Optimal Design of a Distributed Winding Type Axial Flux Permanent Magnet Synchronous Generator

Yong-min You*, Hai Lin** and Byung-il Kwon†

Abstract – This paper presents a distributed winding type axial flux permanent magnet synchronous generator (AFPMSG) with reduced the total harmonic distortion (THD), suitable for wind turbine generation systems. Although the THD of the proposed distributed winding type is more reduced than the concentrated winding type, the unbalance of the phase back EMF occurs. To improve the unbalance of the phase back EMF and the output power of the distributed winding type AFPMSG, the Kriging based on the latin hypercube sampling (LHS) is utilized. Finally, these optimization results are confirmed by experimental results. As a result, the unbalance of the phase back EMF and the output power of the distributed winding type AFPMSG were improved while maintaining the total harmonic distortion (THD) and the average phase back EMF.

Keywords: Axial flux permanent magnet synchronous generator, Optimal design, Kriging model

1. Introduction

Distributed windings have been used extensively in permanent magnet synchronous motors (PMSMs) because this generally results in a more sinusoidal magneto motive force (MMF) distribution and EMF waveform. On the other hand, PMSMs with a concentrated winding have been gaining interest over the last few years. These include high power density, high efficiency, short end turns and a simple structure. In addition, motor size as well as copper loss can be reduced [1, 2].

In general, coreless stator type axial flux permanent magnet synchronous generators (AFPMSGs) with concentrated windings have been mostly used for small wind turbine systems [3, 4]. However, contrary to typical permanent magnet synchronous machines, use of the concentrated winding type in coreless stator type AFPMSGs has no benefits except easy manufacture compared to the distributed winding type because the end turns of the coils are not an issue. Most importantly, a concentrated winding type AFPMSG can cause harmonic distortion. These harmonics shorten the expected life of the wind energy converter and battery. To overcome these problems, production costs are increased because a reactor is required. In addition, they lead to noise, vibration, copper loss and eddy current loss in the magnet [5].

To reduce the harmonics caused by the concentrated winding type AFPMSG, a distributed winding type AFPMSG is proposed in this paper. The Kriging model based on the latin hypercube sampling (LHS) is used for optimization of a distributed winding type AFPMSG. Finally, experimental results are presented and discussed.

2. Distributed Winding Type AFPMSG for Reducing the Total Harmonic Distortion

2.1 Structures and specifications

Fig. 1 shows the structures of a concentrated winding type and a distributed winding type AFPMSG. The A, B, and C phase stator windings of a typical concentrated winding type are arrayed periodically in a circumferential direction as shown in Fig. 1(a). In contrast, those of a distributed winding type are arrayed periodically in the axial direction as shown in Fig. 1(b).

Table 1 presents the specifications of three phase AFPMSGs. The number of coils in the concentrated winding type and the distributed winding type are 9 and 24, respectively. Considering the winding factor and the number of coils, the number of poles in these winding types is 24 and 32, respectively. To compare the performance under the same conditions, the volumes of the coils and permanent magnets in the AFPMSGs are the same.

2.2 Characteristic analysis

Although the analytical method, the equivalent circuit model and the 2D FEM have been used for analysis of AFPMSG [3, 4, 6], the 3D FEM is utilized for accuracy. JMAG-studio ver.10 is utilized as 3D FEM tool. Fig. 2 shows the flux density distribution of AFPMSGs at 1,200 rpm which is the rated speed.
Fig. 3 and Table 2 present the analysis results which show the phase back EMF for one cycle of the electric angle at 1,200 rpm. The average phase back EMF of the distributed winding type AFPMSG is almost equal to that of the concentrated winding type AFPMSG. The fundamental component of the phase back EMF of the distributed winding type AFPMSG is 94.1%, which is 0.9% larger than that of the concentrated winding type. The total harmonic distortion (THD) of the phase back EMF of

Table 1. Specification of AFPMSGs

<table>
<thead>
<tr>
<th>Items</th>
<th>Unit</th>
<th>Concentrated winding</th>
<th>Distributed winding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated output power</td>
<td>kW</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>Number of coils</td>
<td>-</td>
<td>9</td>
<td>24</td>
</tr>
<tr>
<td>Number of poles</td>
<td>-</td>
<td>24</td>
<td>32</td>
</tr>
<tr>
<td>Outer diameter height</td>
<td>mm</td>
<td>Ø163.5</td>
<td>46</td>
</tr>
<tr>
<td>Air-gap</td>
<td>mm</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>Outer diameter of conductor</td>
<td>mm</td>
<td>Ø0.4 (8 parallel wires)</td>
<td></td>
</tr>
<tr>
<td>Turns of conductor per coil</td>
<td>-</td>
<td>132</td>
<td>52</td>
</tr>
<tr>
<td>Resistance per coil</td>
<td>Ω</td>
<td>0.254</td>
<td>0.1</td>
</tr>
<tr>
<td>Residual flux density of the PM</td>
<td>T</td>
<td>1.353</td>
<td></td>
</tr>
<tr>
<td>Volume of the PM</td>
<td>cm³</td>
<td>135</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 1. Structures of AFPMSGs (exploded view)

Fig. 2. Flux density distribution of AFPMSGs at 1,200 rpm

Fig. 3. Phase back EMF of AFPMSGs at 1,200 rpm
the distributed winding type is 1.319%, which is 0.257 % smaller than that of the concentrated winding type AFPMSG. These results show that the distributed winding type has a more sinusoidal back EMF waveform than the concentrated winding type.

