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Analysis of a Coaxial Magnetic Gear Optimally Designed Using Particle Swarm Optimization

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Abstract

One important key to improve the efficiency of adjustable speed drives is using magnetic gears due to their advantages in comparison to their mechanical counterparts. This paper introduces an analysis study for a magnetic gear optimally designed using the particle swarm optimization algorithm (PSO). Moreover, the results of the PSO-based design are compared with the results of another optimization design process based on a genetic algorithm for the same design parameters and constraints. The proposed magnetic gear topology to be optimized is a radially magnetized coaxial configuration with a surface-mounted permanent magnet array. The gear ratio \( G_r \) of the proposed magnetic gear is chosen to be 3.5 while the cogging factor sets at one. Using PSO in magnetic gear design aims to facilitate torque transmission in the maximum possible value while minimizing torque ripples. The performance analysis of torque results and flux density waveforms of the proposed magnetic gear is conducted through the use of Finite Element Analysis (FEA). The results analysis of the proposed magnetic gear shows superior torque production with minimal ripples and customized dimensions thanks to the PSO-based design.

Keywords: 2-D finite element analysis, Coaxial magnetic gear, Finite element method magnetics, Permanent magnets, Particle swarm optimization

1. Introduction

Mechanical gears are frequently utilized across various applications to facilitate the transmission of torque and enable speed modulation between the moving components. Specifically, they are implemented in electric traction systems to reduce speed and in wind energy applications to amplify speed. Nevertheless, these conventional gears are susceptible to drawbacks such as mechanical losses, gear noise, and the ongoing requirement for lubrication. In contrast, magnetic gears (MGs) demonstrate the ability to transmit torque without physical contact, utilizing magnetic interaction principles between their permanent magnets (PMs)-carrying parts (Jing et al., 2019a). Henceforth, MGs have emerged as a contemporary technological alternative to conventional mechanical gears, owing to numerous benefits including reduced vibration, diminished noise, and lower heat generation attributed to decreased contact friction. MGs are characterized by their maintenance-free nature, as there is no necessity to lubricate and cool the gears, and additionally have a built-in feature to protect from overloads (Jing et al., 2019b). Furthermore, they can transmit torque and speed in a straightforward and uncomplicated way (Jing et al., 2014). However, MGs initially garnered limited interest owing to the suboptimal torque density they could generate and the intricate parallel shaft configuration (Hesmondhalgh and Tipping, 1980; Tsurumoto and Kikuchi, 1987; Ikuta et al., 1991; Yao et al., 1996). Subsequently, numerous configurations of MG topologies employing rare-earth PMs are introduced, resulting in elevated torque density (Rens et al., 2008; Huang et al., 2008).

