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COMPARATIVE ANALYSIS OF FIVE-PHASE SYNCHRONOUS RELUCTANCE MOTOR AND PERMANENT MAGNET-ASSISTED SYNCHRONOUS RELUCTANCE MOTOR

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ABSTRACT

The models of five-phase various permanent magnet-assisted synchronous machines and the non-permanent assisted synchronous motor are presented. The machines are modelled for directly online starting using ACEBD winding arrangement. The models are modelled with a permanent assist of sixteen rectangular-shaped magnets placed in the flux barriers. The various materials of Alnico, Strontiumferrite, samarium-cobalt, NdFe35 and graphite, were compared to the performance characteristics of a non-assisted Synchronous Reluctance motor. ANSYS Finite Element Software was used for the analysis and implementation of the model. The machine performance characteristics of the vector potential, inductances, flux linkage and current were considered. The machine speed performance characteristic of the graphite-assisted model shows similar characteristic as the strontiumferrite model especially on loading and at loss of synchronism. The graphite-assisted model records the highest flux linkage, a value of 0.760029ωb, while the least value of 0.752943 ωb is recorded by the NdFe35 magnet-assisted model. Even with the recorded difference between the models, these are significant at the second place of decimal, recording a 0.9323% between the lowest recorded values and the highest recorded value. These recorded characteristics of the graphite-assisted model have invited further investigations as an improved model of material-assisted synchronous reluctance machine.

Keywords: *Synchronous Reluctance Machine, Permanent magnet, Finite Element Analysis, Flux linkage. Graphite assisted*

1. Introduction

The utilization of permanent magnets in electrical machines cuts across many industries, evidence in aviation, rail, electrical vehicles, power generation, etc. These magnets may play a major role in providing the magnetic flux for linkage as in Permanent Magnet Synchronous Machine (PMSM) or assist in the linkage process, as in permanent magnet assisted Synchronous Reluctance Machine (PMASynRM). When the magnet is used as an assist, the machine has to be modelled to assist in flux linkage. Due to the high cost of permanent magnets, the size of the magnet can be reduced by optimization of the machine design, ensuring concentration of flux linkage aiding torque. In the Synchronous Reluctance Machine (SynRM), where the saliency of the machine is of great importance (Obe E. 2011) and the reluctance torque is relevant, the placement of the magnets should be such as to assist the torque. In modelling the 3-phasePMASynRM, the permanent Magnet flux assists the d-axis flux, since higher saliency is experienced in the d-axis (Krause P. 2013). Conversely, in the 5 ph machine, greater reluctance exits in the q-axis and the magnet should be placed such as to assist this flux (Umoh G. 2020).

The choice of the flux barriers for the synchronous reluctance machine also applies to the permanent magnet-assisted synchronous reluctance machine, since the barriers assist in directing the flux as desired, depending on the modelled rotor.

The use of permanent magnets in synchronous reluctance machines is mainly in applications where scheduled task outweighs the cost, especially in high-speed applications (Toliyat H. 1991). Permanent magnets in synchronous generators used in wind power generation (Mashimo A. 2013, Abd El Hamied M. 2016), have also been proven to compete favourably as a double-fed system based on the wound rotor induction generator, going further to replace the need for speed-increasing gears (Mashimo A. 2013). Due to the high cost of permanent magnets low-cost magnets and ferrites appear to be an attractive alternative (Liu H. 2017).

The multi-phase system assisting in torque production without the core loss of the machine increasing is economical and attractive, but a compromise has to be made between the need for a higher phase and the cost of the possible drive system. The choice of a higher phase can assist in the utilization of additional available harmonics for torque production (Toliyat H. 1991, Umoh G. 2017, Parsa L. 2005, Umoh G.2020). The 5-phase synchronous machine has been of much interest to researchers, and a considerable amount of study has been documented (Toliyat H. 1991, 1992 & 1998, Umoh G. 2017.

This study analyses a five-phase Synchronous Reluctance Motor and the Permanent magnet synchronous reluctance motor, investigating their characteristic performance of speed, inductance, flux linkage and current. The system is loaded with ramp load to determine the various loading capacities of the different considered models. ANSYS Finite element

Analysis (FEA) software is used for the analysis of models.

2. Model of Five-Phase Synchronous Reluctance Motor

The synchronous Reluctance motor (SYNRM) was modelled with a cage rotor, having 4-pole and four flux barriers with a double-layer winding arrangement in the stator. The winding layout was arranged in ACEBD configuration separated by $\frac{2\pi}{5}$radian.