However, unbalance of the phase back EMF occurs in the distributed winding type AFPMSG. The back EMF of phase B of the distributed winding type is lower than that of phase A and C because it has a low magnetic flux density located between the upper and lower parts of the permanent magnets.

To analyze the performance of the AFPMSGs with speed, a three-phase diode bridge with a load resistance (8 Ω) is utilized. The variations in the line voltage and the output power characteristics of variable-speed AFPMSGs are shown in Fig. 4. The performance of the distributed winding type AFPMSG is similar to that of the concentrated winding type AFPMSG.

### 3. Optimal Design for Improvement of the Unbalance of the Back EMF and the Output Power

#### 3.1 Optimization techniques

The Kriging model is a group of geostatistical techniques used to interpolate the value of a random field. In this use of the Kriging model, the estimated equation was defined to eliminate bias and thereby minimize error variance [7]. The Kriging model is a weighted linear combination as follows.

\[
z^* = \sum_{i=1}^{n} \lambda_i z_i
\]

where \(z^*\) is an estimated point using the Kriging model, \(n\) is the total number of experiments, \(\lambda_i\) is the weight value function, and \(z_i\) is the experimented point.

The minimized error deviation of the Kriging model can be expressed as

\[
\text{Minimize } \sigma_{OK}^2 = \sigma^2 - 2 \sum_{i=1}^{n} \lambda_i \sigma_{0i}^2 + \sum_{i=1}^{n} \sum_{j=1}^{n} \lambda_i \lambda_j \sigma_{ij}^2
\]

\[\text{With a constraint } 1 \sum_{i=1}^{n} \lambda_i = 0\]

where \(\sigma_{OK}^2\) is a error variance of the Kriging model, \(\sigma^2\) is a variance of \(z_0\), \(\sigma_{0i}^2\) is a covariance of \(z_0\) and \(z_i\), \(\sigma_{ij}^2\) is a covariance of \(z_i\) and \(z_j\), \(z_0\) is a real value to predict.

When the error deviation of the Kriging model is minimized, it can be expressed as

\[
L(\lambda_1, \lambda_2, ..., \lambda_n; \omega) = \sigma^2 - 2 \sum_{i=1}^{n} \lambda_i \sigma_{0i}^2 + \sum_{i=1}^{n} \sum_{j=1}^{n} \lambda_i \lambda_j \sigma_{ij}^2 + 2 \omega \left(1 - \sum_{i=1}^{n} \lambda_i\right)
\]

where \(L(\lambda_1, \lambda_2, ..., \lambda_n; \omega)\) is a Lagrange objective function, \(\omega\) is a Lagrange factor and the coefficient 2 is used for convenience.

The objective function is calculated by a partial derivative of Lagrange factor with respect to \(\lambda\) and \(\omega\) as follows.

\[
\sum_{i=1}^{n} \lambda_i \sigma_{il}^2 - \omega = \sigma_{0l}^2, \quad l = 1, 2, \ldots, n
\]
The error deviation of the Kriging model can be expressed as

$$\sigma_0^2 = \text{Var}(z) = \sum_{i=1}^{n} \lambda_i \text{Cov}(z_0, z_i) + \omega = \lambda^T \sigma^2 \lambda + \omega$$

(5)

where $\sigma_0 = \text{Cov}(z_0, z_i)$. The parameter can be estimated by minimizing the Lagrange object function.

LHS is a space filling design, which tends to uniformly sample points in the whole parameter space. To effectively construct the Kriging model, the LHS is also used for improved accuracy over random sampling and stratified sampling to estimate the means, deviations and distribution functions of an output. Moreover, it ensures that each of the input variables represent all portions of its range.

3.2 Optimization process

Fig. 5 shows the optimal design process to optimize effectively the distributed winding type AFPMSG. The LHS is applied as a method of the design of experiment (DOE) and the Kriging model is used to approximate the objective and constraints functions. Genetic algorithm (GA) is utilized as the optimization algorithm.

3.3 Objective functions, constraints and design variables

To improve the unbalance of the phase back EMF and the output power, the objective function and constraints are established as Eq. (6) and (7), respectively. The objective functions are to reduce the unbalance of the phase back EMF from 9.3 V to below 5 V and to maximize the output power of the distributed winding type AFPMSG. The constraints are the average phase back EMF, THD, and line current considering the performance of the initial model. To satisfy the objective function and the constraints, the design variables are decided as shown in Eq. (8) and Fig. 6.

The total number of the design of experiment (DOE) is 25, taking into account the number of design variables.

