Analysis and optimization of a 12/14 double-stator flux-switching machine using low cost magnet

Seyed Milad Kazemi Sangdehi | Farough Asadi | Seyed Ehsan Abdollahi | Sayyed Asghar Gholamian

Electrical and Computer Engineering Department, Babol Noshirvani University of Technology, Babol, Iran

Correspondence
Seyed Ehsan Abdollahi, Electrical and Computer Engineering Department, Babol Noshirvani University of Technology, Babol, Iran.
Email: e.abdollahi@nit.ac.ir

Abstract
Flux-switching permanent magnet (FSPM) machine attracted a great deal of attention for industrial applications owing to its high efficiency and high torque/power densities. However, on the downside, it suffers from high cost of rare-earth permanent magnets (REPMs). Although employing ferrite magnets remarkably reduces the cost of material, ferrite magnet lower energy product will negatively affect the electromagnetic performance of this machine. As a solution, the double-stator flux-switching permanent magnet (DSFSPM) machine has been presented in this paper to improve the electromagnetic performance of a conventional ferrite based FSPM counterpart. In this regard, a new analytical approach followed by a brief discussion of the influence of rotor pole number on the electromagnetic performance of two DSFSPM machines with 10- and 14-pole rotors are studied. It is shown that 12/14 DSFSPM machine with ferrite magnets generates almost 30% more developed torque than the other with 10-pole rotor. Then, a comprehensive comparison on the electromagnetic performances of a 12/14 DSFSPM machine with ferrite magnets, and two 12/14 FSPM machines with REPMs and ferrite magnets are investigated by finite element method. Besides, a cost study highlights the monetary beneficial of the proposed 12/14 DSFSPM machine for the competitive EVs market. Furthermore, a laboratory scale 12/14 DSFSPM machine is designed based on analytical approach, optimized by Taguchi optimization method, and experimentally tested to validate both analytical and FEM results.

1 | INTRODUCTION

Flux-switching permanent magnet (FSPM) machine generates high efficiency, and high power/torque density caused by PMs [1] which are located in the stator structure and provide a favourable cooling capacity. Furthermore, it features a simple and robust rotor structure [2], which makes it a desirable candidate for high speed applications. These merits attract a lot of attentions in a vast majority of applications like electric vehicle [3], wind generator [4], rail transportation [5], aerospace [6] and direct drive robotics [7]. However, FSPM machine produces high torque ripple and suffers from relatively high total cost which can be traced back to the major utilization of rare-earth permanent magnets (REPMs) in the stator structure. It should be noted that, in general, almost 65% of the total expenses of a machine with REPMs belongs to the cost of magnets [8]. Although the benefits of a FSPM machine outweigh its drawbacks, these disadvantages could be significant issues on competitive markets. To diminish the torque ripple of FSPM machines, some approaches on rotor designing process are used like rotor pole pairing and rotor pole skewing [9] in a salient pole rotor, and rotor pole notching [10] and transverse laminations [11] in a segmented one. Moreover, to reduce FSPM machine costs, the ferrite magnet is proposed as a suitable alternative to the rare-earth one which is because the price of a ferrite magnet is almost 10% of the price of a REPMs [12] in the same size. This outstanding benefit of low-cost ferrite magnets has attracted a great deal of attentions regarding the performance analysis of FSPM machines using this type of magnets in their structures [13,14].

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On the other hand, since the energy product of ferrite magnets are almost 10% of the energy product of rare-earth ones [15,16], a FSPM machine with ferrite magnets generates lower torque in comparison to its counterpart with the same amount of REPMs. As a consequence, several approaches have been proposed in literature to balance the difference between the developed torques caused by ferrite magnets and REPMs by employing several topologies such as hybrid-exited flux-switching machines [17,18] and double-stator flux-switching permanent magnet (DSFSPM) ones [19–21].

Although DSFSPM machine with ferrite magnets generates more developed torque than a same-size FSPM machine using ferrite magnets, the conventional 12/10 DSFSPM structure is not optimized for the maximum output torque point of view. Therefore, in this paper, the impact of increasing the number of rotor teeth from 10 to 14 on the performance of a DSFSPM machine with 12 stator teeth is investigated by FEM and it is shown that selecting 12/14 DSFSPM machine is the best structure regarding the highest torque density point of view. Moreover, a comprehensive comparison between performances of a 12/14 DSFSPM motor with ferrite magnets, a 12/14 FSPM motor with ferrite magnets and a 12/14 FSPM motor with REPMs is carried out to highlight the beneficial of DSFSPM structure. Then, a prototype of this configuration is manufactured to validate the simulation results and analytical findings. In this regard, Section 2 presents the DSFSPM machine concept whereas an analytical analysis is performed in Section 3. Then, the electromagnetic performance of these three machines is investigated by FEM in Section 4. In addition, the economic aspects of the proposed 12/14 DSFSPM machine is compared with the other FSPM machines in this section. Whereas, the design and optimization of a 12/14 DSFSPM prototype based on Taguchi optimization method [22,23] along with a thermal analysis, and the experimental validation are presented in Section 5 and 6, respectively. Eventually, conclusion is provided in Section 7.

