Electromagnetic and mechanical design of module dual stator brushless doubly-fed generator for offshore wind turbine

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Abstract
In order to meet the higher requirements (i.e. large scale, high reliability and direct drive) of generators used for offshore wind turbine, a novel direct drive module dual stator brushless doubly-fed generator (DSBDFG) with cage-barrier rotor having many outstanding merits is proposed in this paper. The fundamental structure, operation principle and power flow are presented. The electromagnetic design methods of the proposed generator including power distribution of inner and outer machines, the relationship of pole number, slot number and module number, and winding design are thoroughly investigated. In order to solve the problems in structure brought by module design and reduce the weight as much as possible, a mechanical construction applied for module DSBDFG is proposed. Finally, the correctness of the proposed electromagnetic design method and the stability of the proposed mechanical construction are verified based on finite element analysis respectively.

1 | INTRODUCTION

Due to the shortage of fossil fuel (i.e. coal and oil) and the environmental problems associated with its use, increasing the proportion of wind power generation in the electrical grids is a strong trend [1]. With the rapid development of offshore wind power generation, higher requirements for the reliability and power density of the generators have been put forward. In recent years, wind power generators are developing toward to large scale, high reliability, and direct drive (DD). In particular, various types of MW-class even above 10 MW wind power generators (such as high temperature superconductivity generator [2], doubly fed induction generator [3], permanent magnet synchronous generator [4] and so on) have been researched to reduce the cost per unit offshore wind power. However, the traditional large scale single stator/rotor generators have the large wasted inner cavity space and relatively low power density. In order to make full use of the inner cavity space of traditional single stator/rotor wind power generator and improve power density further, dual stator/rotor structure has been becoming the new trend in the development of large scale wind power generators.

Many scholars have proposed and researched on kinds of wind power generators with dual stator/rotor structures. In order to improve torque density, flux weakness capacity, and power factor, ref. [5] proposed a double stator flux modulation machine, of which inner stator is wound with DC superconducting windings. A DD dual stator superconducting permanent magnet wind power generator, which replaced traditional copper winding with MaB2 wires, was designed in [6]. A double stator wind power generator with rotating high temperature superconductivity (HTS) field windings has been put forward to obtain higher torque density in [7]. Ref. [8] proposed a dual stator brushless doubly-fed induction generator, in which power winding and control winding are placed in outer and inner stators respectively. A dual stator hybrid excitation synchronous generator and its control system for wind power generation have been studied in [9]. A double stator low temperature superconducting (LTS) Vernier machine, which can provide large torque density, as well as small short-circuit current and torque, has been proposed for direct drive wind power generation in [10]. It is suggested that a 5 MW double stator single rotor permanent magnet synchronous generator (PMSG) for offshore direct drive wind turbines in [11]. A dual rotor multi-phase permanent magnet machine, in which both the inner and outer magnets are polarized in the same direction, has been researched in [12]. Ref. [13] proposed a novel dual stator pseudo-pole five phase PMSG used for wind power generation, which can enhance its power...
density and fault tolerant capacity. A novel scale-down hybrid excited dual permanent magnet synchronous generator for DD-wind power application, in which dual permanent magnet are placed on the outer stator and middle rotor respectively, was proposed in [14]. A dual stator hybrid excitation synchronous wind power generator, in which rotor consists of PM, claw-poles, rotor yoke and cup-rotor, was researched in [15].

According to the above literature, it can be known the dual stator/rotor structure has been applied to various generators. Although the performance of HTS and LTS generators are slightly better than that of traditional generator, its refrigeration system is relatively complex, and then results in the higher running cost. Similarly, PMSG has its own advantages, and is a common used type of wind power generator. However, the large scale PMSGs need a large amount of rare-earth permanent magnet (PM, i.e. Nd-Fe-B) and full power converter, and then result in high system cost. In addition, the harsh environment on the sea may result in the demagnetization of PM. Another common used generator in MW-class variable speed constant frequency (VSCF) wind power generation is doubly-fed induction generator (DFIG). The maintenance cost of DFIG is high, due to the brush and slip-ring. Therefore, the common used generators cannot meet the higher requirements of the offshore wind power generation.

