A fully coreless Multi-Stator Multi-Rotor (MSMR) AFPM generator with combination of conventional and Halbach magnet arrays

Asiful Habib, Hang Seng Che, Nasrudin Abd Rahim, Mahdi Tousizadeh, Erwan Sulaiman

Received 25 October 2019; revised 14 January 2020; accepted 23 January 2020

Abstract An axial flux permanent magnet (AFPM) generator is known to be a good candidate for both low and high-speed application. In this paper, a new design of fully coreless multi-stator multi-rotor (MSMR) AFPM generator has been presented with conventional and Halbach magnet arrangement combined with an ironless (epoxy) rotor. For MSMR topology of AFPM machine, back iron is still present in the middle rotor and to maintain the same distribution of magnetic flux, magnets are used on both side of the middle rotor. This paper suggests replacing the middle iron rotors with a single epoxy rotor which reduces the weight of the machine, hence increase power density. On the other hand, for the elimination of iron and magnets in the middle rotor, conventional magnet arrays are used to maintain a continuous flux path. In addition, Halbach array is adopted on the external epoxy rotor to reduce flux leakage on the external sides of the machine. The performance of the proposed generator is investigated in terms of voltage, current, power, power density, and torque ripple. The analytical design approach is first presented and subsequently validated using ANSYS Maxwell electromagnetic finite element analysis (FEA) software. It is found that a fully coreless MSMR AFPM generator with conventional and Halbach magnet arrays gives higher power density and lower torque ripple with a reduced axial length which is favorable in wind power and pico-hydro applications.

1. Introduction

AXIAL flux permanent magnet (AFPM) machines with coreless topology have some noticeable advantages compared to other conventional PM machines, such as higher power/torque...
densities, torque-to-weight ratios, and geometrically higher aspect ratios [1]. An interesting feature of the AFPM machine is the ease to cascade multiple stages of the machine to attain higher torque/power, such as multi-stator multi-rotor (MSMR) configuration. Among the different AFPM topologies [2], multi-stator multi-rotor (MSMR) configuration is considered to be not only highly efficient but also has high mechanical strength and high power density without increasing diameter of the machine [2,3]. Ship propulsions, aircraft propulsions, pumps, wind energy generation, low and high-speed PM generators are the application of multistage AFPM machines [4]. The construction of a multistage AFPM machine can be made using either double stator single rotor (DSSR) or single stator double rotor (SSDR) configurations [5]. The MSMR AFPM machines can have different topologies such as slotted or slotless, iron core or ironless, NN or NS topologies while their flux paths are the same as their single-stage structures [2]. In particular, coreless AFPM is gaining popularity in applications that require high power/torque density.

Being coreless, the machine does not experience eddy current (hence hysteresis losses) and has lower cogging torque. This allows the machine to run at higher efficiency compared to other conventional machines [6]. Moreover, the coreless structure reduces the weight of the machine significantly making it portable, which facilitates its deployment. In the literature, coreless AFPM machine usually refers to “stator coreless” where ferromagnetic structure (i.e. back-iron) is still used in the rotor [6–14]. A fully coreless design, where both rotor and stator uses non-magnetic materials, will reduce the machine weight as well as cost. Furthermore, mechanical stress also reduces as the machine does not produce attractive forces between the two rotors and stator except between the permanent magnets on the rotors. However, the use of a non-magnetic rotor will result in significant flux leakage on the back surface of the rotor and deteriorates the performance of the machine. The use of a Halbach magnet array provides an interesting solution to the issue: by amplifying the magnetic field on the useful side of the rotor and canceling the magnetic field on the back of the rotor. Several works on the use of Halbach array for AFPM has been presented in [15–19].

Though multistage AFPM machines are not widely found in the literature, several research had been done on it, which shows its scope of possibility for research. In the literature [5,20–25] the review, modeling, design, analysis have been found on multistage AFPM machine, where they have different stator (slot/slotless) and rotor (NN and NS type) structure. To the best of the author’s knowledge a fully coreless/ironless multistage AFPM machine has not been reported in the previous literature.

