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# A COMPARATIVE FEM STUDY BETWEEN PERMANENT MAGNET AND WOUND FIELD SYNCHRONOUS MACHINES

BY

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**Abstract.** In this paper, the performances of a surface-mounted permanent magnet synchronous machine (PMSM) and a wound field synchronous machine (WFSM) are compared to highlight their respective advantages and characteristics.

This study focuses on two 1kW synchronous machines with a 9/10 structure (9 stator poles and 10 rotor poles) with identical stator geometries, the first one excited by permanent magnets and the second excited by an electromagnetic field. The paper includes detailed descriptions of the electrical machines and their parameters. The analysis was performed by using the ANSYS Motor-CAD software to evaluate the performance of the two machines. Simulation results using Finite Element Analysis (FEA) are analyzed, and conclusions are presented. Key performance characteristics, such as output power, developed torque, cogging torque, and efficiency, were compared. The study indicated that PMSM with permanent magnets on the rotor surface (SPM) offers higher performance but at a higher manufacturing cost, while the WFSM presents a more cost-effective solution with slightly lower overall performance.

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**Keywords:** FEM simulation, Ansys Motor-CAD, electrical machine design, PMSM (permanent magnet synchronous machine), WFSM (wound field synchronous machine).

## 1. Introduction

In the current socio-economic context, it is necessary to reduce pollution through various methods to maintain a global thermal balance. One of the viable options for reducing carbon emissions is the reduction of fossil fuel consumption and the electrification of large fossil fuel-consuming industries (e.g. transport sector) (Cifuentes-Faura, 2022).

The main reason for choosing electrification is the high efficiency of electrical machines in converting energy (approximately 80-95%) compared to internal combustion engines (around 20-45%).

The electrification of industries is leading to increased use of electric motors and generators. Currently, electrical machines have an important role in generating and consuming electricity; over 40% of produced electricity is consumed by electric motors (Barta *et al*., 2020).

In this context of electrification, electrical machines must meet new requirements regarding electromagnetic performance. These requirements aim to enhance energy efficiency by reducing Joule losses (through optimized winding designs, advanced cooling techniques, improved materials, or even the use of permanent magnets), increasing power density relative to machine volume/mass, improving the torque produced by the machine, and minimizing harmful harmonics (through active or passive filters and design optimization).

At the current stage, car manufacturers are adopting electric motors and re-entering the market with various advanced technologies, such as high-density batteries (Mesbahi *et al*., 2020; Li *et al*., 2021), high-power density motors, and advanced energy conversion technologies (Santiago *et al*., 2012).

The permanent magnet synchronous machine (PMSM) is one of the electric machines preferred by car manufacturers because of its simple construction, which is more streamlined compared to the wound field synchronous machine (WFSM) - where the excitation winding is replaced by permanent magnets and slip rings are eliminated. It offers high efficiency, reaching up to 97%, and is classified in energy efficiency class IE5, the highest level of energy efficiency (Dambrauskas, 2020). Additionally, it has a high specific power relative to the machine's volume or mass.

At the same time, PMSM has a higher production cost due to the price of permanent magnets (Ostovic, 2014). It is more sensitive to temperature, and the risk of demagnetization of permanent magnets increases with temperature (Huang *et al*., 2020; Gómez *et al*., 2017). Additionally, the excitation flux cannot be modified (unlike in the hybrid version of the synchronous machine – HESM or WFSM).

The aim of this paper is to present the performance of two 1 kW synchronous machines with a 9/10 structure (9 stator poles and 10 rotor poles). The first machine is excited by permanent magnets, while the second is excited by an electromagnetic field. The stator geometry and overall dimensions (length and diameter) are identical for both machines, with the only difference being the rotor.

In Section II, both electrical machines are described, along with their working parameters and main dimensions, as results of their design process. Section III presents a comparison between the two machines through finite element simulations using the Ansys Motor-CAD program, along with some conclusions.

## 2. Sizing and design of the machines

For this comparative analysis, two 1 kW synchronous machines (PMSM and WFSM) with 10 poles and 9 stator coils, with fractional-slot and concentric coils in double layers, were considered.

The working parameters are shown in Table 1, while the main dimensions of the resulting structures are shown in Table 2. Figure 1 presents the linear pattern of the stator winding diagram for PMSM/WFSM, obtained using the Ansys Motor-CAD program. A cross-section through the geometry of the two machines is shown in Fig. 2.