In recent years, brushless doubly-fed generator (BDFG) [16], which has many advantages and is especially suitable for wind power generation, has been paid more attention. In order to make use of the wasted inner cavity space of traditional large scale single stator generator and improve the power density further, a novel module dual stator brushless doubly-fed generator (DSBDFG) with cage barrier rotor is proposed in this paper. In addition, because the modular design is adopted, the proposed generator is easy to transport and maintain, and has higher fault tolerant capacity.

In this paper, the electromagnetic design method of the proposed generator is derived, meanwhile a mechanical construction applied for module DSBDFG is proposed. It is organized as follows. Section 2 introduces the basic structure, operation principle and power flow of DSBDFG. The electromagnetic design method, which includes power distribution of inner and outer machines, combination of stator slot number, pole pair module and module number, and winding design, is researched in Section 3. In Section 4, a mechanical structure applied for module DSBDFG is proposed, and the installation scheme is illustrated. The performance, stress and deformation of the designed prototype are analysed based on finite element method in Section 5. Finally, the conclusion is summarized in Section 6.

2 | THE DSBDFG TOPOLOGY

2.1 | Basic structure of DSBDFG

Figure 1 shows the cross section of DSBDFG. It can be seen that DSBDFG consists of outer stator, inner stator and a shared rotor. Both inner and outer stator slots of DSBDFG have two stator windings, i.e. power winding (PW) and control winding (CW). In theory, both PW and CW of inner and outer stator can be connected in series or in parallel. In order to avoid circulating current in windings, the series connection mode is applied to PW and CW in this paper, and then the total PW and CW are formed. Meanwhile, the CW is used for excitation and energy back, and the PW is used for transmitting energy.

The novel cage-barrier rotor, of which internal and external magnetic circuits are independent of each other, is used for the proposed generators. The coupling relationships between PW and CW of inner and outer stator are realized by the inner and outer cage-barrier respectively. The advantages of novel cage-barrier rotor are as follows:

1. The rotor is formed by a stack of radial lamination, which can minimize the eddy-current loss;
2. Higher coupling capacity;
3. Compared with the traditional cage rotor, the copper loss is smaller;
4. The rotor core consists of \( p_t \) (i.e. number of rotor salient) identical laminations, so it is easy to modularize;
5. The layered cage bar can overcome skin effect effectively.

2.2 | Operation principle of DSBDFG

Figure 2 shows schematic block diagram of DSBDFG system. On the premise that the pole pair number of PW and CW of the outer and inner machine, the relationship of speed, frequency, and pole pair number of DSBDFG is exactly the same as that of single stator BDFG, and as follows [17]:

\[
 n = \frac{60 \left( f_p \pm f_c \right)}{p_p + p_c} \quad (1)
\]

where, \( n \) is the rotation speed, \( f \) and \( p \) are the frequency and pole pair number respectively, the subscripts \( p \) and \( c \) are for PW and CW, respectively.

According to Equation (1), it can be clearly seen that the \( f_p \) can be constant by regulating the \( f_c \), when the speed \( n \) changes. Thus, DSBDFG is extremely suitable for VSCF wind power generation system.
2.3 Power flow of DSBDFG

The input mechanical power $P_{in}$ of DSBDFG provided by prime mover is the same as that of single stator BDFG and can be expressed as:

$$P_{in} = P_{em} + P_{mec} + P_{ad} + P_{rCu-in} + P_{rCu-out} + P_{rFe-in} + P_{rFe-out}$$ (2)

where, $P_{em}$ is the electromagnetic power transmitted from rotor to inner and outer stator windings through air gap, $P_{mec}$ is the mechanical loss, $P_{ad}$ is additional loss, $P_{rCu-in}$ and $P_{rCu-out}$ are the copper loss of inner and outer cage-bar, $P_{rFe-in}$ and $P_{rFe-out}$ are the core loss of inner and outer magnetic barrier.