The comparative analysis outlined in (Gouda et al., 2010) between MGs and mechanical gears substantiates that MGs, characterized by reduced volumes, outperform their mechanical counterparts.
This superiority is evident, with the additional benefit of circumventing inherent mechanical limitations. Research on the development of MGs is ongoing, exemplified by a comparative investigation presented in reference (Park et al., 2020), which examines the properties of MGs employing NdFeB and ferrite PM materials. Reference (Jing et al., 2020) introduces an innovative Hybrid-Excited MG featuring an eccentric PM configuration, and its performance is evaluated through comparison with a conventional coaxial counterpart for enhancement. The researchers in (Gardner et al., 2021) propose an optimized design for a coaxial MG, considering various temperatures and \( G_r \). An alternative optimized design is presented in (Kashani, 2021) featuring two distinct rotor structures, called the Flux Barrier and the salient pole rotor structure. These configurations are suitable for scenarios where the incorporation of PMs on the high-speed rotor is constrained due to mechanical limitations. Previous research efforts have proficiently identified patterns and offered valuable insights into prevailing trends. Further academic papers (Niu et al., 2012; Fu and Li, 2016; McGilton et al., 2017; Wang et al., 2023; Mao and Yang, 2022; Sepaseh et al., 2022; Ruiz-Ponce et al., 2023) has centered on advancing the implementation of MG technology within the industrial sector through the development of methods that aim to facilitate the design of MGs in an efficient and optimized manner in order to achieve any system requirements exactly. In (Niu et al., 2012), the authors optimally designed an MG using the mesh adjustable finite-element algorithm (MAFEA) to achieve maximum torque density. Although MAFEA is well-suited for handling complex structures like MGs, the process can be computationally intensive and time-consuming. In (Fu and Li, 2016), the researchers employed the Tabu Search algorithm in the MG design process to obtain the optimal torque value. While the Tabu Search algorithm is capable of exploring a wide solution space, it is characterized by its inherent complexity with convergence speed mostly depending on the selection of parameters. In addition, it may not efficiently handle the constraints of the optimization problem. In (McGilton et al., 2017; Wang et al., 2023), a genetic algorithm (GA) was employed to achieve the optimal design of magnetic gears and maximize the output torque. Although the GA has a high convergence rate, it may become trapped in the local optimal solution. In addition, GA has high sensitivity to the choice of crossover and mutation rates (Mao and Yang, 2022). Studies in (Sepaseh et al., 2022; Ruiz-Ponce et al., 2023) performed optimization techniques to design an axial flux MG. However, for most applications, the radial flux MG exhibits superiority over the axial flux MG (Gardner et al., 2018).

Hence, this paper employs particle swarm optimization (PSO) as an optimization technique for a radial flux coaxial MG. The proposed MG features the optimized topology identified in (Mao and Yang, 2022) and a cost-effective PM arrangement determined in (Niu and Mao, 2016). The main objective of this optimization process is to determine the thickness of each region within the proposed MG that can maximize the output torque considering flux density saturation and other constraints. PSO can handle the design objective function and its constraints effectively. Additionally, it is characterized by the simple implementation as well as low parameter tuning. Furthermore, PSO exhibits lower computational intensity compared to other techniques (Shami et al., 2022). In order to validate the proposed optimization design, a performance comparison of PSO and GA based optimization for the proposed MG under same conditions and constraints is provided. The comparison focuses on evaluating the achievement of the most optimal results in terms of output torque value and torque ripple. Furthermore, a performance analysis of the optimally designed coaxial MG using PSO is presented. Table 1 outlines the principal features of the proposed system in comparison to previous publications, reflecting the contributions of this work. The proposed MG is designed with a gear ratio \( G_r = 3.5 \). There are several uses for this design, such as electric propulsion systems in addition to wind energy applications that improve harmonic characteristics and minimize the necessity for back-to-back power electronic converters. Moreover, the suggested MG has the capability to function as a clutch in numerous motor drive applications, providing silent operation as an additional benefit.

This paper is organized as follows. The formulation of mathematical modeling and design aspects are given in section 2, whereas the identification of MG’s parameters is given in section 3. The PSO procedures are proposed in section 4 while the performance and result analysis of the simulated case study is presented in section 5. Finally, a conclusion is drawn in section 6.

2. Formulation of mathematical modeling and design aspects

2.1. Construction of the proposed model

The proposed MG, as depicted in Fig. 1, comprises three primary components. These include an inner
rotor (R_{inner}) and an outer rotor (R_{outer}) housing p_1 and p_3 PM pole-pairs, respectively. Additionally, a stationary segment featuring n_2 ferromagnetic pole pieces (FMPPs) is situated between the R_{inner} and the R_{outer}. The FMPPs act as a modulation mechanism situated between the R_{inner} and the R_{outer}. The most optimal configuration for achieving the maximum torque transmission capability is outlined in reference (Gouda, 2014):

\[ n_2 = p_1 + p_3 \]  

(1)

The formula denoted as (2) elucidates the Gr, computation, which establishes the correlation between the speeds of the rotors and their respective torques in the aforementioned configuration.

\[ G_r = \frac{p_3}{p_1} \frac{T_3}{T_1} = \frac{-\omega_1}{\omega_3} \]  

(2)

Where T_1 and T_3 represent the torques exerted by the R_{inner} and the R_{outer}, respectively, whereas \( \omega_1 \) and \( \omega_2 \) denote the angular velocities of the R_{inner} and the R_{outer}, respectively.