2 | THE DSFSPM MOTOR CONCEPT

The name of DSFSPM motor refers to its distinct configuration as it features two stators and one segmented rotor, shown in Figure 1a. It can be seen that the magnetization direction of PM in each inner stator tooth is in contrary to that of the outer stator tooth. On the other hand, a conventional FSPM machine composed of one stator and one integrated rotor as presented in Figure 1b. According to this figure, the volume of magnets in a DSFSPM motor is about twice of that in a conventional FSPM one leading to higher torque density caused by more PMs. Although higher number of PMs could be considered as higher cost of manufacturing, this structure provides the possibility of using low-cost ferrite magnets with improved developed torque in comparison to that of conventional FSPM machine with ferrite magnets. As the price of ferrite magnet is much lower than that of rare-earth one, the total cost of ferrite magnets in a DSFSPM machine is cheaper than the cost of REPMs in a conventional FSPM machine with the same size.

The principle of operation in a DSFSPM machine and a conventional FSPM one is similar which means the flux linkage in each winding is reversed by rotor movement. Therefore, in a rotor tooth pitch, the armature coil flux linkage is switched from the maximum positive to the maximum negative value leading to bipolar flux linkage [7]. For more explanation, four rotor positions regarding the stator teeth of DSFSPM machine are shown in Figure 2. As illustrated in Figure 2a, the maximum flux linkage flows through the path provided by rotor teeth between outer and inner stators at the first rotor position. It can be defined as the maximum positive flux linkage based on PM magnetization direction. When the rotor teeth locate in front of stator slots as shown in Figure 2a, there would be no magnetic path for flux linkage to flow. As a consequence, the effective flux linkage is almost zero. This position could be considered as zero-flux point. As presented in Figure 2c, the maximum flux linkage flows through the path

![Figure 1](image-url)  
**Figure 1** Flux-switching permanent magnet motors [21]. (a) A 12/10 double-stator type with 12 stator and 10 rotor teeth and (b) A 12/10 conventional type with 12 stator and 10 rotor teeth
at the third rotor position, again. However, due to opposite flow direction of flux, it can be defined as the maximum negative flux linkage. When the rotor teeth face PMs in Figure 2d, PM flux flows from a stator tooth and returns to it by a rotor tooth in an useless flux circulation leading to the second zero-flux point.

3 | ANALYTICAL GEOMETRY DESIGN OF A DSFSPM MOTOR

In a DSFSPM structure, increasing the volume of magnets leads to improvement in the developed torque. As a consequence, it provides a capacity to substitute the rare-earth magnet with the ferrite one which cause reduction in the total cost. Therefore, this machine could be a potential decent candidate for several applications, and that makes it essential to develop an analytical design for future performance analysis. Figure 3 shows a two-dimension aspect of a 12/14 DSFSPM machine. As it can be observed, this structure is a combination of an inner rotor flux-switching machine and an outer rotor type. In order to achieve a precise design of these two machines' components, an imaginary boundary in the middle of rotor diameter is considered. This boundary separates the outer FSPM machine and the inner one from each other for analysis simplification.

Considering the same working frequency and rotational speed in these two machines, the number of rotor teeth in both should be equal. Therefore, the number of rotor teeth can be calculated by:

\[ f_e = \frac{N_t \times n}{60} \]  

where \( N_t \), \( n \) and \( f_e \) are the number of rotor teeth, rotational speed (in rpm) and frequency (in Hz), respectively.
After calculating \(N_s\), the number of stator teeth \(N_t\) can be obtained by:

\[
N_t = N_s \pm a_1, \quad a_1 = 1, 2, 3, \ldots \tag{2}
\]

The next step is the calculation of general dimensions of these machines based on field speed, and electrical and magnetic loadings. In this regard, power expression is considered as below [24]:

\[
P_{out} = m UI_s I_f \eta \cos(\phi) \tag{3}
\]

where \(P_{out}\), \(m\), \(U\), \(I_f\), \(I_s\) and \(\cos(\phi)\) are output power, the number of phases, the rated output phase voltage, phase current, efficiency and load power factor, respectively.

Then, the phase rms induced emf can be obtained by:

\[
E = N_s \frac{2 \pi n N_s I_s D_s B_{g_{\text{max}}}}{\sqrt{2}} \tag{4}
\]

where \(N_s\), \(B_{g_{\text{max}}}\), \(I_s\) and \(D_s\) are the number of phase winding turns, the maximum value of airgap flux density, stack length, and the average airgap diameter, respectively.

By combination of Equations (3) and (4), the average airgap diameter is calculable as following [25]:

\[
D_g = \sqrt[3]{\frac{P_{out} N_s}{2 \pi n N_s \eta K_L K_E \cos(\phi) n B_{g_{\text{max}}} A_s}} \tag{5}
\]

where \(K_L\), \(K_E\) and \(A_s\) are aspect coefficient, waveform factor and electrical loading, respectively. They are defined as below:

\[
K_L = \frac{l_s}{D_g} \tag{6}
\]

\[
K_E = \frac{E}{U_f} \tag{7}
\]

\[
A_s = \frac{N_s I_f}{\pi D_g} \tag{8}
\]

Having the average airgap diameter \(D_g\) defined by Equation (5), the stack length \(l_s\) is achievable by Equation (6).