It is interesting to design a MSMR fully coreless AFPM generator using combinations of conventional and Halbach magnets with an ironless (Epoxy) rotor, to get a high power density in AFPM generator. For this purpose, relatively lower speed of 500 rpm has been chosen that will reduce the number of poles which in turn alleviate the design and fabrication complexity. The design has been carried out with respect to torque, voltage, current, power, machine weight and power density. The whole design process presented in the analytical equation and validated with 3-D finite element analysis (FEA) software named ANSYS Maxwell.

The paper is organized in the following sequence: the fundamental concepts of Halbach and conventional magnet arrangements are first discussed in Section 2. The analytical calculations are given in Section 3. The conventional and fundamental structure of a MSMR coreless AFPM, as well as the proposed MSMR topology is presented in Section 4. All the comparison, results and discussions for the proposed fully coreless MSMR have been given in Section 5. Finally, in Section 6 conclude the whole design.

2. Conventional and Halbach array

The arrangement of magnets is an important design criterion for AFPM machine, and two arrangements are considered here: the ‘conventional array’ and the Halbach array. For conventional array, the magnets are arranged with alternating north and south poles, either in radial (Fig. 1(a)) or tangential direction (Fig. 1(b)). The ‘Halbach Array’ can be considered as a combination of two conventional arrays (radial and tangential), as illustrated in Fig. 1(c). The arrangement of the magnet poles in the Halbach array helps to strengthen the field in one side of the array while canceling out the field on the other side (Fig. 1(d)) [19].

According to the structure of the machine, the two-disc rotors associated with magnets have an axial gap between them to fit the coil with an optimized physical gap between the magnet discs. Normally iron core rotors enhance the magnetic field and as a result, higher air-gap magnetic flux density leads to a higher power. In the case of a conventional array, the magnetic field is active for both side of the array and the use of epoxy for the rotors leaves one side of the field unused.
That is why for conventional array iron core rotors are preferable for an AFPM machine. For ironless rotor structure, Halbach array can be useful by canceling out the fluxes on the back of the rotor and strengthen up the field to the active site of the array, thus help to obtain high magnetic flux density in the air gap that leads to the high power density [26]. Fig. 2 shows the schematic of rotor poles with an opposite arrangement (N-S type) and the associated flux paths for the Halbach epoxy rotor generator. The epoxy materials used in stator and rotor are temperature and pressure resistant. Apart from that, the pole pair formation due to magnets is different from one another. In conventional array, two magnets create one pole, whereas in Halbach array four magnets create one pole. Fig. 3 shows the pole pair wavelength (\(l_a\)) of both arrays. Here magnet width to pole pitch ratio (\(a_p\)) defines the gap between the magnets. For conventional array an optimum gap (\(a_p\)) between the magnets is necessary to get a high air-gap magnetic flux, on the other hand for Halbach array to strengthen the field in one side of the array, the gap (\(a_p\)) should be as less as possible.

3. Analytical design of AFPM generator

For analytical design, some inductive design assumptions based on sizing equations are necessary. The parameters for initial design are the phase number (\(m\)), output power (\(P_o\)), speed (\(N_s\)), magnetic loading (\(B_m\)), electrical loading (\(A_m\)). For machine design, the main parameter to be decided first is diameter (\(D_{out}\)). Based on the sizing equation the \(D_{out}\) can be determined as [3,27]:

\[
D_{out} = \left( \frac{P_o}{\frac{1}{2} K_{size} B_m A_m L_{sc} \left( 1 - \lambda^2 \right) \left( \frac{1}{2} \right) } \right)^{\frac{1}{4}}
\]

where \(K_{size} = k_v k_s k_p\). For sinusoidal waveform, the values of \(k_v\), \(k_s\), \(k_p\) are briefly explained in [3,27] where maximum parameter’s value required in Eq. (1) comes from the very initial assumption. The airgap magnetic flux density \(B_g\) is normally dependent on the magnet geometry as well as magnet grade.

The ratio of inner and outer diameter (\(\lambda\)) is considered as another important parameter for AFPM machine design in maximizing the output power. From previous research, optimized values of \(\lambda\) were chosen for different AFPM design, out of which, 1/\(\sqrt{3}\) and 1/\(\sqrt{2.5}\) are common for the most of the configurations [28–30]. In the present study, the value of \(\lambda\) is chosen 1/\(\sqrt{3}\), for getting maximum power.