2.2. Cogging torque factor

Cogging torque manifests in MGs as a result of the attractive forces between the PMs on the rotors and the FMPPs (Rens et al., 2008). Therefore, the component of the gear system that exerts the most significant cogging torque is the high-speed (inner) rotor, as indicated by (Gouda et al., 2010). Cogging torque leads to fluctuations in torque output, giving rise to undesirable phenomena such as torque ripples, which, in turn, induce undesired speed variations, vibrations, and audible noise. Consequently,
it is imperative that the design of both the Rinner and the Rout outer focuses on minimizing cogging torque.

The term ‘cogging factor (Cf)’ as introduced in (Zhu and Howe, 2000), serves as a criterion for choosing the optimal combination of FMPPs and PMs for each rotor in a PM machine. This factor aids in the selection process, specifically concerning minimizing cogging-related considerations:

\[
C_f = \frac{2p_1 \times n_2}{\text{LCM}(2p_1, n_2)}
\]  

(3)

Where LCM denotes ‘Least Common Multiple’.

Generally, enhancements to both the cogging factor and the magnitude of cogging torque can be achieved through an increase in the LCM and/or a reduction in the number of poles. Furthermore, careful choice of the parameters \(p_1\) and \(n_2\) leads to a diminished cogging torque on the Rinner and optimizing their values contributes to attaining the best possible cogging factor (i.e., \(C_f = 1\)) according to (Gouda et al., 2010). In the suggested MG system featuring a \(G_r = 3.5\), the selection of parameters \((p_1 = 2, n_2 = 9, p_3 = 7)\) results in an optimal configuration that maximizes torque transmission capability while minimizing cogging torque.

3. Identification of MG’s parameters

To attain an optimal design for the MG and maximize torque capability, the effective dimensions of the proposed MG undergo optimization through a formulated optimization problem. Typically, the optimization problem comprises three primary components: the objective function, constraints, and decision variables. The primary goal of the objective function, denoted as \(F_{obj}\), is to maximize the output torque \(T_{out}\) generated by the MG for the same MG’s volume. The focus of optimal design pertains to the dimensions of the MG. The objective is to determine the appropriate thickness for each region within the MG, as illustrated in Fig. 2, with the goal of achieving maximum torque while ensuring that the flux density does not surpass the saturation threshold \((B_{sat} = 1.5\ \text{Tesla})\). It is worth noting that certain parameters of the proposed MG have predetermined values based on the specified size and mechanical considerations. These parameters are held constant to meet the required design criteria such as:

(1) The radius of the shaft.
(2) The axial length.
(3) The external radius of the Rout outer \((R_{out})\).

(4) The thicknesses of the air gaps, denoted as \((W_3, W_5)\), are fixed at 2 mm due to mechanical considerations.

Table 2 provides the values for the constant parameters of the proposed MG. As a result, \(T_{out}\) is expressed as a function dependent on the other unknown parameters pertaining to the proposed MG, serving as the decision variables in the optimization problem (4). The constraints specified in (5) are taken into consideration for the optimization problem associated with \(T_{out}\).

\[
F_{obj} = \max [T_{out}(W_1, W_2, W_4, W_6, W_7)]
\]  

(4)

\[
\begin{align*}
W_{1\_min} & \leq W_1 \leq W_{1\_max} \\
W_{2\_min} & \leq W_2 \leq W_{2\_max} \\
W_{4\_min} & \leq W_4 \leq W_{4\_max} \\
W_{6\_min} & \leq W_6 \leq W_{6\_max} \\
W_{7\_min} & \leq W_7 \leq W_{7\_max}
\end{align*}
\]

(5)