The electromagnetic power $P_{em}$ can be expressed as:

$$P_{em} = P_{pem} \pm P_{cem}$$ (3)

where, ‘±’ is decided by the operation mode, namely, ‘+’ and ‘−’ are suitable for super-synchronous and sub-synchronous operation mode respectively. $P_{pem}$ and $P_{cem}$ are the electromagnetic power transmitted from rotor to power winding and control winding through air gap respectively, and can be expressed as:

$$\begin{cases}
P_{pem} = P_{p-Sout} + P_{p-Sin} + P_{pCu-Sout} + P_{pFe-Sout} + P_{pCu-Sin} + P_{pFe-Sin} \\
P_{cem} = P_{c-Sout} + P_{c-Sin} + P_{cCu-Sout} + P_{cFe-Sout} + P_{cCu-Sin} + P_{cFe-Sin}
\end{cases}$$ (4)

where, $P_p$ is the output power of PW, $P_e$ is the excitation power under sub-synchronous operation mode or feedback power under super-synchronous operation mode, $P_{pCu}$ and $P_{eCu}$ are the copper loss of PW and CW, $P_{pFe}$ and $P_{eFe}$ are the core loss resulted from PW and CW, the subscript Sin and Sout represent the inner stator and outer stator, respectively.

According to Equations (2)–(4), the power flow chart of DSBDFG under super-synchronous and sub-synchronous operation modes can be obtained and are shown in Figure 3.

3 ELECTROMAGNETIC DESIGN OF DSBDFG

Although module DSBDFG has many merits, there are many problems to be solved in the design process. Therefore, this section focuses on the main electromagnetic design issues of modular DSBDFG with cage-barrier rotor, including power distribution of inner and outer machines, relationship of pole number, slot number and module number, stator winding and rotor design. The design flow chart of module DSBDFG is shown in Figure 4.

In this paper, a 10 MW module DSBDFG is seen as the research object. The main design inputs of the designed generator, such as rated power $P$, voltage $U$, frequency $f$, speed $v$ and speed range, are shown in Table 1.

3.1 Power distribution of outer and inner machines

In order to improve the volume power density of DSBDFG, it is significant to distribute the power of outer and inner machines reasonably, namely, the power ratio of outer and inner machine should be as small as possible.

Induced electromotive force (EMF) of PW of outer and inner machines of DSBDFG can be expressed as [18]:

$$\begin{cases}
E_{po} = 4.44f_pN_{po}k_{po}B_{po}D_1L/p_p \\
E_{p_i} = 4.44f_pN_{pi}k_{pi}B_{pi}D_2L/p_p
\end{cases}$$ (5)
where, \( D_1 \) is the insider diameter of outer machine, \( D_2 \) is the outside diameter of inner machine, \( L \) is core length, \( N_p, k_{gap}, B_p \) are turns-in-series of each phase, winding coefficient, and air-gap flux density respectively. And the subscripts i and o are represented as inner and outer machines, respectively.

The air gap magnetic flux density produced by PW of outer and inner machines can be expressed as [19]:

\[
\begin{align*}
B_{po} (\varphi, t) &= f_{po} (\varphi, t) \lambda_{go} (\varphi, t) \\
B_{pi} (\varphi, t) &= f_{pi} (\varphi, t) \lambda_{gi} (\varphi, t)
\end{align*}
\] (6)

where, \( f_p(\varphi, t) \) is the magnetomotive force (MMF) of PW, \( \lambda_g(\varphi, t) \) is the air gap magnetic conductance, \( \varphi \) is the position angle (mechanical angle).

The MMF can be expressed as [20]:

\[
f_p(\varphi, t) = F_{pm} \cos(p_p \varphi - \omega_p t)
\] (7)

where, \( \omega_p \) is angular frequency of PW, \( F_{pm} \) is the amplitude value of MMF, and can be expressed as:

\[
F_{pm} = \frac{3 \sqrt{2} N_p k_p I_p}{\pi}
\] (8)

where \( I_p \) is the current of PW.

The air gap magnetic conductance can be expressed as:

\[
\lambda_g(\varphi) = \lambda_0 + \lambda_1 \cos \left[ p_c (\varphi - \theta_{c0} - \omega_{rm} t) \right]
\] (9)
where, $\theta$ is the mechanical angle between the rotor and MMF of PW, $\omega_{mm}$ is mechanical angular speed, $\lambda_0$ and $\lambda_1$ are expressed as:

$$\lambda_0 = \alpha \frac{\mu_0}{\pi}$$  \hspace{1cm} (10)

$$\lambda_1 = 2 \left( \sin \left( \frac{\alpha \pi}{\pi} \right) \right) \frac{\mu_0}{g}$$  \hspace{1cm} (11)

where, $\alpha$ is the pole arc coefficient, $g$ is the air gap width.