At the end, the number of phase winding turns is computable:

\[
N_t = \frac{N_s E}{2 \pi n K_L N_s D_g^2 n B_{g_{\text{max}}}} \tag{9}
\]

To achieve torque improvement and cogging torque reduction, the optimal values of the width of permanent magnet, the width of stator slot and the width of stator tooth were obtained by FEM simulation. They can be calculated by equations below based on rotor pole pitch \(\tau_r\) [24,25]:

\[
W_{PM} = \frac{\tau_r}{5} \tag{10}
\]

\[
W_s = \frac{\tau_r}{4} \tag{11}
\]

\[
W_{ts} = \frac{\tau_r - W_s - W_{PM}}{2} \tag{12}
\]

where \(W_{PM}\), \(W_s\) and \(W_{ts}\) are permanent magnet width, stator slot width and the stator tooth width, respectively, which are shown in Figure 4.

The stator slot area \(A_{\text{slot}}\) is equal to:

\[
A_{\text{slot}} = 2 \frac{A_c}{K_{\text{fill}}} \tag{13}
\]

where \(A_c\) is coil side surface and \(K_{\text{fill}}\) is the fill factor.

Furthermore, other parameters in Figure 4, such as stator slot height \(h_{ts}\), stator yoke height \(h_{ys}\) and permanent magnet height \(h_{PM}\) are easily achievable as following:

\[
h_{ts} = \frac{A_{\text{slot}}}{W_s} \tag{14}
\]

\[
h_{ys} = \frac{6}{5} W_{ts} \tag{15}
\]

\[
h_{PM} = h_{ts} + h_{ys} \tag{16}
\]

Considering a same airgap length \(g\) for both stators, and After calculating \(D_{go}\) and \(D_{gi}\) from Equation (5) for the outer and inner stators, and \(h_{PMo}\) and \(h_{PMi}\) from Equation (16) for the outer and inner stators, the outer diameter of outer stator \(D_{out}\) and inner diameter of inner stator \(D_{in}\) can be obtained from:

\[
D_{out} = D_{go} + g + 2 \times h_{PMo} \tag{17}
\]

\[
D_{in} = D_{gi} - g - 2 \times h_{PMi} \tag{18}
\]

\textbf{FIGURE 4} Design parameters
Having geometrical design done, the electromagnetic torque $T$ is achievable by:

$$T = \frac{3}{2} \times N_r (\Psi_{PM} i_q + (L_d - L_q) i_d i_q) \quad (19)$$

where $\Psi_{PM}$ is PM flux linkage, $L_d$ and $L_q$ are $d$- and $q$-axis inductances, and $i_d$ and $i_q$ are $d$- and $q$-axis currents, respectively.

Due to the fact that in FSPM machines $L_d$ and $L_q$ are approximately the same, electromagnetic torque can be rewritten as:

$$T = \frac{3}{2} N_r \Psi_{PM} i_q \quad (20)$$

4 | FINITE ELEMENT ANALYSIS AND PERFORMANCE COMPARISON OF DIFFERENT FSPM MACHINES

The aims of this section are investigation of the developed torques of both 12/10 and 12/14 DSFSPM machines with ferrite magnets along with a comprehensive comparison of the performances of a 12/14 DSFSPM machine with low-cost ferrite magnets to two FSPM machines with ferrite magnets and REPMs in the same size.

4.1 | Influence of the number of rotor poles on the performance of a DSFSPM machine

According to Equation (1) and (2), at a specific speed and frequency with different values of $a_1$, achieving a proper combination of stator and rotor teeth is possible. In this regard, a 12/10 DSFSPM machine with ferrite magnets is selected from [21], whereas its design parameters are represented in Table 1. Then, the number of rotor poles is increased to 14 by keeping the stator structure unchanged. As a consequence, a 12/14 DSFSPM machine with ferrite magnets is derived. The performances of these two machines with different rotor pole numbers are simulated by 2D FEM. The electromagnetic torque, torque–current, torque–speed and power–speed characteristics of these two machines are investigated in this subsection.

4.1.1 Airgap flux density and flux density distribution

The flux density distribution caused by PMs of these two machines are shown in Figure 5. The maximum flux density of 12/10 DSFSPM one equals to 1.98 T and the maximum flux density of 12/14 DSFSPM one reaches to 2.23 T.

4.1.2 Electromagnetic torque

The electromagnetic torque of these two machines at 1200 rpm rotor speed and 122 A rms phase current are shown in Figure 6, indicating that 12/14 DSFSPM machine generates higher electromagnetic torque. As it can be seen, the developed torque of 12/14 DSFSPM machine peaks at 533.2 Nm while it used to be 398.22 Nm in 12/10 DSFSPM machine. The average electromagnetic torques, torque ripples and the average and maximum output powers of these two machines are represented in Table 2. As can be seen in this Table, the maximum output power of 12/14 DSFSPM machine equals to 67 kW which is 17 kW more than that of 12/10 DSFSPM one. That means the power is increased about 25%.

4.1.3 Torque–current characteristic

The torque–current characteristics of 12/10 and 12/14 DSFSPM machines are illustrated in Figure 7. As it can be observed, by increase in current, the saturation of 12/14 DSFSPM structure happens slightly earlier than 12/10 DSFSPM one. Moreover, the first structure generates more electromagnetic torque in all stages in comparison to the latter one.