Fig. 2 Schematic of Poles with an opposite arrangement (N-S type) and the associated flux paths for Halbach Array in SSDR AFPM.

Fig. 3 Schematic of pole pair wavelength (a) Halbach and (b) conventional.

The rotating speed \(N_s\) is used to determine the pole number using (2) and from pole number, the coil number can be easily determined by (3).

\[
N_s = \frac{120 f}{p}
\]

(2)

\[
Q = \frac{3}{4} \times p
\]

(3)

where \(f\) is the frequency, \(p\) is the pole number and \(Q\) is the number of the coil. The electrical loading (\(A_m\)) is used for the sizing equation [27].

\[
A_m = 4 m N_{cph} I_{ph} / \pi D_{out} (1 + \lambda)
\]

(4)

where \(N_{cph}\) is the number of conductor per phase \(I_{ph}\) is the current per phase. From Eq. (5) \(N_c\) can be determined as

\[
N_c = \frac{\pi a_u D_{out} (1 + \lambda) A_m}{4QI_{ph}}
\]

(5)

where \(a_u\) is the number of parallel current paths.

3.1. Magnet geometry

The air-gap magnetic flux density \(B_g\) and PM axial height \(h_{pm}\) has a strong contribution as shown in

\[
h_{pm} = \frac{\mu_m B_g (L_{pm} + 2g)}{2 (0.9 B_r - \frac{B_g}{\lambda})}
\]

(6)

where \(\mu_m\) is the magnet permeability, \(B_r\) is PM residual flux density, \(g\) is the air-gap length and \(K_{pm}\) is PM leakage flux factor. As the machine is pure coreless the inner and outer diameter is actually the magnet outer and inner diameter. In this case, the magnet has a trapezoidal shape and is defined by the inner and outer magnet width as shown in Fig. 4. The outer magnet width (\(w_{pmo}\)), inner magnet width (\(w_{pmi}\)) and magnet length (\(L_{pm}\)) can be calculated as

Fig. 4 Schematic geometry of magnet.
w_{pmo} = \frac{2\pi r_o - (n_M x_o)}{n_M} \tag{7}

w_{pml} = \frac{2\pi r_l - (n_M x_o)}{n_M} \tag{8}

l_{pm} = w_{pmo} - w_{pml} \tag{9}

where \( n_M \) is the total number of the magnet.

3.2. Air gap magnetic flux

The main difference between the Halbach and conventional array is on the magnetic flux density and distribution, as explained in Section 2. Geometry and other parameters can be kept the same for better comparison except for the magnet size. For the different characteristics of the two topologies, the size of the magnet cannot be the same for a fixed rotor diameter. The number of magnets used for Halbach configuration is double that of the conventional array. In order to maintain the same total magnet volume, the axial height of the magnets are adjusted while the magnet length was kept constant for both. Though the wavelengths are same for the both conventional and Halbach, they have different effect for magnet width to pole pitch ratio \( (a_p) \). For conventional rotor, optimal \( a_p \) is required for less torque ripple with maximum average torque [31]. On the other hand, Halbach rotor needs to minimize the gap between magnets \((a_p = 1)\) to ensure effective cancelling of magnetic field on one side and the strengthening of flux on the other side. Thus there are two different equations for calculating \( B_g \). The equations of the air gap magnetic flux density of Halbach array and conventional array can be written as (10)-(14).

\[
B_g(h) = B_r [1 - \exp(-\beta h_{pm})] \frac{\sin(\pi/n_M)}{\pi/n_M} \tag{10}
\]

where \( \beta \) is the \( 2\pi/l_o \) and \( l_o \) is the spatial period (wavelength) of the array, \( n_M \) is the number of magnet per wavelength. For \( l_o \) the value differs for the two different topologies of Halbach array and conventional array. For Halbach array, four magnets create one full wavelength or one pole pair as there is no gap between the magnets, refer to (11). In Fig. 3, the schematic is shown for \( l_o \) [26].

\[
l_o = 4w_{pm} \tag{11}
\]