Here, \(W_{1\_min}\) and \(W_{1\_max}\) represent the minimum and maximum values, respectively, for the back-iron thickness of the MG Rinner \((W_1)\). Similarly, \(W_{2\_min}\) and \(W_{2\_max}\) denote the minimum and maximum values for the Permanent Magnet (PM) thickness of the MG’s Rinner \((W_2)\). \(W_{4\_min}\) and \(W_{4\_max}\)

<table>
<thead>
<tr>
<th>Description</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius of MG’s shaft</td>
<td>mm</td>
<td>20</td>
</tr>
<tr>
<td>Air gaps in MG ((l_g))</td>
<td>mm</td>
<td>2</td>
</tr>
<tr>
<td>External radius of MG’s outer rotor</td>
<td>mm</td>
<td>125</td>
</tr>
<tr>
<td>Axial length ((l))</td>
<td>mm</td>
<td>100</td>
</tr>
<tr>
<td>Permanent magnet remanence</td>
<td>Tesla</td>
<td>1.25</td>
</tr>
<tr>
<td>Saturation value of flux density ((B_{sat}))</td>
<td>Tesla</td>
<td>1.5</td>
</tr>
</tbody>
</table>
represent the minimum and maximum values for the FMPPs thickness of the MG (\( W_4 \)), while \( W_{6,\text{min}} \) and \( W_{6,\text{max}} \) correspond to the minimum and maximum values for the PM thickness of the MG’s \( R_{\text{outer}} \) (\( W_7 \)). Lastly, \( W_{7,\text{min}} \) and \( W_{7,\text{max}} \) signify the minimum and maximum values for the back-iron thickness of the MG’s \( R_{\text{outer}} \) (\( W_7 \)).

4. PSO procedures

In 1995, James Kennedy and Russell Eberhart introduced PSO, an optimization algorithm inspired by the social interactions observed in birds and fish. This algorithm mimics the collaborative and communicative behavior of individuals within a group, referred to as particles. The objective is to collectively explore and communicate to discover the optimal path or location within a specified search space (Kennedy and Eberhart, 1995). The steps involved in PSO, along with their corresponding mathematical expressions, are outlined as follows:

(1) PSO’s parameters initialization: space search domain, number of unknown variables \( (m) \), size of population (i.e., number of particles) \( (n) \), inertia factor \( (w) \), damping ratio of inertia factor \( (w_{\text{damp}}) \), personal and social acceleration coefficients \( (C_1, C_2) \), convergence criterion, iteration time \( (\Delta t) \) maximum number of iterations \( (t_{\text{max}}) \), etc.

(2) Particle Initialization: PSO algorithm is initiated with a set of randomly generated particles, with each individual particle constituting a potential solution.

   a) Initialize the position \( (x_i^0) \) randomly for each particle.
   b) Initialize the velocity \( (v_i^0) \) randomly for each particle.

   c) Calculate the initial best position \( (P_i^0) \) for each particle corresponding to each particle’s initial position.

   d) Evaluate the global best position among the initial particles \( (g^0 = \max f(P_i^0)) \).

Where \( i \) refers to the particle number.

(3) Update the velocity of each particle for the next iteration \( v_{i}^{t+1} \) by equation (6):

\[
v_{i}^{t+1} = w_t v_{i}^{t} + c_1 r_1 (P_i^t - x_i^t) + c_2 r_2 (g^t - x_i^t) \tag{6}
\]

Where \( t \) denotes the iteration number, whereas \( r_1 \) and \( r_2 \) represent a randomly selected value falling within the range \([0, 1]\).