Because the series connection mode is applied to the PW of inner and outer machines, $I_{po} = I_{pi}$. And assume that the $k_{ew}$, $\alpha$ and $g$ of outer and inner machine are the same, the relationship of $B_{po}$ and $B_{pi}$ can be expressed as:

$$\frac{B_{po}}{B_{pi}} \propto \frac{N_{po}}{N_{pi}}$$  \hspace{1cm} (12)

According to the Equations (5)–(12), the output power ratio of PW of inner and outer machine can be expressed as:

$$\frac{P_{po}}{P_{pi}} \propto \frac{N_{po}^2 D_1}{N_{pi}^2 D_2}$$  \hspace{1cm} (13)

where, $P_{po}$ and $P_{pi}$ are the PW output power of outer and inner machines, respectively.

According to Equation (13), it is extremely significant to determine a reasonable ratio of $D_1$ to $D_2$. Figure 5 shows the diagram of geometry dimensions of DSBDFG, where, $d_1$ and $d_5$ are salient pole height of inner and outer magnetic barrier, $d_2$ and $d_4$ are rotor yoke thickness of inner and outer magnetic barrier, $\delta_1$ and $\delta_2$ are inner and outer air gap width, and $d_3$ is thickness of no-magnetic ring.

According to Figure 5, it can be clearly known that the main diameters of DSBDFG need to satisfy the following relationship:

$$\frac{D_1 - D_2}{2} \geq d_1 + d_2 + d_3 + d_4 + d_5 + \delta_1 + \delta_2$$  \hspace{1cm} (14)

Under the premise that the yoke of inner and outer magnetic barrier meets the requirement of magnetic density, $d_2$ and $d_4$ can be expressed as:

$$d_2 \geq (D_1 - 2\delta_1) \sin \left( \frac{2\pi \alpha}{2\pi r} \right)$$  \hspace{1cm} (15)

$$d_4 \geq (D_2 + 2\delta_2) \sin \left( \frac{2\pi \alpha}{2\pi r} \right)$$  \hspace{1cm} (16)

Therefore, Equation (14) can be rewritten as Equation (17) by substituting Equations (15) and (16) to Equation (14).

$$\frac{D_1 - D_2}{2} \geq (D_1 - 2\delta_1) \sin \left( \frac{2\pi \alpha}{2\pi r} \right) + (D_2 + 2\delta_2) \sin \left( \frac{2\pi \alpha}{2\pi r} \right)$$

$$+ d_1 + d_3 + d_5 + \delta_1 + \delta_2$$  \hspace{1cm} (17)

Selecting different salient pole height will have effect on the coupling capacity and performance of DSBDFG, and the minimum value of salient pole height can approach 0. In order to simplify the calculation, both $d_1$ and $d_5$ are selected as 1.05, considering the rotor spoke thickness and salient pole height of inner and outer magnetic barrier.

Therefore, the ratio of $D_1$ and $D_2$ can be further expressed as:

$$\frac{D_1}{D_2} > \frac{1 + 2 \sin \left( \frac{2\pi \alpha}{2\pi r} \right)}{1 - 2 \sin \left( \frac{2\pi \alpha}{2\pi r} \right)}$$  \hspace{1cm} (18)

In this paper, the value of $\alpha$ is 0.7. According to the rated rotation speed in Table 1, it can be known that $\omega_r = 240$. Therefore, the ratio of $D_1$ and $D_2$ should be greater than 1.04. In this paper, the ratio of $D_1$ and $D_2$ is selected as 1.05, considering the rotor spoke thickness and salient pole height of inner and outer magnetic barrier.

After determining the power distribution ratio of inner and outer machine, the main dimensions can be calculated by referring to the calculation method of main design dimensions of single stator BDFM mentioned in [21].

