Novel rotor design of dual-stator brushless doubly fed generator based on surrogate model

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Abstract
Dual-stator brushless doubly fed generator (DSBDFG) is a novel generator applied for wind power generation, and the electromechanical energy conversion between the stator and rotor is realised by the magnetic field modulation of the special rotor structure. Therefore, the rotor design is critical to improve the performance of DSBDFG. In this study, the different rotor structures are compared and analysed, and the position of the non-magnetic ring is determined. In order to reduce the computational cost and improve the optimisation efficiency, the surrogate model coupled with the multi-island geometric algorithm is applied for the optimisation of the magnetic barrier layer of the cage barrier rotor. In addition, in order to reduce the effect of skin effect on the copper loss of cage bars of the rotor, the different simulation models, whose cage bars have different layer number, are simulated and analysed. Finally, the simulation and experimental results verify the correctness of the theoretical analysis and the effectiveness of surrogate model used for the rotor optimisation design of DSBDFG.

1 | INTRODUCTION

In recent years, renewable energy power generation, especially large-scale offshore wind power generation, has been developing rapidly because of the scarcity of tradition energy and environment pollution [1]. The mainly traditional generators, which have been used for offshore wind power generation, are doubly fed induction generator (DFIG) and permanent magnet synchronous generator (PMSG). Due to the brush and slip ring, the operation reliability of DFIG is lower, and then higher maintenance costs are required [2]. Recently, the price of rare-earth permanent magnet (PM) fluctuated greatly, and PM is prone to demagnetisation under the action of salt spray [3]. In addition, the direct drive (DD) PMSG has a large volume and requires a full power converter. Besides, the dual-stator winding induction generator (DSWIG) [4, 5], which has two stator windings with the same pole in the stator slot, is also applied to the wind turbine. The output power of the power winding of DSWIG is direct current, which needs to be converted into alternating current (AC). In addition, the power winding is connected with AC excitation capacitor and rectifier. Therefore, the system with DSWIG is complex. In conclusion, the traditional generators cannot meet the higher requirements put forward by large scale offshore wind power generation. Brushless doubly fed generator (BDFG) [6, 7], in which the advantages are no brush and slip ring, easy to realise DD, small capacity of the required converter and so on, has been becoming the research hotspot of the offshore wind power generator. In order to make full use of the inner space of large-scale wind power application and improve the power density of BDFG further, dual-stator BDFG (DSBDFG) is proposed in this study.

It is well known that the rotor has an important effect on the performance of BDFG because the coupling of two stator winding is realised by the special rotor structure. Many scholars have done a lot of research work on rotor design and optimisation for BDFG. In [8], a ‘double sine’ wound rotor for BDFG [6, 7], in which the advantages are no brush and slip ring, easy to realise DD, small capacity of the required converter and so on, has been becoming the research hotspot of the offshore wind power generator. In order to make full use of the inner space of large-scale wind power application and improve the power density of BDFG further, dual-stator BDFG (DSBDFG) is proposed in this study.

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With the rapid development of computer technology, many novel optimisation methods have been proposed. Especially, the surrogate model, which can reduce the computational costs of optimisation, has been becoming the hotspot and applied in multiple areas. In recent years, the surrogate model has also been used in the motor design area. In [11], the optimisation design of DFIG for maximum output power based on the surrogate optimisation algorithm was presented. To optimise an interior PM synchronous motor for an electric vehicle, a new surrogate-assisted multi-objective optimisation algorithm was proposed in [12]. In order to improve the sensorless control capacity, a novel multi-objective evolutionary algorithm based on the surrogate model was applied to optimise a surface mounted PM motor in [13]. An efficient model based on Kriging model to optimise the air-gap flux density waveform of flywheel motor has been established in [14].

In this study, surrogate model based on finite element analysis (FEA), which can improve the optimisation efficiency, is applied for optimisation of the magnetic barrier layer of cage barrier rotor, and the cage bars with several layers are used to reduce the effect of skin effect on the copper loss of the rotor. The remainder of this study is structured as follows. In Section 2, the basic construction of DSBDFG is introduced, and the different rotor topologies are compared and analysed. In Section 3, the position of the non-magnetic ring is determined, and four geometric parameters of the magnetic barrier layer are optimised based on the surrogate model with multi-island geometric algorithm (MIGA). In addition, the different simulation models with different layer number are simulated and compared. In Section 4, the simulation and experimental results are presented to verify the theoretical analysis. Finally, the conclusions are summarised in Section 5.