(4) Update the position of each particle for the next iteration \( x_{i}^{t+1} \) by equation (7):

\[
x_{i}^{t+1} = x_{i}^{t} + v_{i}^{t+1} \Delta t \tag{7}
\]

(5) Update the best position for each particle for the next iteration \( (P_i^{t+1}) \) by equation (8):

\[
\begin{cases}
\text{If } f(x_{i}^{t+1}) > f(P_i^t) \rightarrow (P_i^{t+1}) = x_{i}^{t+1} \\
\text{Otherwise } (P_i^{t+1}) = P_i^t
\end{cases} \tag{8}
\]

(6) Update the global best position among the updated particles for the next iteration \( (g^{t+1}) \) by equation (9):

\[
\begin{cases}
\text{If } f(x_{i}^{t+1}) > f(g^t) \rightarrow (g^{t+1}) = x_{i}^{t+1} \\
\text{Otherwise } (g^{t+1}) = g^t
\end{cases} \tag{9}
\]

(7) If the following stopping criteria is achieved, terminate the solution, and output \( g^{t+1} \) as the optimal solution. Otherwise, repeat from step (3)

   a) \( t \geq t_{\text{max}} \), or
   b) \( \Delta g = \varepsilon \).

Where \( \Delta \) denotes the difference between the current and the last solution, whereas \( \varepsilon \) is a very small number \( = 10^{-5} \).

The preceding procedures of the PSOs are encapsulated in a flowchart, depicted in Fig. 3.

5. Performance and result analysis of the simulated case study

The application of the finite element method in the analysis produces results closely aligned with realistic outcomes. In comparison to other methods, the two-dimensional Finite Element Analysis (FEA) simulation is relatively rapid, with the model’s uncomplicated setup contributing to time savings. At the beginning, the proposed MG is simulated by utilizing the Finite Element Method Magnetics (FEMM) program (Wang et al., 2023), in combination with PSO techniques implemented through MATLAB subroutines. The flowchart of using the FEMM program combined with the PSO algorithm is depicted in Fig. 4. Then, the identical proposed MG is optimized using the GA technique along with the FEMM program to compare its results with the PSO.

The specifications of the used Laptop are Intel(R) Core (TM) i5-6440HQ CPU 2.60 GHz with installed RAM of 16 GB. The FEMM provides an exceptional level of flexibility, allowing for the analysis of a broad spectrum of topologies, even those with random variations. The applied torque on both the inner and
Fig. 3. PSO flowchart.
The static torque of the \( R_{\text{inner}} \) can be computed, utilizing the FEMM program, by rotating the \( R_{\text{inner}} \) one-half of a full revolution while the other components remain stationary. Fig. 6 depicts the static torque of the \( R_{\text{inner}} \) for the PSO-based MG design. The maximum torque \( (T_{\text{max}}) \) is approximately 108 Nm. The fluctuation in \( T_{\text{max}} \) can be determined by maintaining the FMPPs fixed. Subsequently, the shift angle between the \( R_{\text{inner}} \) and the \( R_{\text{outer}} \) is maintained constant at the \( T_{\text{max}} \) position. Following this, the rotors are revolved in opposite directions while maintaining their relative angular positions and taking the \( G_r \) into account. Fig. 7 shows the fluctuation in \( T_{\text{max}} \) for both rotors in the PSO-based MG design, while Fig. 8 illustrates the fluctuation in \( T_{\text{max}} \) for both rotors in the GA-based MG design. It can be noted that the torque ripple for the high-speed rotor (i.e., \( R_{\text{inner}} \)) for the PSO-based MG design is slightly less than for the GA-based MG design. Hence, the variation in the \( T_{\text{max}} \) for both rotors is highly negligible and can be disregarded. This is due to the predetermined selection of MG combination \((p_1, n_2, p_3)\) that achieves a minimal cogging torque \( (i.e., C_f = 1) \).

For the PSO-based MG design, the absolute value of average torque for the \( R_{\text{inner}} \) is \( \sim 100 \) Nm, whereas the corresponding value for the \( R_{\text{outer}} \) is 350 Nm. This indicates that the ratio of the average torque for the \( R_{\text{outer}} \) to that of the \( R_{\text{inner}} \) is nearly 3.5, consistent with the required \( G_r \) for the designed MG. The same required \( G_r \) is achieved for the GA-based MG design.