### 3.2 Combination of stator slots number, pole pair number and module number

In order to reduce the effect of module design on the electromagnetic relationships and operation performance of
TABLE 2  Different combination of stator slot number, pole number and module number

| Module number | 24  | 40  | 60  |
|---------------|-----|-----|-----|
| Pole number of each module | 12/8 | 8/4 | 6/2 |
| Slot number   |     |     |     |
|               | 864 | 960 | 1080|
|               | 1296| 1200| 1620|

TABLE 3  Simulation results of outer machine

| Speed/rpm | 12+8/864 | 8+4/960 | 6+2/1080 |
|-----------|----------|---------|----------|
| 5         | 1.96     | 3.60    | 6.90     |
| 10        | 3.88     | 11.24   | 11.92    |
| 15        | 6.81     | 21.41   | 11.61    |
| 20        | 13.69    | 37.87   | 22.43    |

TABLE 4  Simulation results of inner machine

| Speed/rpm | 12+8/864 | 8+4/960 | 6+2/1080 |
|-----------|----------|---------|----------|
| 5         | 1.82     | 3.11    | 6.89     |
| 10        | 3.96     | 10.94   | 12.21    |
| 15        | 7.10     | 21.03   | 18.07    |
| 20        | 14.35    | 37.52   | 24.12    |

DSBDFG, it is significant to study the relationship of stator slot number, pole pair number and module number.

In order to facilitate the realization of stator module, both the stator slot number and the pole pair number of PW and CW can be divided by the module number, therefore, the relationship can be expressed as:

\[
\exists \text{CD}(Z, p_p) = k \\
\exists \text{CD}(Z, p_c) = k
\]  \hspace{1cm} (19)

where, \(Z\) is the stator slot number, \(k\) is the module number, \(\text{CD}\) is the abbreviation of common divisor.

For example, the different combination of stator slot number, pole number and module number are shown in Table 2.

In order to analyse the effect of pole combination with different modular number, the three different combination mentioned in Table 2 are analysed and compared. Because the power grid has the higher requirement for the quality of electricity generated by the wind power generator, total harmonic distortion (THD\%) of voltage is seen as the object of comparison. The simulation results of outer and inner machines are shown in Tables 3 and 4 respectively.

4.3  Winding design

In order to achieve the electrical isolation between all modules of DSBDFG, the unequal span winding is applied to inner and outer stators, namely, long span coil is embedded in reverse direction.

The pitch of short span coil should be:

\[
\begin{align*}
Y_p &= \frac{Z}{k} - \nu_p \\
Y_c &= \frac{Z}{k} - \nu_c
\end{align*}
\]  \hspace{1cm} (20)

where, \(5/6\) is the short pitch factor, which purpose is to reduce the 5th and 7th harmonic content.

The pitch of long span coil should be:

\[
\begin{align*}
\nu_p &= \frac{5}{6} \frac{Z}{p_p} \\
\nu_c &= \frac{5}{6} \frac{Z}{p_c}
\end{align*}
\]  \hspace{1cm} (21)

According to analysis, it can be obtained at the same time that the number of long and short span coil should be equal to the pitch of short and long span coil respectively.

For example, when the slot number is 864 (24 modules), and the pole number of PW and CW of each module is 12 and 8, the number of long span coil of PW and CW is 2 and 4 respectively. The winding expansion diagrams of PW and CW are shown as Figure 6.
3.4 Rotor module design

In this paper, the novel cage-barrier rotor is used for the proposed DSBDFG. A notable advantage of this rotor is easy to realize module design, which can meet the requirement of convenient transportation and installation for large-scale wind power generator. In this paper, the rotor modularity is achieved by that the dovetail of the inner and outer magnetic barrier is embed in the dovetail groove of rotor support. And the diagram of rotor modular is shown in Figure 7.

4 CONSTRUCTION DESIGN

In order to make use of the inner cavity space and improve the power density, the proposed generator adopts dual stator structure. In addition, in order to improve fault tolerant capacity and facilitate transportation and installation, the modular design is also adopted. Therefore, the mechanical structure of the proposed DSBDFG is relatively complex, and it is significant to research on the mechanical design and installation method.

A new mechanical structure used for the module DSBDFG is proposed in this paper, and shown in Figure 8. In order to avoid the change of the air gap width caused by rotor shaking, the double end support structure, which can enhance the stability of the mechanical structure is adopted by the shared rotor. The volume and weight of the MW-class is large, and results in many problems in transportation and installation. Therefore, the weight should be reduced, under the premise of ensuring the normal operation of the machine. In order to reduce the weight of the machine in this paper, the stationary shaft is hollow, and there are weight reducing hole on the flange of rotor spoke and inner stator spoke. In order to avoid the corrosion of internal materials caused by the salt spray, there is no weight reducing hole on the flange of housing case.