4.1.4 Torque–speed and power–speed characteristics

The torque–speed and power–speed characteristics of these two machines are shown in Figure 8a,b. As it can be seen,
switching it to a better electromagnetic structure, it generates lower electromagnetic ripple, whereas, as it inherits the electromagnetic ripple of 12/10 Double Sided Flux Switching Permanent Magnet (DSFSPM) machine, it is considered as an excellent candidate with a 10-pole rotor.  

4.1.5 | Performance comparison with an interior permanent magnet synchronous machine

As it is represented, a 12/14 DSFSPM machine benefits from better combination than a 12/10 DSFSPM one from the developed torque point of view, because 12/14 DSFSPM structure generates higher electromagnetic torque with lower torque ripple in comparison to the latter topology. This makes it a suitable candidate for various applications. Whereas, as it was shown in Ref. [21], even 12/10 DSFSPM machine inherits better performances in comparison with a same size interior permanent magnet synchronous machine (IPMSM) with REPMs which is widely used in most electrical vehicles on the competitive EVs market [26].

4.2 | Comparison of 12/14 DSFSPM machine with two 12/14 FSPM machines (one with REPMs and another with ferrite magnets)

In this subsection, the first 12/14 FSPM machine structure is derived from 12/14 DSFSPM machine by keeping the outer stator configuration unchanged, and replacing inner stator and segmented rotor with a conventional 14-pole salient rotor. Then, the second 12/14 FSPM machine is achieved by replacing ferrite magnets with rare-earth ones. Following that, the electromagnetic performances of these three flux-switching machines are investigated and compared.

4.2.1 | Flux density distribution

The flux density distributions caused by PMs of these three machines are shown in Figure 9. As it is shown, the maximum flux density of 12/14 DSFSPM machine with 2.23 T is higher

| TABLE 2 | Torque and power performances of the 12/10 and 12/14 DSFSPM machines at rated rms phase current and 1200 rpm rotor speed |
|---|---|---|
| Structure | 12/10 DSFSPM | 12/14 DSFSPM |
| The average torque (Nm) | 380.17 | 516.91 |
| Torque ripple at rated torque (%) | 8.12 | 7.64 |
| Average power (kW) | 48 | 65 |
| Maximum power (kW) | 50 | 67 |

Abbreviation: DSFSPM, double-stator flux-switching permanent magnet.
than that of 12/14 FSPM machine using ferrite magnets with 1.94 T, and lower than that of 12/14 FSPM machine using REPMs with 2.45 T.

4.2.2 | Cogging torque

The cogging torque waveforms caused by PMs in these three flux-switching machines are shown in Figure 10. Regarding this figure, the peak to peak value of the cogging torque of 12/14 DSFSPM machine with 23.82 Nm is higher than that of 12/14 FSPM machine with rare-earth and ferrite magnets with 19.28 Nm and 15.43 Nm, respectively. However, 12/14 DSFSPM structure generates more developed torque than 12/14 FSPM machine with ferrite magnets, thus the effect of cogging torque in 12/14 DSFSPM machine could be assumed lower than that of the latter one.

4.2.3 | Back-EMF

The back-EMF waveforms and amplitude spectra of these three flux-switching machines at 1200 rpm rotor speed are illustrated in Figure 11a,b, respectively. It can be observed that 12/14 DSFSPM machine produces slightly higher back-EMF than 12/14 FSPM one with REPMs. Moreover, 12/14 FSPM machine with ferrite magnets stands in third place from maximum back-EMF point of view. The rms value of back-EMF, the maximum back-EMF, and THD are represented in Table 3. Regarding this Table, the rms value of back-EMF in 12/14 DSFSPM machine with 249.4 V is higher than that of 12/14 FSPM machine with REPMs with 246.78 V, and 12/14 FSPM one with ferrite magnets with 215.61 V. However, 12/14 FSPM motor with REPMs inherits the lowest THD among all three structures with 1.64%.

4.2.4 | Electromagnetic torque

The electromagnetic torque of these three machines at 1200 rpm rotor speed and 122 A rms phase current are shown in Figure 12. As shown in this Figure, the electromagnetic torque of 12/14 FSPM machine with NdFeB magnets peaks at 663.6 Nm while the electromagnetic torque of its counterpart with ferrite magnets reaches to 389.9 Nm. However, the maximum value of electromagnetic torque of 12/14 DSFSPM machine equals to 533.2 Nm. Although REPM generates more electromagnetic torque than the same-size ferrite magnet, the cost of REPM is higher than that of ferrite one. Therefore, the magnet cost of 12/14 DSFSPM machine with ferrite magnets is much lower than that of 12/14 FSPM one with NdFeB PMs. In addition, the performance of 12/14 DSFSPM machine is better than that of IPMSM which is widely used in EVs application. As a consequence, 12/14 DSFSPM machine is a suitable candidate for EVs application on the competitive markets. The average electromagnetic torques, torque ripples, the average and maximum output powers and the efficiencies of these three machines are represented in Table 4. As can be seen in this table, the maximum output power of 12/14 DSFSPM machine equals to 67 kW which is 18 kW higher than that of 12/14 FSPM one with ferrite magnets and 16.4 kW lower than that of 12/14 FSPM one with NdFeB PMs.