**Table 1**
*Working parameters of the machines*

| Parameter's Name | Value | |
|---|---|---|
| | PMSM | WFSM |
| *Rated power* | 1 kW | |
| *Rated speed* | 1100 rpm | 1500 rpm |
| *Rated voltage* | 48 V | |
| *Rated current* | 13.91 A | |
| *Frequency* | 125 Hz | |
| *Number of phases* | 3 | |
| *Connection* | Star - Y | |

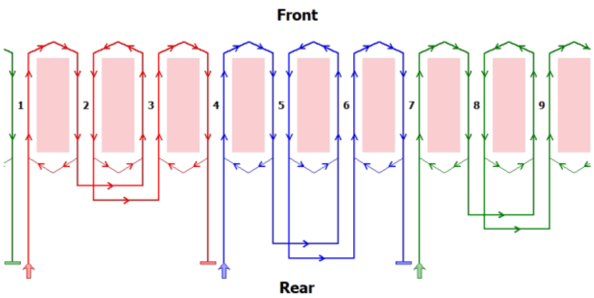


Fig. 1 – The linear pattern of the PMSM/WFSM stator winding diagram.

For this study, for theoretical economic reasons, we chose permanent magnets with a width of 5 mm and a thickness of 2 mm; therefore, each pole contains five such magnets. These were selected as N30UH type, with radial magnetization and weaker magnetic characteristics.

A silicon steel M250-35A was used for the stator core and a silicon steel M350-50A for the rotor core. To ensure optimal distribution of the magnetic flux through the rotor core, a non-ferromagnetic material was chosen for the shaft: stainless steel 302.

**Table 2**
*Main dimensions of the machines*

| Parameter's Name | Value | |
|---|---|---|
| | PMSM | WFSM |
| *Stator lenght* | 40 mm | |
| *Stator outer diameter* | 140 mm | |
| *Stator inner diameter* | 100 mm | |
| *Stator slot number* | 9 | |
| *Stator tooth width* | 16.5 mm | |
| *Stator winding turns per phase* | 93 | |
| *Minimum airgap* | 0.5 mm | |
| *Rotor pole number* | 10 | |
| *Rotor length* | 40 mm | |
| *Permanent magnets length* | 40 mm | - |
| *Permanent magnets thickness* | 2 mm | - |
| *Permanent magnets width* | 5 x 5 mm | - |
| *Pole surface radius* | - | 49.5 mm |
| *Rotor pole width* | - | 8.5 mm |
| *Rotor winding turns per pole* | - | 332 |
| *Excitation current* | - | 2.22 A |

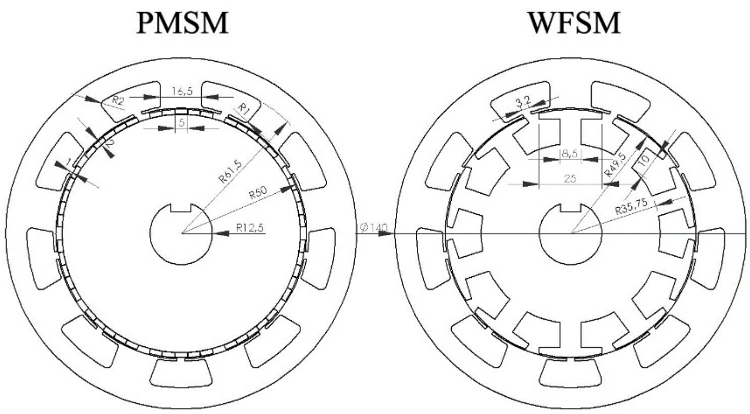


Fig. 2 – Geometry cross section – PMSM and WFSM.

## 3. Comparative FEM simulation results

The results of this study, for the two proposed structures, were obtained through transient simulations with a constant load, using the 2D FEM analysis of the Ansys Motor-CAD program.

The color maps of the magnetic flux density and the flux lines for the PMSM and WFSM machines are displayed in Fig. 3.