A reasonable mount strategy is significant for the operation of the proposed generator. Figure 9 shows the installation scheme of inner and outer stator module. It can be known that the swallow tail of outer stator module is embed in dovetail groove of housing case. Similarly, the swallow tail of inner stator is also embed in dovetail groove of inner stator spoke. The housing case, rotor spoke, inner stator spoke, and their flange consist of $k$ modules, and therefore, it is significant to connect the adjacent modules. Figure 10 shows the connection diagram of adjacent module.

5 PERFORMANCE SIMULATION ANALYSIS

According to simulation and analysis, the specifications and design details of a 10 MW DSBDFG are obtained and showed in Table 5. And the meanings of symbols are also reported in Table 5.

5.1 Electromagnetic analysis

In order to confirm the feasibility of electromagnetic design method studied above of DSBDFG, in this section, the
Figure 10 Connection diagram of adjacent module (a) housing case, (b) flange

Table 5 Specifications and design details

| Parameters/symbol (units) | Value         |
|---------------------------|---------------|
| Module number/$k$         | 24            |
| Pole number of PW (each module)/$p_p$ | 12           |
| Pole number of CW (each module)/$p_c$ | 8             |
| Rotor pole number/$p_r$   | 240           |
| Slot number of inner machine/$Z_{in}$ | 864          |
| Slot number of outer machine/$Z_{out}$ | 864          |
| Internal diameter of outer machine/$D_1$ (mm) | 9386         |
| External diameter of inner machine/$D_2$ (mm) | 8940         |
| External diameter of outer machine/$D_3$ (mm) | 9686         |
| Internal diameter of inner machine/$D_4$ (mm) | 8640         |
| Core length/$l$(mm)       | 3000          |

The simulation model of the designed DSBDFG is established, and the no-load and load performance are characterized through finite element method. The simulation results are shown in Figures 11–13 respectively.

Figure 11 shows the no-load characteristic curve of the designed DSBDFG. It can be seen that the increase value of no-load voltage gradually decreases, when the excitation current is greater than 600 A.

The flux line distribution and flux density distribution of the designed DSBDFG under rated operation mode are shown in Figure 12. It can be clearly seen that the flux line distribution and flux density distribution are reasonable.

Figure 13 shows the terminal voltage of PW of the designed DSBDFG. It can be clearly seen that the terminal voltage of PW is very sinusoidal. And then the feasibility of the design method of DSBDFG has been verified effectively.

5.2 Construction analysis

The reasonable mechanical structure should not only use as little material as possible, but also ensure the normal operation of the wind power generator, especially to ensure the size of the air gap. Therefore, it is extremely significant to analyse the stress and deformation of main structure parts. In this section, the simulation model of 1/24 DSBDFG will be established and analysed.

In this part, the main structure parts, i.e. the flanges of housing case, inner stator spoke, and rotor spoke, will be analysed. In the process of analysing stress and deformation of the rotor,
the main factors considered conclude operation torque, gravity, and the centrifugal force (rotational velocity). And the main factors which mainly effect the stress and deformation of outer and inner stator include the operation torque, gravity [3]. And the simulation results are shown in Figures 14–16.

According to the Figures 14–16, it can be known that all the maximum stress of the flange of housing case, inner stator spoke and rotor spoke are far less than the maximum allowable stress of the used materials, and the radial deformation can meet the requirement. Therefore, the stability of the designed mechanical structure has been verified.

6 | CONCLUSION

In this paper, a novel module DSBDFG with cage-barrier rotor was proposed, and its electromagnetic and mechanical design method was discussed in detail. The detail electromagnetic design methods including power distribution of inner and outer machines, the relationship of pole number, slot number and module number, and winding design have been presented. A mechanical structure applied for the module DSBDFG was proposed, and the assembly method was introduced. Furthermore, the correctness of electromagnetic design methods and the stability of the proposed mechanical structure were verified based on the magnetic and mechanical finite element analysis.

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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.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this paper.

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