From Eq. (10) the peak value of magnetic flux density at the active surface of Halbach array can be calculated. As seen in Fig. 5, the tangential and normal component of the magnetic flux in the space between two discs are given by [26]

\[
B_x(x, z) = B_r \frac{1}{\beta} \cos(\beta x) \frac{2\sinh(Bz)}{\exp(\beta t/2)} \tag{12}
\]

\[
B_z(x, z) = B_r \sin(\beta x) \frac{2\cosh(Bz)}{\exp(\beta t/2)} \tag{13}
\]

where \( B_x \) is the tangential component (along the x-axis), \( B_z \) is the normal component (along z-axis). For the proposed design the significance of normal component is higher as the design is dual disc rotor topology of axial flux machine. At a glance, the value of \( B_x, B_z \) is minimum in the middle of the two rotor discs and closer to the magnets the value becomes maximum. For conventional array the equation [32] is given by

\[
B_g(c) = \frac{1}{\mu_0} \int \frac{r B_x B_z dS}{s} \tag{14}
\]

where \( \mu_0 \) is the permeability of free space, \( r \) is the radius of the rotor, \( S \) is the integration surface of the mid plane of the air-gap, \( B_x \) and \( B_z \) depend on the optimized geometry of the machine parameter, like \( a_p \).

3.3. Stator coil geometry

For higher efficiency and lower cost, non-overlapping concentrated windings have been used since it needs less volume of copper which reduces the copper losses and increases generator efficiency. In this design single layer trapezoidal coil shape is chosen for shortening the end winding length \( l_c \) as compared to active coil length \( l_{w_c} \) of the coil that helps to maximize the coil flux linkage. A shorter \( l_c \) reduce the resistive losses in the inactive part of the coil. The calculation of \( l_c \) and \( w_c \) are done based on the design for non-overlapping windings [33]. Fig. 6 shows the schematic of the coil geometry. On the other hand, only the stator coil axial height \( (l_{w_c}) \) and coil cross-section area \( (S_{c_1}) \) is considered because the coil height has an impact on the geometry of the axial height of the machine via the air-gap length from magnet associated rotor disk to another side of the rotor disk. An optimized \( l_{w_c} \) is required for higher output power. A large \( l_{w_c} \) increases the total air-gap length as well as the active area length of the magnetic flux density and finally will decrease the magnetic flux density in the air-gap. On the
other hand, very short axial length will require a higher \( S_w \) in a result large width of coil \( w_c \). For a fixed diameter the high \( w_c \) increases the difficulty to fit all the coils in the limited circular space. The \( L_{sw} \) and \( S_w \) can be obtained as follows:

\[
S_w = \frac{2I_{ph}N_c}{K_f\alpha_p J_a}
\]  

(15)

\[
L_{sw} = \frac{2S_w Q}{k_S\pi D_{in}}
\]  

(16)

Table 1  Difference of figures for two topology.

<table>
<thead>
<tr>
<th>Conventional MSMR</th>
<th>Proposed MSMR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Complete model for Axial length</td>
<td>Complete model for Axial length</td>
</tr>
<tr>
<td>Whole model for different parts</td>
<td>Whole model for different parts</td>
</tr>
<tr>
<td>Flux Path</td>
<td>Flux Path</td>
</tr>
</tbody>
</table>

Fig. 7  Schematic of Internal and external rotor with conventional and Halbach magnet arrays respectively.

Fig. 8  Resistive load of different MSMR for a fixed stator current.

\[ S_w = \frac{2I_{ph}N_c}{K_f\alpha_p J_a} \]  

(15)

\[ L_{sw} = \frac{2S_w Q}{k_S\pi D_{in}} \]  

(16)

where \( K_f \) is the fill factor, \( J_a \) is the current density, and \( k_S \) is the space utilization factor. For coil winding, \( K_f \) is an important factor as it signifies the cross-section of the coil \( S_w \). As a rule of thumb, the value of \( K_f \) for manually constructed winding with circular cross section is around 0.55–0.78 [34] The factor \( k_s \) is related to the mechanical strength of the stator structure. The coreless structure should be mechanically strong enough to hold the coils and against the attraction of magnets. Winding factor \( (K_w) \) is another important parameter for the
coil design as well as the total torque and the power, which is typically a value between $0.9 \leq K_w \leq 1$ \cite{35}.