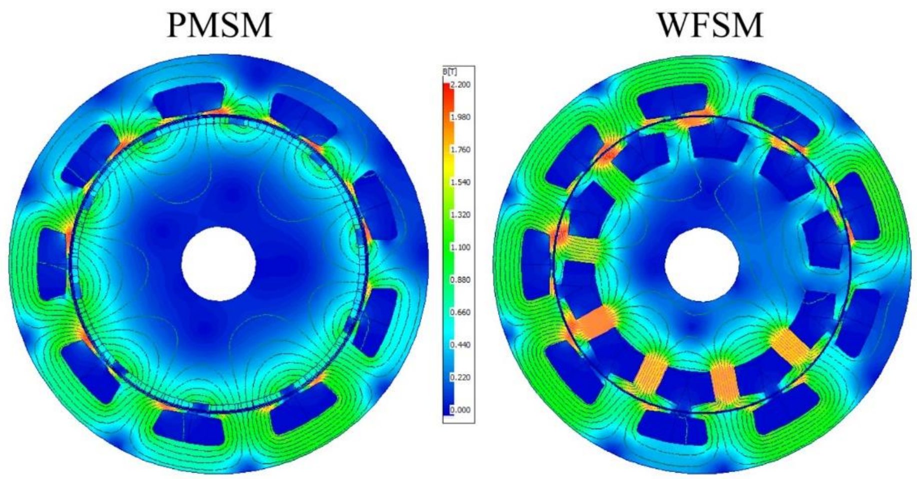


Fig. 3 – Color maps of the magnetic flux density and the flux lines at 45° mechanical degree displacement of the rotor – PMSM and WFSM.

For both structures, small differences in the magnetic flux density at the stator teeth can be observed. The most notable differences appear in the rotor, where the WFSM structure reaches higher magnetic flux density values compared to the PMSM. This indicates that the WFSM requires a higher magnetic load to match the performance of a permanent magnet, even if the latter has lower magnetic properties.

The airgap magnetic flux density distribution is presented in Fig. 4. The PMSM structure exhibits higher flux density values in the airgap, indicating improved magnetic flux stability due to the nearly constant airgap. This stability is essential for achieving higher efficiency by minimizing torque ripple, harmonics, and overall machine losses, ensuring consistent performance under varying operating conditions.

As observed in Fig. 4, the WFSM structure has a higher harmonic content, leading to waveform distortion and reduced machine performance. Additionally, the ten poles can be observed.

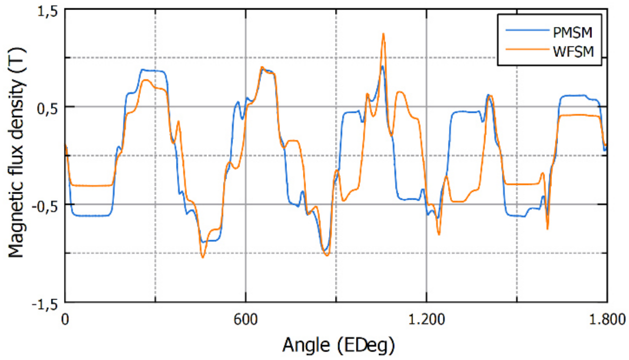


Fig. 4 – Airgap magnetic flux density distribution of PMSM and WFSM.

Figure 5 shows the waveforms of the Back EMF line voltages. Due to the spatial distribution of the permanent magnets, the back EMF has a trapezoidal shape (specific for PMSM). On the other hand, because of the variable nature of the magnetic flux generated by the excitation coils, the waveform of back EMF, has a sinusoidal form.

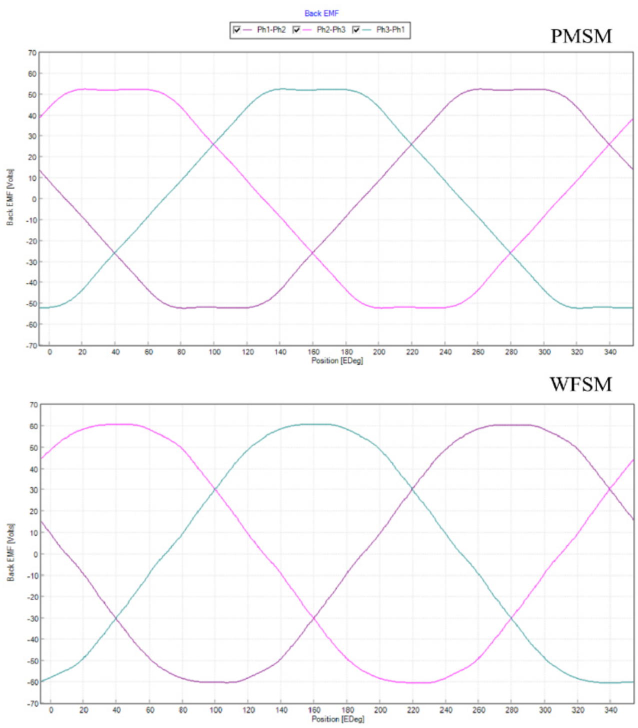


Fig. 5 – Back EMF of PMSM and WFSM.

Figure 6 and Fig. 7 show the comparative results for the developed torque and the cogging torque, calculated for the two structures. As can be seen, the developed torque values are higher for the PMSM machine due to the better magnetic characteristics of the permanent magnets compared to the excitation field created by the coils. The torque ripple is also higher for the PMSM structure due to the interaction of the permanent magnets with the stator poles.