2 | BASIC CONSTRUCTION, OPERATION PRINCIPLE, AND ROTOR TOPOLOGY

2.1 | Basic construction

DSBDFG consists of two stators and one share rotor (concludes non-magnetic ring, outer and inner layer), and its basic construction and schematic block diagram shown are shown in Figures 1 and 2. Both inner and outer stator slots own two sets of windings, that is, power winding (PW) and control winding (CW). The PW (CW) of inner and outer stator have the same pole pair number. In addition, the PW (CW) of outer and inner stator are connected in series.

2.2 | Operation principle

The operation principle of DSBDFG is different from the traditional wind power generators. The frequency of generation power (i.e. the frequency of PW) of DSBDFG is as follows [15]:

\[ f_p = \frac{n (p_p + p_c)}{60} \pm f_c \]  

(1)

where \( p_p \) and \( p_c \) are the pole pair number of PW and CW, \( n \) is the rotation speed, \( f_c \) and \( f_p \) are the frequency of CW and PW, ‘±’ is determined by the phase sequence of the PW and CW.

According to Equation (1), it can be clearly seen that the \( f_p \) is related to the \( n \) and \( f_c \). Therefore, the \( f_p \) can be maintained by adjusting the \( f_c \) when the rotation speed \( n \) changes. Therefore, DSBDFG has a bright future in the field of variable speed constant frequency wind power generation.

2.3 | Rotor topology

The commonly used rotor of BDFG concludes cage rotor, wound rotor, and reluctance rotor [16]. In this study, the hybrid rotor, which consists of magnetic barrier layers and cage bars, is used for DSBDFG. The prototype of the hybrid rotor is shown in Figure 3.

In order to improve the performance of the designed generator, two different structures of magnetic barrier layers, which also can reduce the pulse array loss produced in the stator core, are proposed and shown in Figure 4. In order to compare the performance of DSBDFG with two proposed magnetic barrier layers, the no-load characteristic of the simulation models are analysed and shown in Figure 5.
According to Figure 5, it can be clearly seen that the performance of outer machine of 1# is better than that of outer machine of 2#; on the contrary, the performance of inner machine of 2# is better than that of inner machine of 1#. Therefore, the final proposed magnetic barrier layer is a combination of outer magnetic barrier layer of 1# and inner magnetic barrier layer of 2# and shown in Figure 6.

3 | ROTOR OPTIMISATION DESIGN

The optimisation design of the hybrid rotor consists of three parts: Determining the position of the non-magnetic ring, design of magnetic barrier layer and design of cage bar. In order to reduce the computational costs, the surrogate model and MIGA is used in this part. The main parameters of the designed DSBDFG are shown in Table 1. The detailed flowchart of rotor optimisation design is shown in Figure 7.
3.1 | Position of non-magnetic ring

Figure 8 shows the geometry diagram of rotor, where $R_1$ and $R_2$ are the radius of the geometric centre circle of rotor and non-magnetic ring, respectively. The position of non-magnetic ring will affect the core saturation of outer and inner magnetic barrier layer, and then affect the performance of the machine. Therefore, it is significant to determine the position of non-magnetic ring. For the convenience of expression, the variable $d$ (the difference of $R_1$ and $R_2$, i.e. $d = R_1 - R_2$) is introduced to describe the position of non-magnetic ring.

In order to determine the position of non-magnetic ring, the simulation models with different $d$ are established and simulated respectively. Figure 9 shows the relationship of total voltage (sum of output voltage of inner and outer machine) and $d$. It can be clearly seen that the total voltage increases with the increase of $d$. In order to make full use of the core material of inner and outer magnetic barrier layer, the flux density distribution of each simulation model is also analysed. The flux density distribution of the model ($d = 15$ mm) is shown in Figure 10, and it can be known that the maximum flux density of inner and outer magnetic barrier layer is basically consistent. Therefore, the value of $d$ is determined as 15 mm.