### 3.4. Magnetic pull on rotor discs

In a SSDR AFPM generator there exist magnetic pull between the two rotors which exerts mechanical stress to the structure. For ironless rotor, this magnetic pull is due to the magnetic attractions between the magnets, while for the case of iron rotor, additional attraction exists between the magnets and the iron rotors.

The attraction force due to two magnets placing in a distance of $g$ apart, with a magnet surface area of $S_{PM}$, a magnet thickness of $t_{PM}$ and an air-gap magnetic flux density $B_g$ can be expressed as follows:

$$F = \frac{2 \cdot B_g \cdot h_{PM} \cdot S_{PM}}{\mu_0 g^2}$$

(17)

### 4. MSMR coreless AFPM generator

Multistage AFPM generator can be based on double stator single rotor (DSSR) or single stator double rotor (SSDR) configurations \cite{5}. Here, the SSDR configuration is selected, where N-stage MSMR machine will have N stators and (N + 1) rotors. For the purpose of discussion in this paper, a two-stage ($N = 2$) MSMR machine is considered.

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Common input parameters for all four topology.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter Name</td>
<td>Unit</td>
</tr>
<tr>
<td>General parameters</td>
<td></td>
</tr>
<tr>
<td>Number of Pole ($P$)</td>
<td>–</td>
</tr>
<tr>
<td>Number of rotors</td>
<td>3</td>
</tr>
<tr>
<td>Number of coreless stators</td>
<td>2</td>
</tr>
<tr>
<td>Number of Coils ($C$)</td>
<td>–</td>
</tr>
<tr>
<td>Rotational Speed ($N$)</td>
<td>rpm</td>
</tr>
<tr>
<td>No of Turns per Coil ($N_C$)</td>
<td>–</td>
</tr>
<tr>
<td>Specific design parameters</td>
<td></td>
</tr>
<tr>
<td>Ratio of Inner &amp; Outer diameter ($\lambda$)</td>
<td>–</td>
</tr>
<tr>
<td>Outer Diameter ($D_o$)</td>
<td>mm</td>
</tr>
<tr>
<td>Inner Diameter ($D_i$)</td>
<td>mm</td>
</tr>
<tr>
<td>Air-gap between rotor &amp; stator ($t_g$)</td>
<td>mm</td>
</tr>
<tr>
<td>Density of magnet (NdFeB)</td>
<td>g/cm$^3$</td>
</tr>
<tr>
<td>Iron Density (steel M19G)</td>
<td>g/cm$^3$</td>
</tr>
<tr>
<td>Epoxy Density</td>
<td>g/cm$^3$</td>
</tr>
<tr>
<td>Copper Density</td>
<td>g/cm$^3$</td>
</tr>
<tr>
<td>Magnet Length ($M_L$)</td>
<td>mm</td>
</tr>
<tr>
<td>Total Magnet Volume ($M_V$)</td>
<td>mm$^3$</td>
</tr>
<tr>
<td>Magnet Weight</td>
<td>kg</td>
</tr>
<tr>
<td>Stator coil weight</td>
<td>kg</td>
</tr>
<tr>
<td>Stator epoxy weight</td>
<td>kg</td>
</tr>
<tr>
<td>Coil Axial thickness ($t_{CA}$)</td>
<td>mm</td>
</tr>
<tr>
<td>Coil Bandwidth ($C_BW$)</td>
<td>mm</td>
</tr>
<tr>
<td>Conventional rotor thickness ($t_{CR}$)</td>
<td>mm</td>
</tr>
<tr>
<td>Halbach rotor thickness ($t_{HR}$)</td>
<td>mm</td>
</tr>
<tr>
<td>Modified Rotor thickness ($t_{Mot}$)</td>
<td>mm</td>
</tr>
<tr>
<td>Magnet Width pole Pitch ratio ($a_p$)</td>
<td>–</td>
</tr>
<tr>
<td>Number of Magnet ($M_n$)</td>
<td>–</td>
</tr>
<tr>
<td>Magnet Upper Width ($M_{HU}$)</td>
<td>mm</td>
</tr>
<tr>
<td>Magnet Lower Width ($M_{HL}$)</td>
<td>mm</td>
</tr>
<tr>
<td>Magnet Axial Thickness ($t_{MA}$)</td>
<td>mm</td>
</tr>
<tr>
<td>Rotor Weight</td>
<td>kg</td>
</tr>
<tr>
<td>Total weight of the Generator</td>
<td>kg</td>
</tr>
<tr>
<td>Total Axial Length of Machine ($T_L$)</td>
<td>mm</td>
</tr>
<tr>
<td>Load Resistance</td>
<td>$\Omega$</td>
</tr>
</tbody>
</table>