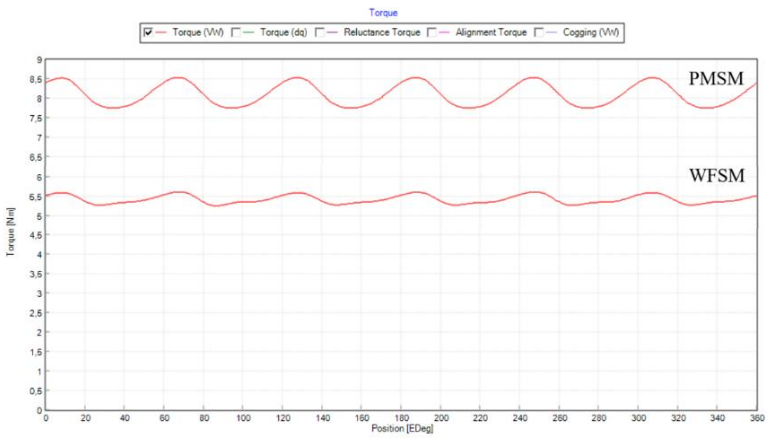


Fig. 6 – The developed torque by PMSM and WFSM.

Similarly, for the cogging torque, the higher values are observed for the PMSM structure, because the phenomenon of the rotor poles "sticking" to the stator poles occurs, resulting in the acceleration or braking of the electric machine.

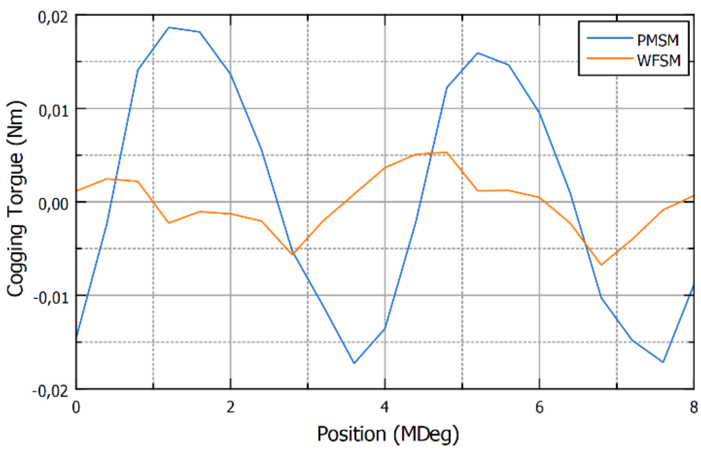


Fig. 7 – The cogging torque of PMSM and WFSM.

At the end of this section, Table 3, with the most conclusive data for this study, will be presented. The data were extracted as results from Ansys Motor-CAD after simulations.

Comparing the performance of the two types of studied synchronous machines, based on the data obtained in Table 3, it is observed that both the PMSM and WFSM have similar input power values, with PMSM having a value of 1048.8 W and WFSM having 1046.2 W. However, the differences become evident in the output power. The PMSM delivers an output power of 926.31 W, while the WFSM only delivers 825.45 W, suggesting higher performance of the PMSM in energy conversion.

This output power difference is highlighted by the total losses in the machines, which are considerably lower for the PMSM (122.5 W) compared to the WFSM (220.8 W), which also explains the efficiency of the machines, 88.3% for PMSM versus 78.9% for WFSM. The total losses calculation includes losses from machine excitation, which are noticeably high for the WFSM at 78.51 W (field DC copper loss), while for the PMSM, they are very low, at only 0.34 W (magnet loss).

**Table 3**

*Data results from Ansys Motor-CAD*

| Parameter's Name | Value | |
|---|---|---|
| | PMSM | WFSM |
| *Input power (Electric power)* | 1048.8 W | 1046.2 W |
| *Output power (Mechanical power)* | 926.31 W | 825.45 W |
| *Efficiency [%]* | 88.3 | 78.9 |
| *Shaft torque* | 8.04 Nm | 5.25 Nm |
| *Torque ripple* | 0.72 Nm | 0.3 Nm |
| *Torque ripple [%]* | 8.89 | 5.69 |
| *Cogging torque* | 0.018 Nm | 0.005 Nm |
| *Total loses (open circuit)* | 5.55 W | 84.9 W |
| *Total loses (on load)* | 122.5 W | 220.8 W |
| *Magnet loss* | 0.34 W | - |
| *Field DC Copper loss* | - | 78.51 W |
| *Magnet weight* | 0.15 kg | - |
| *Field winding weight* | - | 0.51 kg |
| *Rotor lamination weight* | 1.91 kg | 1.55 kg |
| *Total Weight* | 5.05 kg | 5.05 kg |

Regarding the developed torque, the PMSM machine produces a torque of 8.04 Nm, significantly higher than the 5.25 Nm in the WFSM. This is due to the uniform and constant distribution of the magnetic flux across the entire machine, because of the permanent magnets placed on the rotor surface. The torque ripple is also higher in the PMSM (8.89%) compared to the WFSM

(5.69%), as well as the cogging torque. This indicates a higher tendency for the permanent magnets to align with the stator slots in the case of PMSM.