3.2 | Design of magnetic barrier layer

3.2.1 | Definition of design variables

In order to define the structure parameters of the magnetic barrier layer vividly, the diagram of the outer magnetic barrier layer is shown in Figure 11. The main structure parameters of inner and outer magnetic barrier layer, which have a significant impact on the performance of DSBDFG, are pole arc coefficient (PAC, i.e. the ratio of $\theta_1$ and $\theta_2$), the number of magnetic layer (NML), and width ratio (WR) of the magnetic and non-magnetic layer (i.e. ratio of $d_1$ and $d_2$). Because the NML only can take on a small number of discrete values (about three values), the NML will not be considered directly when constructing the surrogate model. Therefore, there are four design variables of magnetic barrier layer in this study, that is, PAC\textsubscript{out}, PAC\textsubscript{in}, WR\textsubscript{out}, and WR\textsubscript{in}, where the subscripts ‘out’ and ‘in’ represent the outer and inner magnetic barrier layers, respectively.

In this study, the no-load voltage $U$ (under the same excitation current) is seen as the optimal objective.

3.2.2 | Design of experiments (DoE)

DoE, which is the preparatory work of constructing surrogate models, is a very important work [9]. The common methods of DoE include full factorial design, orthogonal array (OA), centre composite design, Latin hypercube design and so on. In this study, OA, whose advantage is that it can use the least sample points to achieve the best combination of design variables, is selected for the DoE. Fifty original samples for four design variables are obtained, and the objective function value of each sample point is calculated based on the finite element analysis (FEA).
3.2.3 Construction of surrogate models

Surrogate model, which uses a continuous function to present the relationship between the response and design variables, can replace the simulation models with a large amount of calculation, and then can greatly reduce the workload in the design or optimisation process. In recent years, the surrogate model has been widely used in various engineering fields. The common and mainly used surrogate models have three types, that is, Kriging model [17], response surface methodology (RSM) model [18], radial/elliptical basis functions (RBF/EBF) network model [19].

Different kinds of surrogate models are suitable for different practical problems. The coefficient $R^2$ is always used to evaluate the precision of the surrogate model [14] and shown as Equation (2). The range of $R^2$ is from 0 to 1, and $R^2$ should be as close to 1 as possible:

$$R^2 = 1 - \frac{\sum_{i=1}^{n} (\hat{y}_i - y_i)^2}{\sum_{i=1}^{n} (y_i - \bar{y})^2}$$

where $n$ is test sample point, $y_i$ and $\hat{y}_i$ are the actual and predicted value of the $i$th test sample point, respectively, and $\bar{y}$ is the average value of actual response of all test sample points.

In order to select the most suitable surrogate model for magnetic barrier layer of DSDBDFG, the surrogate models with RSM model, Kriging model, and RBF/EBF network model are established, respectively. Then, 10 test sample points are selected and used to test the precision of the established surrogate models.

**RSM model**

The approximation expression of RSM is a polynomial function, and the order of polynomial function will affect the precision of the model. The second-order polynomial function is always used. In order to improve the precision of the model, the fourth-order polynomial function is used in this study, which is expressed as

$$\hat{y} = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_m x_m$$

$$+ \beta_{m+1} x_1^2 + \beta_{m+2} x_2^2 + \ldots + \beta_{2m} x_m^2$$

$$+ \beta_{2m+1} x_1^3 + \beta_{2m+2} x_2^3 + \ldots + \beta_{3m} x_m^3$$

$$+ \beta_{3m+1} x_1^4 + \beta_{3m+2} x_2^4 + \ldots + \beta_{4m} x_m^4 + \sum_{i \neq j} \beta_{ij} x_i x_j$$

where $\hat{y}$ is predicted response, $\beta$ is the coefficients, $x$ is the design variable, and $m$ is the number of design variables.

**Kriging model**

The relationship between the response and design variables of the Kriging model [13] can be expressed as (4)

$$y(x) = f^T(x) \beta + \zeta(x)$$

where $f^T(x) \beta$ is the regression model, $\beta$ is the coefficients, $\zeta(x)$ is the random process, and

$$E[\zeta(x)] = 0$$

$$\text{Var}[\zeta(x)] = \sigma^2$$

$$E[\zeta(x), \zeta(w)] = \sigma^2 R(x, w)$$

where $x$ and $w$ are the different sample points, $R(x, w)$ is the correlation function, and the correlation function is always Gaussian function. So the $R(x, w)$ can be expressed as

$$R(x, w) = \prod_{j=1}^{n} \exp(-\vartheta_j d_j^2)$$

where $n$ is the dimension of $R(x, w)$, $\vartheta$ is the unknown coefficient, and $d$ is the distance of two sample points.