4.2.5 | Torque–current characteristic

The torque–current characteristics of these three machines are illustrated in Figure 13. As it can be observed, by increasing in current, the saturation of 12/14 FSPM structure with ferrite magnets happens earlier than the others. From the same point of view, 12/14 DSFSPM machine and 12/14 FSPM one with REPMs stand in second and third places, respectively. However, 12/14 FSPM structure with NdFeB magnets generates more electromagnetic torque in all stages in comparison to the other two machines. Although 12/14 DSFSPM machine stands in second place in almost all currents, its developed torque is almost equal to that of 12/14 FSPM machine with REPMs at low currents.

4.2.6 | Torque–speed and power–speed characteristics

The torque–speed and power–speed characteristics of these three machines are shown in Figure 14a,b, respectively. As it is shown, the two flux-switching machines with ferrite magnets
benefit from a better flux weakening capability in comparison with 12/14 FSPM machine using REPMs because of utilization of ferrite magnets in their structures.

Generally, the flux weakening capability of a FSPM machine can be defined by the flux weakening factor $K_{fw}$ as following [27]:

$$K_{fw} = \frac{L_d I_{\text{max}}}{\Psi_{PM}}$$

(21)

**FIGURE 9** Flux density distributions caused by PMs. (a) 12/14 double-stator flux-switching permanent magnet motor, (b) 12/14 flux-switching permanent magnet (FSPM) motor with ferrite magnet and (c) 12/14 FSPM motor with rare-earth permanent magnets

**FIGURE 10** Cogging torque waveform of three flux-switching permanent magnet (FSPM) machines

**FIGURE 11** Back-EMF of three flux-switching permanent magnet (FSPM) machines. (a) Waveform and (b) Amplitude spectra (FFT)
TABLE 3  Back-EMF specifications of 12/14 DSFSPM machine and two other FSPM ones at rated speed

| Structure | 12/14 FSPM (ferrite) | 12/14 DSFSPM (ferrite) | 12/14 FSPM (NdFeB) |
|-----------|----------------------|------------------------|---------------------|
| Rms value of back-EMF (V) | 215.61 | 249.40 | 246.78 |
| Maximum back-EMF (V) | 323.40 | 369.60 | 358.40 |
| THD (%) | 3.75 | 3.24 | 1.64 |

Abbreviations: DSFSPM, double-stator flux-switching permanent magnet; FSPM, flux-switching permanent magnet.

FIGURE 12  Electromagnetic torque waveform of these three flux-switching permanent magnet (FSPM) machines at 1200 rpm rotor speed and rated rms current

On one hand, a FSPM machine with higher \( K_{fw} \) inherits better flux weakening capability. On the other hand, the flux linkage of ferrite magnet is lower than that of REPM which leads to superior flux weakening capability of a FSPM machine with ferrite magnets (which can reach to infinite speed) to that of a FSPM machine with REPMs due to Equation (21) [28]. As a consequence, the flux weakening capability of 12/14 DSFSPM machine is better than that of 12/14 FSPM machine with ferrite magnets and much better than that of 12/14 FSPM machine with REPMs.

4.2.7  Economical evaluation

The dimensional parameters and the electromagnetic performance of 12/14 DSFSPM machine, and the other two 12/14 FSPM ones with ferrite and rare-earth magnets are shown in Table 5, whereas the rest of design parameters were introduced in Table 1. As can be seen, all of them are designed and compared in the same size. Following that, the material mass and cost comparison of these three machines are represented in Table 6. The calculation of the material cost in this table is derived based on monetary information in Ref. [13]. As it was expected, the material cost of 12/14 DSFSPM machine is higher than that of 12/14 FSPM machine with ferrite magnets. However, 12/14 DSFSPM one generates almost 37% more electromagnetic torque than the latter one. By comparing the material cost of 12/14 DSFSPM machine and 12/14 FSPM one with rare-earth magnets, it can be observed that the material cost of 12/14 DSFSPM machine with 176.466$ is almost 63% lower than that of 12/14 FSPM one with 478.283$. Nonetheless, 12/14 DSFSPM structure generates almost 80% of electromagnetic torque of 12/14 FSPM machine using REPMs. On the downside, as it is illustrated in Figure 18, 12/14 DSFSPM machine suffers from higher manufacturing cost due to the more complicated structure and cost of holders. But it is possible to reduce the cost of manufacturing by building inner and outer stators integrated with a small rib behind of each magnet with a little sacrifice on the overall electromagnetic performance of the machine caused by flux leakage in ribs. It also reduces cost of cutting the inner and outer stators iron sheets.

5  |  DESIGN, OPTIMIZATION AND THERMAL ANALYSIS

Considering the financial limits of a research work, a small size 12/14 DSFSPM machine is designed and proposed here based on analytical procedure in Section 3 to be manufactured then. The built prototype will be presented in the next section. As it was shown, 12/14 DSFSPM machine generates 30% higher electromagnetic torque than its other counterpart with a 10-pole rotor, no more optimization with the aim of increasing in the developed torque is required. However, as the developed torque and power are increased enough in the same machine size, reducing cogging torque would be desirable. As a consequence, in this section, a cogging torque mitigation optimization is discussed to complement the design approach. Finally, a thermal analysis investigates the heat transfer of the 12/14 DSFSPM prototype design.