Although both machines have the same mass (5.05 kg), the power density relative to mass is different, being higher in the case of the PMSM. The weight distribution is also different: for the PMSM, the permanent magnets weigh 0.15 kg and the rotor lamination weighs 1.91 kg, while for the WFSM, the copper winding weighs 0.51 kg and the rotor lamination weighs 1.55 kg.

Regarding costs, it is important to mention that although both PMSM and WFSM have the same total mass and dimensions, the manufacturing cost of the PMSM machine is significantly higher. This is due to the much higher price of the permanent magnets used in the PMSM structure, which are typically ten times more expensive than the copper used in WFSM machines.

The dimensions and mass of the PMSM machine's rotor could have been significantly reduced compared to the current state; however, this study focused on maintaining the same mass for both structures. Both synchronous machine structures can be optimized to achieve performance levels far superior to those presented.

## 4. Conclusions

The purpose of this comparative study was to highlight the performance of the Permanent Magnet Synchronous Machine (PMSM) and the Wound Field Synchronous Machine (WFSM). In this study, neodymium permanent magnets with lower magnetic properties were used for the PMSM. However, these magnets are much more efficient and significantly more expensive than ferrite magnets.

Based on the comparison between the PMSM and WFSM structures, it is evident that both machines exhibit distinct performance characteristics. The results obtained from this study show that the PMSM machine presents significantly superior performance compared to the WFSM machine. Despite both PMSM and WFSM having similar input power and the same total mass, the PMSM delivers superior performance in terms of output power, efficiency, developed torque, and loss distribution, with much lower losses compared to the WFSM, particularly due to the reduced losses of the permanent magnets.

Additionally, although both machines have the same mass, the weight distribution and power density per unit of mass differ significantly, favouring the PMSM. These findings demonstrate that the PMSM could be more advantageous for applications where performance and efficiency are prioritized, while the WFSM may be more suitable for cases where adaptability to varying load conditions is more important.

Regarding costs, the PMSM incurs a higher manufacturing cost due to the use of permanent magnets, which are considerably more expensive than the copper windings used in the WFSM. This makes the WFSM a more cost-effective choice, despite its lower overall performance.

Optimization of the proposed machines is considered for further studies, along with a comparison to a synchronous machine using weaker permanent magnets, such as ferrite magnets.

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# STUDIU COMPARATIV FEM ÎNTRE MAȘINILE SINCRONE CU MAGNEȚI PERMANENȚI ȘI CELE CU EXCITAȚIE ELECTROMAGNETICĂ

(Rezumat)

În această lucrare sunt comparate performanțele unei mașini sincrone cu magneți permanenți plasați pe suprafața rotorului (PMSM – Permanent Magnet Synchronous Machine) și ale unei mașini sincrone cu excitație electromagnetică (WFSM – Wound Field Synchronous Machine), în vederea evidențierii avantajelor și a caracteristicilor specifice ale fiecărui tip de mașină.

Studiul se concentrează asupra a două mașini sincrone de 1 kW, având structura 9/10 (9 poli statorici și 10 poli rotorici) și geometrii statorice identice, prima mașină fiind excitată cu magneți permanenți, iar cea de-a doua excitată electromagnetic. Lucrarea include descrieri detaliate ale geometriilor mașinilor electrice și ale parametrilor acestora. Analiza a fost realizată utilizând software-ul ANSYS Motor-CAD, pentru a evalua performanțele celor două mașini. Rezultatele simulărilor, obținute prin metoda elementelor finite (FEM), sunt analizate, iar concluziile sunt prezentate. Au fost comparate caracteristici esențiale de performanță, precum puterea de ieșire, cuplul dezvoltat, cuplul de blocare și randamentul. Studiul realizat evidențiază faptul că mașina sincronă cu magneți permanenți plasați pe suprafața rotorului (SPM – Surface Permanent Magnet) oferă performanțe superioare, însă implică un cost de fabricație mai ridicat, în timp ce mașina cu excitație electromagnetică constituie o alternativă mai avantajoasă din punct de vedere economic, dar cu performanțe electromagnetice ușor inferioare.