**RBF/EBF network model**

The RBF/EBF network model always can be expressed as [20]

$$f(x) = \sum_{i=1}^{N} \beta_i \phi(r)$$

where $N$ is the sample point number, $\beta$ is the coefficients, $\phi(r)$ is the basis function, $r$ is the distance between $x$ and sample point $x_i$.

The predicted values of 10 test simple points obtained by different surrogate models are compared with their actual values, respectively, and shown in Figure 12. According to Figure 12, It can be clearly seen that the $R^2$ of EBF network model is 0.9920, and it is higher than that of other surrogate models. Therefore, the EBF network model is selected in this study.

Figure 13 shows the relationship of output parameter and the design variables based on EBF network model. Figure 13 can indicate a good prediction between design variables and output parameter.

3.2.4 Optimisation based on MIGA

In this study, the optimisation objective is to optimise the rotor for improving the coupling capacity, and the objective is shown as follows:

$$\begin{align*}
\text{Objective} & \quad \text{Maximum } U \\
\text{s.t.} & \quad 0.6 \leq \text{PAC}_{\text{out}} \leq 0.8 \\
& \quad 1 \leq \text{WR}_{\text{out}} \leq 3 \\
& \quad 0.6 \leq \text{PAC}_{\text{in}} \leq 0.8 \\
& \quad 1 \leq \text{WR}_{\text{in}} \leq 3
\end{align*}$$
Because geometric algorithm (GA) is very effective for highly non-linear function, it is a very commonly used method to solve the optimisation problems \[21\]. In recent years, MIGA \([22]\), which is based on the traditional GA, has been proposed. MIGA divides the population into multiple sub-population (i.e. island), and the periodic migration operation between the islands can maintain the diversity of population and avoid to fall into local premature converge. Therefore, MIGA has a better global solution capacity and computational efficiency, compared with traditional GA. The process of MIGA is shown as follows:

1. Create an initial population (include several sub-population).
2. Calculate the fitness value of each chromosome.
3. Select the useful chromosomes, according to the rule related to the fitness value.
4. Crossover the \(k\)th and \(l\)th chromosome.
5. Make the \(j\)th gene of \(i\)th chromosome mutation.
6. Output the optimal result, when meeting the requirements.

Instead, repeat the steps (2)–(5).

In addition, the flowchart of MIGA is shown in Figure 14.

The optimal combination of four design variables solved by MIGA is shown in Table 2. The predicted value obtained by constructed surrogate model and the actual value obtained by FEA are also presented in Table 2. Through comparison, it can be seen that the error between the predicted and actual values are very small, which is only 0.22\%. Therefore, the accuracy of the constructed surrogate model is verified further.
### TABLE 2 Combination of design variables and response

| Parameter (units) | Values     |
|------------------|------------|
| PAC<sub>out</sub> | 0.7524     |
| WR<sub>out</sub>  | 2.2612     |
| PAC<sub>in</sub>  | 0.7411     |
| WR<sub>in</sub>   | 2.1706     |
| Predicted value (V) | 242.25   |
| Actual value (V)  | 242.78     |

*Note*: PAC is pole arc coefficient, WR is width ratio, and the subscripts 'out' and 'in' represent the outer and inner magnetic barrier layers, respectively.

### TABLE 3 Radial length of cage bar

| Cage bar | Value (mm) | Cage bar | Value (mm) |
|----------|------------|----------|------------|
| CCB<sub>out</sub> | 49.8       | CCB<sub>in</sub> | 24.8       |
| CB1<sub>out</sub>  | 29.8       | CB1<sub>in</sub>  | 17.8       |
| CB2<sub>out</sub>  | 19.8       | CB2<sub>in</sub>  | 9.8        |

*Note*: CCB is common cage bar, where the subscript 'out' represents the outer rotor.

### TABLE 4 Copper loss of each cage bar

| Cage bar | Copper loss (W) | Cage bar | Copper loss (W) |
|----------|-----------------|----------|-----------------|
| CCB<sub>out</sub> | 1059.07   | CCB<sub>in</sub> | 658.27 |
| CB1<sub>out</sub>  | 11.99     | CB1<sub>in</sub>  | 1.41   |
| CB2<sub>out</sub>  | 12.71     | CB2<sub>in</sub>  | 0.8    |

*Note*: CB1 cage bar 1, CB2 cage bar 2.