5.1  |  Initial design

In order to evaluate the analytical and FE analysis results, a prototype of the proposed 12/14 DSFSPM machine is designed and presented in Table 7.

In general, the stator tooth arc to stator pole pitch ratio of a FSPM machine with REPMs is considered equal to one fourth (25%). However, the PM thickness is designed in the same length as stator tooth arc to accommodate 25% of the stator pole pitch. In Ref. [14], the stator tooth arc to stator pole pitch ratio is proposed to be one fifth (20%) in a FSPM machine using ferrite magnets. This is because the ferrite magnet generates lower energy in comparison with rare-earth magnet leading to lower flux density in the stator tooth which is also lower than the stator core saturation limit. As a consequence, considering the stator tooth arc to
The stator pole pitch ratio equals to 25% could be assumed as the under-utilization of the stator core materials. However, it is not investigated in a DSFSPM machine with ferrite magnets. Therefore, an optimization with the aim of cogging torque mitigation will be presented in the following subsection.

### 5.2 Optimization

Keeping the overall parameters of initial design constant, outer stator tooth arc, inner stator tooth arc, outer arc of the rotor pole and inner arc of the rotor pole should be optimized. Due to the available ferrite PMs on the market, the arc of PMs in outer and inner stators are defined as constant. Therefore, the mentioned parameters could be presented as several ratios regarding the width of PMs. These ratios are defined as following:

(a) $K_{oto}$: outer stator tooth arc to outer stator PM arc ratio  
(b) $K_{ito}$: inner stator tooth arc to inner stator PM arc ratio  
(c) $K_{or}$: outer arc of rotor pole to outer stator PM arc ratio  
(d) $K_{ir}$: inner arc of rotor pole to inner stator PM arc ratio

Three levels are considered for each above ratio and presented in Table 8. Regarding the discussed aspect in pervious subsection, the limit of $K_{oto}$ and $K_{ito}$ are set between 0.8 and 1, whereas the $K_{or}$ and $K_{ir}$ are assumed to vary in interval $1\sim 1.2$. These ratios are called control factors in the following investigation as the Taguchi optimization method is used.

![Image](image_url)

**Figure 13** Torque–Current characteristics of three flux-switching permanent magnet (FSPM) machines at 1200 rpm rotor speed

**Figure 14** Characteristics of 12/14 double-stator flux-switching permanent magnet (DSFSPM) machine, 12/14 flux-switching permanent magnet (FSPM) machine with ferrite magnets and 12/14 FSPM one with rare-earth permanent magnets at 122 A rms current ($I_{\text{max}} = 172.5$ A). (a) Torque-Speed and (b) Power-Speed

As there are four control factors with three levels for each, the number of experiments for full factorial design would be $3^4$. Therefore, this approach is very time consuming. As a solution, the Taguchi optimization method offers a suitable alternative to the full factorial design [22]. This method uses fractional factorial experiments in an array which is called the Orthogonal Arrays to reduce the number of experiments. In this case, a $L_0$ array is selected and represented in Table 9. The next step is calculating signal to noise ratio for each level of each control factor due to the optimization goal. In this step, there would be three options based on optimization objective as following:

(a) Maximum yield (the larger $S/N$ is better)

\[
S/N = -10 \log \left( \frac{1}{n} \sum_{i=1}^{n} \frac{1}{s_i^2} \right)
\]  

(22)
(b) Nominal yield (the nominal S/N is best)

\[ S/N = -10 \log \left( \sum_{i=1}^{n} (y_i - m)^2 \right) \]  

(23)

(c) Minimum yield (the smaller S/N is better)

\[ S/N = -10 \log \left( \frac{1}{n} \sum_{i=1}^{n} y_i^2 \right) \]  

(24)

Where \( n \) is the number of repetitions in each experiment, \( y_i \) is output of the experiment in the \( i^{th} \) repeat and \( m \) is the nominal value of the output [22].

The \( L_9 \) orthogonal array is applied to the geometry and the cogging torque is simulated as output. Then, the signal to noise ratio formula which is proportional to the minimum yield optimization goal is applied to calculate the S/N ratio for each level of each control factor, as shown in Figure 15. In case of cogging torque reduction, smaller S/N ratio is better with the aim of minimum yield for optimization. Therefore, in Figure 15, the minimum S/N ratio of each control factor is

| Machine | 12/14 FSPM (ferrite) | 12/14 DSFSPM (ferrite) | 12/14 FSPM (NdFeB) |
|---------|----------------------|------------------------|---------------------|
| Outer diameter (mm) | 269 | 269 | 269 |
| Stack length (mm) | 136 | 136 | 136 |
| Stator iron volume (dm\(^3\)) | 2.2857 | 3.3931 | 2.2857 |
| Rotor iron volume (dm\(^3\)) | 2.5379 | 0.4475 | 2.5379 |
| Ferrite PMs volume (dm\(^3\)) | 0.7979 | 1.4162 | 0 |
| REPMs volume (dm\(^3\)) | 0 | 0 | 0.7979 |
| Copper volume (dm\(^3\)) | 0.3335 | 0.4020 | 0.3335 |
| Active volume (dm\(^3\)) | 5.955 | 5.659 | 5.955 |
| Max power (kW) | 49 | 67 | 83.4 |
| Max torque (Nm) | 389.9 | 553.2 | 663.6 |