It is worth noting that the performance of MG can be affected by the change in PM temperature. The increase in PM temperature results in a decrease in the expected achievable torque. Therefore, specific PM materials should be selected for the applications subjected to higher temperature limits. However, the change in PM temperature does not have a notable effect on the optimal design parameters (Gardner et al., 2021). This means the MG dimensions obtained based on PSO can still achieve a higher output torque value than that obtained by the GA optimization.

5.2. Flux density waveforms

This paper focuses on analyzing the flux density waveforms in the PSO-based MG design. Fig. 9
shows the magnetic field distribution of the optimized MG in the magnetics postprocessor window of FEMM. The presence of FMPPs modifies the magnetic flux generated by each of the two PM rotors, resulting in various space harmonics (Jing et al., 2019a). The primary space harmonics are represented by \( p_1 \) in the \( \text{g}_{\text{inner}} \) and \( p_3 \) in the \( \text{g}_{\text{outer}} \). These dominant harmonics interact with each other, playing a key role in torque transmission. Conversely, the remaining space harmonics generate torque ripples but have little effect in the average torque transfer.

The number of pole pairs of the space harmonics can be calculated using equation (10) as a part of harmonic study outlined in (Atallah et al., 2005):

\[
p_{m,q} = |m p_1 + q n_2| \tag{10}
\]

### Table 3. The dimensions of optimized MG, in mm, resulting from performing PSO using FEA.

<table>
<thead>
<tr>
<th>Description</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Back-iron thickness of the MG's ( \text{R}_{\text{inner}} ) (( W_1 )).</td>
<td>mm</td>
<td>24.0</td>
</tr>
<tr>
<td>PM thickness of the MG's ( \text{R}_{\text{outer}} ) (( W_6 )).</td>
<td>mm</td>
<td>10.4</td>
</tr>
<tr>
<td>Stator pole pieces thickness of the MG (( W_4 )).</td>
<td>mm</td>
<td>19.8</td>
</tr>
<tr>
<td>PM thickness of the MG's ( \text{R}_{\text{inner}} ) (( W_2 )).</td>
<td>mm</td>
<td>18.5</td>
</tr>
<tr>
<td>Back-iron thickness of the MG's ( \text{R}_{\text{inner}} ) (( W_4 )).</td>
<td>mm</td>
<td>28.3</td>
</tr>
</tbody>
</table>

### Table 4. The dimensions of optimized MG, in mm, resulting from performing GA using FEA.

<table>
<thead>
<tr>
<th>Description</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Back-iron thickness of the MG's ( \text{R}_{\text{outer}} ) (( W_7 )).</td>
<td>mm</td>
<td>23.3</td>
</tr>
<tr>
<td>PM thickness of the MG's ( \text{R}_{\text{outer}} ) (( W_6 )).</td>
<td>mm</td>
<td>12.3</td>
</tr>
<tr>
<td>Stator pole pieces thickness of the MG (( W_4 )).</td>
<td>mm</td>
<td>20.0</td>
</tr>
<tr>
<td>PM thickness of the MG's ( \text{R}_{\text{inner}} ) (( W_2 )).</td>
<td>mm</td>
<td>13.4</td>
</tr>
<tr>
<td>Back-iron thickness of the MG's ( \text{R}_{\text{inner}} ) (( W_4 )).</td>
<td>mm</td>
<td>32.0</td>
</tr>
</tbody>
</table>

Fig. 5. The performance of the cost function (MG's \( \text{R}_{\text{inner}} \) torque) value versus the iteration number for PSO and GA.

Fig. 6. The \( \text{R}_{\text{inner}} \) 's static torque for the PSO-based MG design.

Fig. 7. Fluctuation in \( T_{\text{max}} \) for the PSO-based MG design.
Where \( m = 1, 3, 5, \ldots, \infty \), while \( q = 0, \pm 1, \pm 2, \pm 3, \ldots, \pm \infty \).