*(C): Internal rotor with conventional magnet array and (H): External rotor with Halbach magnet array

![Fig. 9](image-url)  
Fig. 9 Plane region for proposed MSMR generator.
4.1. Conventional direct cascade

The simplest form of MSMR machine is to directly cascade two or more AFPM machine together [2]. For example, two sets of SSDR machines can be simply combined to yield a two-stage MSMR to increase the torque/power while maintaining the machine’s diameter. As illustrated in the left column of Table 1, the direct cascade MSMR has 2 stators and effectively 3 rotors (2 external rotors and 1 internal rotor). Due to direct cascading, the internal rotor is essentially back-to-back rotors of a SSDR machine. The stator coils are single layer concentrated windings of trapezoidal geometry which are embedded in epoxy and covered with composite material hardener to ensure sufficient mechanical strength.

4.2. Proposed topology

Here, a fully coreless MSMR AFPM machine is proposed where the iron rotors are replaced with epoxy rotors to improve the torque and power density. There are two significant modifications to the convention direct cascade MSMR machine:

1. Halbach arrays are used on the external rotors to avoid leakage flux toward the exterior of the machine.
2. The back-to-back internal rotors are combined into a single internal epoxy rotor with conventional magnet array to simplify design and save materials.

By analyzing the flux path, it can be observed that the proposed topology retains similar path with the conventional direct cascade MSMR machine. However, the proposed topology is more compact and has lower weight due to the elimination of the back iron on the rotor. The magnet volume is kept constant as previous direct cascaded MSMR, by adjusting the magnet thickness of each rotor disc. Hence the thickness of the magnets of two external discs rotor and the thickness of the magnets of internal rotor are same whereas the total number of magnets are increased here from previous direct cascade MSMR. Fig. 7 shows the difference between the external rotor and internal rotor of the proposed MSMR AFPM machine. The rotor structure is formed by trapezoidal shape magnets, rotor core, and shaft. The gap between the rotor and stator are kept at 0.5 mm on both sides for both topologies. For stator part, the proposed topology maintains the same stator coil numbers, windings layout and geometry used in the direct cascade MSMR.

In addition, the current loading for the stator coil is fixed here, in order to get the performance of the modified rotor design. To make a fair comparison with the direct cascade MSMR, a fixed stator current of 5.23 A peak is considered here based on the stator wire gauge, which is AWG16. Fig. 8 represents the different load resistance for both MSMR with a fixed current loading. Since the back emf of the proposed MSMR and conventional MSMR generators are slightly different, proper load resistance need to be selected to obtain the same current loading. As seen in Fig. 8, the current drawn from the generator reduces when load resistance increases. For a fixed 5.23 A peak stator current (black color line), the value of the load resistance is 38.50 Ω for proposed MSMR and 41.10 Ω for conventional MSMR. As the two different magnet arrangements (conventional and Halbach) are used in the design, the proposed machine is named as “fully coreless MSMR Halventional AFPM” generator. The generator is designed with 12 poles, and 18 coils (both stators) for a speed of 500 rpm at 50 Hz. The input parameters for the proposed and direct cascade design are shown in Table 2. The weights of machines are obtained by multiplying the volume of the
components (using dimensions obtained from FEA software) with the densities of the respective materials. However, the plane region of the whole model for proposed design has been given in Fig. 9 for better understanding of the design.