### FIGURE 16 $K$ of cage bars under different frequency

\[
K_k = \frac{\xi_k \sin 2\xi_k + \sin 2\xi_k}{\sinh 2\xi_k - \cos 2\xi_k}
\]

where \( b \) is radial length of cage bar, \( f_k \) is the \( k \)th frequency of current induced in cage bars, \( \mu \) is the magnetic conductivity, \( \rho \) is the resistivity of cage bar.

According to Equations (11) and (12), the coefficient \( K \) under the different frequency of each cage bars are shown in Figure 16. According to Figure 16, it can be known that the value of \( K \) increases with the crease of current frequency and radial length of cage bar.

Then, the copper loss of each cage bar has been calculated and shown in Table 4.

In order to reduce the influence of skin effect on the copper loss of the rotor, the cage bars will be layered in radial direction in this study. According to Table 4, it can be known that the copper loss of CB1<sub>out</sub>, CB2<sub>out</sub>, CB1<sub>in</sub>, CB2<sub>in</sub> is very small, compared with the copper loss of CCB<sub>out</sub> and CCB<sub>in</sub>. Therefore, only CCB<sub>out</sub> and CCB<sub>in</sub> will be layered, and CB1<sub>out</sub>, CB2<sub>out</sub>, CB1<sub>in</sub>, CB2<sub>in</sub> will not be considered. Figure 17 shows the copper loss of CCB<sub>out</sub> and CCB<sub>in</sub> with different layers.

According to Figure 17, it can be clearly seen that when the layer number of CCB<sub>out</sub> and CCB<sub>in</sub> are 3 and 2, the copper loss of both CCB<sub>out</sub> and CCB<sub>in</sub> are smallest, and are 833.23 and 591.41 W, respectively. Therefore, the layer number of CCB<sub>out</sub> and CCB<sub>in</sub> are determined as 3 and 2, respectively.

Table 5 shows the copper loss of cage bars with single layer and multi-layers. It can be known that when the multi-layer cage bars are used, the copper loss of rotor could decrease by 16.8%.

### TABLE 5 Copper loss of cage bars

|                | Single-layer | Multi-layers | Reduced |
|----------------|--------------|--------------|---------|
| Copper loss (W)| 1744.24 W    | 1451.54 W    | 16.8%   |
4 | SIMULATION AND EXPERIMENT VERIFICATION

A 50 kW BSBDFG with original rotor lamination structure and geometric dimension has been manufactured. The test platform of DSBDFG prototype has been set up and shown as Figure 18.

### 4.1 No-load test

Figure 19 shows the simulation and experimental results of no-load characteristic of original machine. According to Figure 19, it can be found that the simulation results are in good agreement with the experimental results. Therefore, in order to verify that the DSBDFG with optimised rotor has better performance, the simulation results of the original machine and optimised machine are compared and are shown in Figure 20. As shown, the no-load electromotive force of optimised machine is higher than that of the original machine under the same rotation speed (i.e. 360 rpm) suggesting the stronger coupling capacity of the optimised machine.

### 4.2 Load test

Under the same load condition (i.e. 360 rpm, 51 kW), DSBDFG with original and optimised rotor are simulated and analysed, respectively. Figure 21 shows the excitation current of DSBDFG with the optimised and original rotors. Through
It can be known that the excitation current of the optimised machine is 4.4 A lower than that of the original machine, namely, the excitation current decreases by 5.6%. Therefore, DSBDFG with the optimised rotor has the stronger coupling and overload capacity.

5 | CONCLUSION

This study has presented the detailed rotor optimisation design of DSBDFG, including the selection of rotor topology, optimisation of structure parameters of magnetic barrier layer based on a surrogate model with MIGA, and reducing the effect of skin effect on copper loss of cage bars by delamination. The performance of the optimised and original machines have been compared. The following conclusion can be made from the above analysis:

1. It can be known that the $R^2$ of EBF network model is 0.9920 and is higher than that of the other surrogate models; therefore, EBF network model is the most suitable surrogate model for the optimisation of rotor magnetic barrier layer.

2. Through analysis, it can be known that the copper loss of rotor is reduced 16.8% by delamination. Therefore, the effect of skin effect on copper loss can be reduced effectively by delamination. But it is not that the more the layers, the lower the copper loss of cage bars.

3. The DSBDFG with optimised rotor has stronger coupling and overload capacity.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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