The identification of the dominant harmonic can be achieved through the application of the FEA using the FEMM software. Notably, in this analysis, the pole pairs number associated with space harmonics that lead to the removal of FMPPs (i.e., \( q = 0 \)) is deliberately excluded or disregarded.

The distribution of flux density in radial direction \( B_{\text{radial}} \) in the middle of the \( \Omega_{\text{inner}} \) resulting only from the PMs in the \( R_{\text{inner}} \) is depicted in Fig. 10, while Fig. 11 illustrates the associated harmonic spectrum. Clearly, the main harmonic order, preventing the removal of FMPPs (i.e., \( q = 0 \)), is identified as 2. Therefore, it is essential for the \( R_{\text{outer}} \) to possess a number of pole-pairs equal to the order of this harmonic order to interact with each other and effectively transfer torque.

Likewise, Fig. 14 displays the distribution of radial flux density in radial direction \( B_{\text{radial}} \) at the \( \Omega_{\text{inner}} \)'s mean length, focusing solely on the PMs of the \( R_{\text{outer}} \). Simultaneously, Fig. 15 illustrates the associated harmonic spectrum. Clearly, the main harmonic order that does not result in the removal of FMPPs (i.e., \( q = 0 \)) is identified as 2. Therefore, it is essential for the \( R_{\text{inner}} \) to possess a number of pole-pairs equal to the order of this harmonic order to interact with each other and facilitate torque transfer.
On the opposing side, the distribution of flux density in radial direction \( B_{\text{radial}} \) in the middle of the \( g_{\text{outer}} \) focusing solely on the PMs of the Router is shown in Fig. 16, while Fig. 17 presents the associated harmonic spectrum. The critical harmonic order, preventing the elimination of FMPPs (i.e., \( q = 0 \)), is identified as 7, the same number of Router’s pole-pairs which is essential to interact and transfer torque effectively.

Finally, the resultant \( B_{\text{radial}} \) distributed at the \( R_{\text{inner}} \)’s mean length, considering both rotors’ PMs is depicted in Fig. 18, while Fig. 19 displays the associated harmonic spectrum. Clearly, the critical harmonic order, preventing the removal of FMPPs (i.e., \( q = 0 \)), is identified as 2, the same number of Router’s pole-pairs which is essential to interact and transmit torque effectively.
Likewise, the resultant $B_{\text{radial}}$ distributed at the $R_{\text{outer}}$'s mean length, considering both rotors' PMs rotors is illustrated in Fig. 20, while Fig. 21 shows the corresponding harmonic spectrum. Clearly, the critical harmonic order, preventing the elimination of FMPPs (i.e., $q = 0$), is identified as 7, the same number of $R_{\text{outer}}$'s pole-pairs which is essential to interact and transfer torque effectively.

5.3. Conclusion

The primary objective of this study is to show the performance of a coaxial MG optimally designed using PSO and characterized by a $G_r = 3.5$ while maintaining a cogging factor of one. The outcomes of the PSO-based MG design are compared with those of the MG design employing GA. While the GA-based MG design exhibits a notable
convergence rate, it tends to stall at an output torque value lower than that achieved by the PSO-based MG design. Furthermore, the PSO-based MG design yields reduced torque ripples for both rotors compared to the GA-based counterpart. The outcomes of the harmonic spectrum analysis confirm the pivotal influence of the FMPPs in modulating the \( g_{\text{inner}} \) and \( g_{\text{outer}} \) magnetic fields. This modulation facilitates the transfer of torque by coupling the inner and outer PMs. The proposed MG holds potential applications in motor drive systems, wind turbine-based energy conversion, and various electromechanical systems.

**Author credit statement**

Yasser Kassab: contributed to data collection, resource management, modeling, software, simulation, and original draft writing. Abdelhady Ghanem: assisted with modeling, editing, language proofreading, and writing review. Eid Gouda: was involved in data analysis, language proofreading, and supervision.

**Conflicts of interest**

The authors declare that they have no conflict of interest.

**References**