4.3. Analysis of mechanical deflection of rotor

For the construction of the MSMR AFPM machine, the two opposite rotors attached with magnets are attracted to each other. Although attraction force works for both ferromagnetic and non-ferromagnetic rotor, for non-ferromagnetic rotor it is slightly less. The strong attraction force between the magnets imposes an opposite pulling force on the rotor that tends to bend the rotor structure leading to a collision between the

---

Fig. 12 Air-gap magnetic flux density in the mid of air-gap between the internal and external rotors (Proposed Design).

Fig. 13 Simulated flux path for the conventional (left) and proposed (right) MSMR AFPM generator (hiding the external rotor discs).

Fig. 14 Magnetic flux density of the stator coils (flux linkage) for conventional MSMR.

Fig. 15 Magnetic flux density of the stator coils (flux linkage) for Proposed MSMR.
rotor and stator or can reduce the air-gap distance between them; as a result, a non-uniform and unbalanced magnetic flux density will be formed in the air-gap. Hence, mechanical deflection is another important point of consideration to design optimum rotor thickness for the four topologies. Eq. (17) is showing the force calculation for the magnetic pull on rotor discs. To find an optimum thickness of the rotor, the force is applied to the various thickness of the rotor for both ferromagnetic and non-ferromagnetic material. In order to do that four rotors have been chosen for bending test with different combination of magnet arrangement and material selection. The two different magnet arrangements (Conventional and Halbach), are combined with two different materials (iron and epoxy) of the rotor, to give the following four types of rotor:

(i) Conventional magnet array with iron rotor (C-I Rotor)
(ii) Conventional magnet array with epoxy rotor (C-E Rotor)
(iii) Halbach magnet array with iron rotor (H-I Rotor)
(iv) Halbach magnet array with epoxy rotor (H-E Rotor)

The major difference among the four topologies lies in the arrangement of the magnets and disparity of materials for the rotor discs. Fig. 10 shows the deflection of the rotor from von Mises stress analysis for the four topologies, while Fig. 11 shows the particular von Mises test result from the AutoCAD Mechanical.

It is evident that deflection is higher in non-ferromagnetic rotor compared with ferromagnetic material. Thus, to ensure that deflection is within the acceptable range thickness of non-ferromagnetic rotor should be greater than that of the ferromagnetic one. According to Fig. 10, the thickness of 8 mm and 4 mm is chosen for C-I and H-I Rotor respectively that comes with negligible deflection values which is 10% of allowable bending. On the other hand, with the maximum allowed deflection of 0.2 mm, the thickness of the C-E and H-E Rotor are selected to be 18 and 10 mm respectively which is safe bending for the epoxy rotors.
5. Results and performance comparison

The results and performance of the proposed design are analyzed based on four important parameters, i.e., average torque, power, power density, and torque ripple. For analyzing the above parameters some fundamental parameters like magnetic flux density, voltage, current, FFT of voltage and magnetic flux are considered and present here. The simulated results for both magneto-static and transient (ANSYS Maxwell) are provided here for the better understanding and analyzing of the proposed design. From the magneto-static simulation, the magnetic flux density of the machine shows underneath in various point of view. Figs. 12–15 is showing all the magnetic flux density analysis from simulation results. Fig. 12 shows mid-air gap flux density for both upper and lower side of the Proposed design. Fig. 13 shows the flux density for the whole machine for both conventional and proposed MSMR, whereas Figs. 14 and 15 are showing the magnetic flux density of the stator coils, where Fig. 14 is for the conventional (direct cascade) MSMR and Fig. 15 is for the proposed (Halventional) MSMR. Since the two machines utilize the same stator coils, both figures look similar apart from the separation between two sets of stator coils. It is worth highlighting that even though the overall volume of the proposed MSMR is significantly smaller than the conventional MSMR generator, the peak flux densities of the two machines are comparable. This is the reason why the proposed MSMR generator is able to achieve better torque density than the conventional MSMR generator. Figs. 16–18 show the voltage, current, average torque, and torque ripple \( (T_{rk}) \) respectively for the both proposed and conventional MSMR generator. The proposed generator is able to deliver sinusoidal voltage and current similar to the conventional MSMR which is required for a three-phase generator. Here it is important to mention that the current (Fig. 17) is same for the both design as it was designed with same stator current loading. In terms of torque ripple, the proposed MSMR machine shows lower torque ripple of 13.2% compared to 18.6% in the direct cascade MSMR machine (Fig. 18). Figs. 19 and 20 show the FFT of the magnetic flux density of the two machines. It can be concluded that the flux density is the direct cascade.