Abbreviations: DSFSPM, double-stator flux-switching permanent magnet; FSPM, flux-switching permanent magnet; PM, permanent magnet; REPM, rare-earth permanent magnet.

| Machine | 12/14 FSPM (ferrite) | 12/14 DSFSPM (ferrite) | 12/14 FSPM (NdFeB) |
|---------|----------------------|------------------------|---------------------|
| Stator iron mass (kg) | 17.696 | 26.269 | 17.696 |
| Rotor iron mass (kg) | 20.021 | 3.530 | 20.021 |
| Ferrite PMs mass (kg) | 3.99 | 7.081 | 0 |
| REPMs mass (kg) | 0 | 0 | 6.055 |
| Copper mass (kg) | 2.956 | 3.563 | 2.956 |
| Active mass (kg) | 44.663 | 40.443 | 46.728 |
| Stator iron cost ($) | 39.079 | 58.011 | 39.079 |
| Rotor iron cost ($) | 43.708 | 7.706 | 43.708 |
| Ferrite PMs cost ($) | 39.9 | 7.81 | 0 |
| REPMs cost ($) | 0 | 0 | 362.361 |
| Copper cost ($) | 33.135 | 39.939 | 33.135 |
| Active cost ($) | 155.822 | 176.466 | 478.283 |
| Power/active mass (kW/kg) | 1.097 | 1.657 | 1.785 |
| Torque/active mass (Nm/kg) | 8.728 | 13.184 | 14.201 |
| Torque/active cost (Nm/$) | 2.502 | 3.022 | 1.387 |

Abbreviations: DSFSPM, double-stator flux-switching permanent magnet; FSPM, flux-switching permanent magnet; PM, permanent magnet; REPM, rare-earth permanent magnet.
TABLE 7 Parameters of the initial design of 12/14 DSFSPM machine

| Parameter                              | Value |
|----------------------------------------|-------|
| Outer stator slot number               | 12    |
| Inner stator slot number               | 12    |
| Rotor pole number                      | 14    |
| Airgap length (mm)                     | 0.5   |
| Machine outer diameter (mm)            | 140   |
| Active axial length (mm)               | 35    |
| Outer stator PM arc (degree)           | 7.8   |
| Inner stator PM arc (degree)           | 7     |
| Turns per coil (outer stator)          | 26    |
| Turns per coil (inner stator)          | 6     |
| Total number of turns per phase        | 128   |
| PM remanence (T)                       | 0.41  |
| Rated rotor speed (rpm)                | 1200  |
| Phase current (A, rms)                 | 7     |

Abbreviation: PM, permanent magnet.

TABLE 8 Four control factors and their levels

| Control factors | Level 1 | Level 2 | Level 3 |
|-----------------|---------|---------|---------|
| $K_{lot}$       | 0.8     | 0.9     | 1.0     |
| $K_{lst}$       | 0.8     | 0.9     | 1.0     |
| $K_{lar}$       | 1.0     | 1.1     | 1.2     |
| $K_{lar}$       | 1.0     | 1.1     | 1.2     |

TABLE 9 The $L_{0}$ orthogonal array

| Number of experiments | $K_{lot}$ | $K_{lst}$ | $K_{lar}$ | $K_{lar}$ |
|-----------------------|-----------|-----------|-----------|-----------|
| 1                     | 1         | 1         | 1         | 1         |
| 2                     | 1         | 2         | 2         | 2         |
| 3                     | 1         | 3         | 3         | 3         |
| 4                     | 2         | 1         | 2         | 3         |
| 5                     | 2         | 2         | 3         | 1         |
| 6                     | 2         | 3         | 1         | 2         |
| 7                     | 3         | 1         | 3         | 2         |
| 8                     | 3         | 2         | 1         | 3         |
| 9                     | 3         | 3         | 2         | 1         |

chosen to obtain the optimized level of that factor. As it is illustrated, factor $K_{lot}$ should be selected in its third level with the aim of cogging torque minimization. In addition, the other parameters including $K_{lst}$, $K_{lar}$ and $K_{lar}$ should be set on their second level.

TABLE 10 Some losses of the proposed machine

| Type of loss            | Value (W) |
|-------------------------|-----------|
| Outer stator coil joule  loss | 3.5407    |
| Inner stator coil joule loss | 2.2401    |
| Outer stator iron loss  | 1.7149    |
| Inner stator iron loss  | 1.3987    |
| Rotor iron loss         | 1.7750    |

The cogging torques of initial design and optimum design are compared in Figure 16. As it is shown, the optimum design represents lower cogging torque.

5.3 Thermal analysis

In this subsection, a temperature dispatching analysis of the proposed 12/14 DSFSPM machine is investigated. In this regard, heat sources of the machine which can be traced back to coils and PMs joule losses, and stator and rotor iron losses have to be evaluated by finite element method first. Ferrite magnets are usually considered as electrically insulated materials due to their high electrical resistivity. Therefore, the joule loss of ferrite PMs has no considerable effect on temperature and could be assumed negligible. However, other losses
were represented in Table 7. The inner and outer stators, stator holders and the rotor structure are clearly shown in an exploded view as presented in Figure 18. The manufactured stator configuration including the inner and outer stator, and the assembled 14-pole rotor are shown in Figure 19a,b, respectively. Then, the implemented 12/14 DSFSPM machine is tested via the test setup shown in Figure 20. The induced back-EMF and developed average torque are extracted for experimental validation. This machine generates 37 V of back-EMF at 1200 rpm rotor speed and 2.7 Nm of average electromagnetic torque at rated 7 A rms phase current and 1200 rpm rotor speed.

