gear ratio**

Parameter	Value
Phase Load [ohm]	0.58
External Load [ohm]	5.8
V <sub>load</sub> [V <sub>rms</sub> ]	268.791
I <sub>ph</sub> [A]	24.322
V <sub>i</sub> [V <sub>rms</sub> ]	138.901
Current density [A/mm <sup>2</sup> ]	5.159
Eddy current Loss [W]	9.729
CoreLoss [W]	121.935
CopperLoss [W]	1029.28
Total Loss [W]	1160.944
Output Power [W]	10013.026
Efficiency [%]	89.61
Total Mass [kg]	108.696

## 2.3. No-Load Analysis of Improved Design Model

The key factors affecting the improved design were as follows; maintain (or reduce) the outer size of the stator, and adjust the shape of the permanent magnet, slot, and length of the stack. These adjustments would both reduce the weight, and improving efficiency. Finally, we analyzed the radial force density of the improved model. Figure 5 shows the 48/54 combination as the improved design model. The improved model had a chamfering effect on the PM and teeth of the slots, to reduce the cogging torque. This also maintains the counter electromotive force and inductance. In particular, the optimum shape of chamfering on the PM and the teeth of the slots were selected by parametric analysis. The optimum shape is shown in Figure 5, and Table 4 shows the no load results.

**Figure 4: FE Analysis model of the PMSG: (a) improved design model, (b) magnetic flux density****Figure 5: Shape of the chamfering effect on the permanent magnet and the teeth of the slot****Table 4: No-load FE Analysis result of the improved design model**

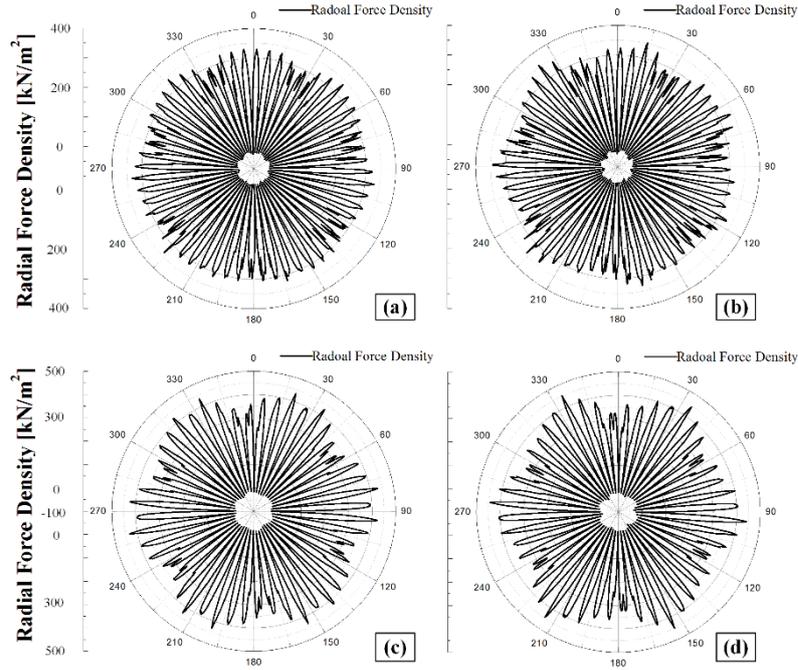
Parameter	Value
Emf [V <sub>max</sub> ]	204.8680
Emf [V <sub>rms</sub> ]	161.0041
Emf [V <sub>rms</sub> ]	277.5631
Cogging Torque [Nm]	2.3822
Inductance [mH]	4.60E-03

## 2.4. Comparative Analysis of AC Load and Radial Force Density of the Improvement Design Model

Table 5 shows the results of the ac load analysis of the improvement design model. It can be obtained that the efficiency increased by approximately 5%, and the overall weight was reduced by approximately 30 kg. This resulted in the stack length of the basic model being reduced by 50 mm. Figure 6 shows the results of the radial force density analysis of the best-fit design model. The excitation circle is one method for predicting the balance between the outer core and the inner core, by analyzing the vibration and noise of a rotating machine. Radial Force Density (RFD) can be obtained by using Equation (2) [5-7]:

$$F_{rad} = \frac{1}{2\mu_0} (B_n^2 - B_t^2) \quad (2)$$

Where  $\mu_0$  is the mean permeability in a vacuum,  $n$  is the normal component, and  $t$  is the tangential component.



**Figure 6:** The Radial Force Density: (a) NO load (basic model), (b) AC load (basic model), (c) NO load of the Improved Design Model, (d) AC load of the Improved Design Model.

**Table 5:** Velocity and force error result according to gear ratio

Parameter	Value
Phase Load [ohm]	0.58
External Load [ohm]	5.8
V_load [V <sub>rms</sub> ]	268.791
I <sub>ph</sub> [A]	24.322
V <sub>t</sub> [V <sub>rms</sub> ]	138.901
Current density [A/mm <sup>2</sup> ]	5.159
Eddy [W]	9.729
CoreLoss [W]	121.935
CopperLoss [W]	1029.28
Total Loss [W]	1160.944
Output Power [W]	10013.026

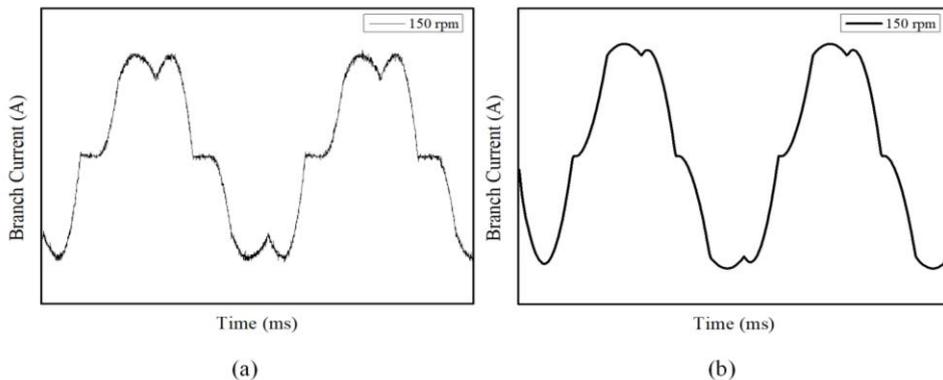
Efficiency [%]	89.61
Total Mass [kg]	108.696

**2.5. Experimental Verification of Improved Design Model**

Figure 7 shows the completed improved design model. Figure 8 shows the current waveform in the DC load analysis of the fabricated model, and the results are same that. Thus, the analysis results proved the validity of the improvement design model.



**Figure 7:** The Completed Improvement Design Model



**Figure 8:** Current Waveform at DC load: (a) Experimental Result, (b) FE analysis Result

### 3. Conclusion

In this paper, an improved design of the basic model was carried out. First, after proving the reliability of the FE Analysis results, the optimal pole/slot combination was selected based on the results. Second, the shape of the PM and teeth were changed and optimized. This will be cited as a reference design for the optimization initial design of the PMSG.

### Acknowledgment

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