- Objective functions (at 1,200 rpm)
  The unbalance of the phase back EMF $\leq 5$ V
  Maximize the output power

- Constraints (at 1,200 rpm)
  The average phase back EMF $\geq 50$ V
  THD of the phase back EMF $\leq 1.35\%$
  Line current $\leq 11$ A

- Design variables
  \(42 \leq X_1\ (\text{Turns per coil of phase A and C}) \leq 62\)
  \(42 \leq X_2\ (\text{Turns per coil of phase B}) \leq 62\)
  \(0.5345 \leq X_3\ (\text{Pole arc to pole pitch ratio}) \leq 0.7345\)
  \(6\ mm \leq X_4\ (\text{Thickness of permanent magnet}) \leq 14\ mm\)

3.4 Optimization results

The optimal values of the design variables, by using the Kriging model based on the LHS, are determined as Table 3. The optimized results are verified by 3D FEM as shown in Table 3 and Fig. 7, and they show that the unbalance of the phase back EMF was reduced by 6.8 V compared to the initial model. The output power of the optimized model was also improved by 96 W compared to the initial model.

Table 3. Optimal design results at 1,200 rpm

<table>
<thead>
<tr>
<th>Items</th>
<th>Unit</th>
<th>Distributed winding (3D FEM)</th>
<th>Optimized (3D FEM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design variables</td>
<td>X1</td>
<td>Turns</td>
<td>52 (Ø0.4)</td>
</tr>
<tr>
<td></td>
<td>X2</td>
<td>turns</td>
<td>52 (Ø0.4)</td>
</tr>
<tr>
<td></td>
<td>X3</td>
<td>-</td>
<td>0.6345</td>
</tr>
<tr>
<td></td>
<td>X4</td>
<td>mm</td>
<td>10.0</td>
</tr>
<tr>
<td>Phase back EMF</td>
<td>phase A</td>
<td>Vrms</td>
<td>53.1</td>
</tr>
<tr>
<td></td>
<td>phase B</td>
<td>Vrms</td>
<td>43.8</td>
</tr>
<tr>
<td></td>
<td>phase C</td>
<td>Vrms</td>
<td>53.1</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>Vrms</td>
<td>50.0</td>
</tr>
<tr>
<td></td>
<td>Unbalance</td>
<td>Vrms</td>
<td>9.3</td>
</tr>
<tr>
<td>THD</td>
<td>%</td>
<td>1.319</td>
<td>1.323</td>
</tr>
<tr>
<td>Line current</td>
<td>Irms</td>
<td>11.0</td>
<td>11.4</td>
</tr>
<tr>
<td>Output power</td>
<td>W</td>
<td>953</td>
<td>1,049</td>
</tr>
</tbody>
</table>
The optimized model also maintains the average phase back EMF and THD of the initial model. The line current of the optimal model is 11.4 A, and it is slightly out of the constraint of the optimization process due to the error between the predicted value of Kriging model and the verified value by 3D FEM.

4. Experimental results

To verify the accuracy of the optimization results, a prototype of the optimized distributed winding type AFPMSG was built and tested as shown in Fig. 8. The unbalance of the phase back EMF of the optimized model was improved compared with the initial model as shown in Fig. 9. There is good agreement between the analytical and experimental results as described in Table 4 and Fig. 10.

![Fig. 7. Phase back EMF of the optimized model at 1,200 rpm](image)

### Table 4. Analytical and experimental results at 1,200 rpm

<table>
<thead>
<tr>
<th>Items</th>
<th>Unit</th>
<th>Initial</th>
<th>Optimized</th>
</tr>
</thead>
<tbody>
<tr>
<td>phase A</td>
<td>Vrms</td>
<td>53.1</td>
<td>54.4</td>
</tr>
<tr>
<td>phase B</td>
<td>Vrms</td>
<td>43.8</td>
<td>42.7</td>
</tr>
<tr>
<td>phase C</td>
<td>Vrms</td>
<td>53.1</td>
<td>49.7</td>
</tr>
<tr>
<td>Average</td>
<td>Vrms</td>
<td>50.0</td>
<td>48.9</td>
</tr>
<tr>
<td>Unbalance</td>
<td>Vrms</td>
<td>9.3</td>
<td>9.37</td>
</tr>
<tr>
<td>Line current</td>
<td>Irms</td>
<td>11.0</td>
<td>10.8</td>
</tr>
<tr>
<td>Output power</td>
<td>W</td>
<td>953</td>
<td>949</td>
</tr>
</tbody>
</table>

![Fig. 8. Prototype and experimental setup to test AFPMSG](image)

5. Conclusion

This paper has presented the structure of a distributed winding type AFPMSG that can reduce harmonic distortion. The distributed winding type has a smaller THD value compared to the concentrated winding type AFPMSG. The
line voltage and the output power of the distributed winding type AFPMSG were almost equal to those of the concentrated winding type AFPMSG.

To optimize the distributed winding type AFPMSG, the Kriging model based on the LHS is applied. The optimized results show that the unbalance of the phase back EMF is decreased and the output power is increased. The optimization results are confirmed by experimental results. From these results, the proposed distributed winding type AFPMSG shows sufficient applicability to wind turbine systems.

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References


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