Figure 21 represents the developed torque of the proposed 12/14 DSFSPM machine as a function of rms phase current. As shown in this figure, when rms phase current is equal to 8 A, the developed torque of the motor is just above 5 Nm. Moreover, the developed torques comparison of the proposed machine computed by analytical modelling, and FEM are reported in Table 11, and show a close compliance of modelling and experimental test results.

Furthermore, EMF voltages of the inner and outer stators at no-load are shown in Figure 22a,b, respectively. As shown in this figure, the maximum back-EMF voltage of inner stator is almost 7.5 V, whereas that of outer stator peaks at almost 30 V which is due to different number of turns in armature coils in inner and outer stators. In addition, it can be observed from the phase voltage illustration in Figure 22c that the voltage of phase peaks at 37 V which is the sum of

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**FIGURE 17** Temperature distribution of the proposed 12/14 double-stator flux-switching permanent magnet machine

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**FIGURE 18** Exploded view of the 12/14 double-stator flux-switching permanent magnet prototype

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6 | EXPERIMENTAL VALIDATION OF THE PROPOSED 12/14 DSFSPM MOTOR

In order to validate the analytical and FE analysis results, a prototype of the proposed 12/14 DSFSPM machine, designed and optimized in pervious section, is implemented in laboratory scale. The design parameters of this machine

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presented in Table 10, are evaluated at 7 A rms phase current and 1200 rpm rotor speed.

For thermal analysis, two heat transfer conditions including air free heat transfer and air forced heat transfer are considered, and 0.5 mm liner is applied to each stator slot. Moreover, the heat transfer coefficient (or convection coefficient, h) for air free convection is considered equal to 100 which can reach to 200 for air forced convection [29].

Figure 17 represents the temperature distribution of the proposed 12/14 DSFSPM machine caused by losses at 7 A rms phase current and 1200 rpm rotor speed under both air free convection and air forced convection conditions. As it is shown and expected, the maximum temperature is obtained in inner stator coils with 137°C and 93°C for free and forced convections, respectively.

It is because the inner stator has lower access to the air than the outer stator. Moreover, the temperature of the inner ferrite PMs reaches to almost 118°C and 79°C in free and forced air convections, respectively.
the maximum of back-EMF obtained from both inner and outer stators coils.

As shown in Figures 21 and 22, the experimental results match with 2D-FEM simulation results with an acceptable degree of corresponding. Therefore, the experimental results validate the designing process including the analytical and the FEM analyses.

7 | CONCLUSION

Generally, the high cost of rare-earth magnet is a significant drawback of FSPM machines on the competitive EVs market. However, the 12/10 DSFSPM machine using low-cost ferrite magnets has been proposed as a suitable alternative to the conventional FSPM machine with high-cost REPMs. It is shown that 12/14 DSFSPM machine can generates 30% higher electromagnetic torque in comparison to its other counterpart with a 10-pole rotor. Then, a comprehensive study compares the electromagnetic performances of 12/14 DSFSPM machine with two 12/14 FSPM machine using REPMs and ferrite magnets, respectively. Moreover, an economic study highlights the monetary beneficial of 12/14 DSFSPM structure in comparison to the others. It is shown that 12/14 DSFSPM machine generates almost 80% of the electromagnetic torque of 12/14 FSPM machine with REPMs, while the cost of material in the first structure with 176,466$ is almost 63% lower than that of the latter one with 478,283$. It represents a significant reduction in total material cost due to replacing high cost REPMs by low-cost ferrite magnets.

Following that, a 12/14 DSFPM machine is designed and optimized by Taguchi method with the aim of cogging torque reduction. Then, a thermal analysis under two thermal conditions including free air and forced air convections is investigated to represents the heat transfer capacity of the designed 12/14 DSFSPM machine. Eventually, for experimental validation a prototype of the proposed machine is built in laboratory scale. The experimental results show good compliance of analytical and FEM analyses and validates them.
TABLE 11 Developed torque at different rms phase current

| Rms phase current (A) | Analytical (Nm) | FEM (Nm) | Measured (Nm) |
|-----------------------|-----------------|----------|---------------|
| 2                     | 0.86            | 0.8      | 0.71          |
| 4                     | 1.73            | 1.65     | 1.57          |
| 6                     | 2.4             | 2.3      | 2.2           |
| 8                     | 3.11            | 3.07     | 2.93          |
| 10                    | 3.82            | 3.75     | 3.63          |

FIGURE 22 The voltage of 12/14 double-stator flux-switching permanent magnet machine. (a) Inner stator back-EMF, (b) outer stator back-EMF and (c) phase back-EMF

ORCID
Seyed Milad Kazemi Sangdehi  
https://orcid.org/0000-0002-0174-6643
Seyed Ehsan Abdollahi  
https://orcid.org/0000-0003-2277-1060

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