MSMR is higher which translate to higher voltage and torque generated. However, there is slightly higher 3rd and 7th harmonic current in the machine which can contribute to the higher torque ripple when compared to the proposed MSMR machine. Although the 5th harmonic in the proposed design is higher than the conventional design, it cannot affect the torque ripple of the proposed design as the overall torque ripple reduction happened due to the lower 3rd and 7th harmonics. Table 3 shows the performance comparisons between the proposed MSMR with direct cascade MSMR which are further illustrated in Fig. 21. The proposed fully coreless MSMR Halventional AFPM generator offers higher power density, lower torque ripple and lower axial length of the whole generator. The higher power density comes basically from two important modification of the generator. The first one is the reduction of the internal rotor as well as one side of magnets and the second one is the combination of the Halbach and conventional magnets. The lower torque ripple comes for lower amplitude of the 3rd and 7th harmonic, which has less interaction with the fundamental harmonics. The reduced axial length of the machine is the cause of internal rotor modification as well as the one side magnet array elimination.

6. Conclusion

This paper demonstrated the possibility to implement a fully coreless MSMR AFPM by implementing a novel structure instead of mere cascading the AFPMs. The proposed design combines the use of Halbach array and conventional magnet arrays to achieve desirable characteristics: Halbach arrays are used for the external rotors to eliminate rotor back iron, while the internal rotors uses simple conventional magnet arrays for better flux density and lower complexity. Detailed design considerations were discussed to obtain the desired electromagnetic performance of the proposed machine. In addition, von Mises stress analysis was conducted to determine the required rotor thickness in the proposed coreless structure to compensate for the reduction in structural strength. Analysis showed that even though 80% increase in rotor thickness is necessary there is still a net reduction in the overall machine’s weight due to the substitution of iron rotor with epoxy rotor.

The proposed structure was validated using ANSYS Maxwell® 3D FEA software and compared with direct cascaded

<table>
<thead>
<tr>
<th>Machine Name</th>
<th>Generator Weight (kg)</th>
<th>Power (Watt)</th>
<th>Power density (W/kg)</th>
<th>Average torque ( (T_{avg}) )</th>
<th>Torque Density ( (Nm/kg) )</th>
<th>Torque per unit Volume ( (Nm/mm^3) )</th>
<th>Torque Ripple ( (T_{rk}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct cascaded MSMR</td>
<td>6.84</td>
<td>1659</td>
<td>242</td>
<td>31.69</td>
<td>4.63</td>
<td>( 1.10 \times 10^{-5} )</td>
<td>18.6%</td>
</tr>
<tr>
<td>Proposed MSMR</td>
<td>5.87</td>
<td>1510</td>
<td>257</td>
<td>28.85</td>
<td>4.91</td>
<td>( 1.32 \times 10^{-5} )</td>
<td>13.2%</td>
</tr>
</tbody>
</table>

Table 3 Performance comparison of two MSMR AFPM generator.
MSMR AFPM. Simulation results showed that even though eliminating rotor back iron reduces the air gap flux density slightly the proposed structure still provide numerous advantages over direct cascaded MSMR AFPM like:

1. increasing power density by 6%
2. reducing torque ripple by 5.4%
3. reducing axial length by 24%

Furthermore, the fully coreless structure provides interesting potential for cost saving, not only in terms of the material (substituting iron with plastic), but also manufacturing cost via the use of additive manufacturing (3D printing).

Declaration of Competing Interest

The authors declared that there is no conflict of interest.

Acknowledgment

The authors thank the technical and financial assistance of Ministry of Education Malaysia, University Malaya and UM Power Energy Dedicated Advanced Centre (UMPEDAC). This project is funded by the Higher Institution Centre of Excellence (HICoE) Program Research Grant, Fundamental Research Grant Scheme MO013-2016, UMPEDAC-2018 (MOHE HICoE-UMPEDAC), RU007-2018 and RU012-2019.

References