The machine dimensions and circuit parameters are presented in Table 1.

Table 1: 5-Phase SRM machine dimensions and circuit parameters

Quantity	Value	Quantity	Value
Stator Outer / inner radius	87.5 / 51 mm	Number of Poles	4
Rotor Radius	50 mm	Frequency	50 Hz
Effective stack length	110 mm	PM Length (mm)	5,7,11,13
Number of slots	40	phase voltage V_{ph}	220v
Number of turns	48	Main air-gap length g_a	1 mm
PM thickness	3 mm	Number of slots	40

The 2-D finite element model of the machine is shown in Figure 1.

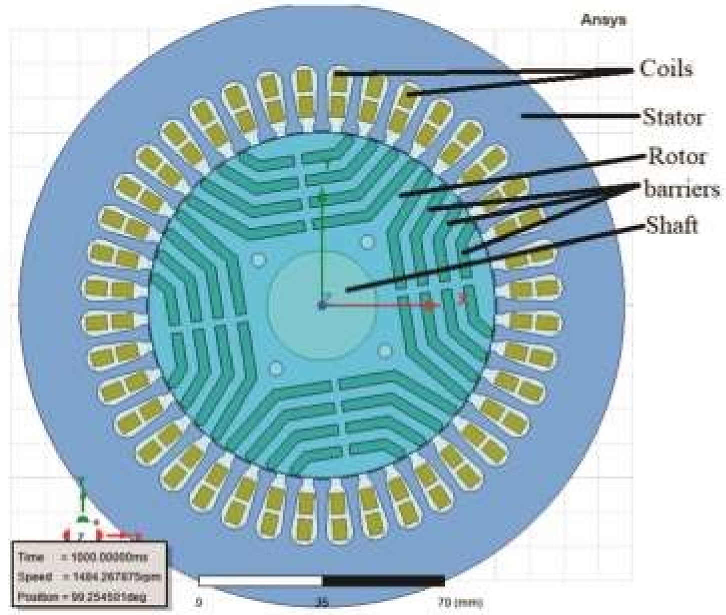


Fig. 1: 5-phase Synchronous Reluctance Machine Model

3. Model of Five-Phase Permanent Magnet-Assisted Synchronous Reluctance Motor

The machine parameters for the PMA SynRM and the SynRM models are tabulated in Table 1. The assisted material was placed in the barrier in a pattern as shown in figure 2. These arrangements support a four-pole magnetic configuration. The dimensions of the magnets are given in table 1.

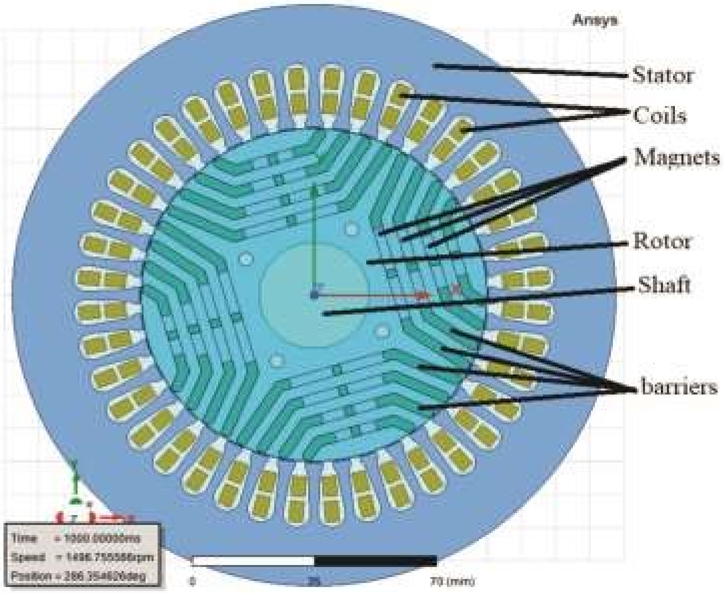


Fig.2: 5-phase Permanent Magnet Assisted Synchronous Reluctance Machine Model

The materials employed for the models are tabulated in Table 1.

The magnetic properties of the assisted material are tabulated in Table 2, in Figure 3. Shows a B-H curve of Alnico.

Table 2: Properties of the assisted materials in the SynRM

S/N	Material	Relative Permeability	Magnetic Coercivity (A/m)	Mass density
1	NdFe35	1.099779	-8.9e4	7400
2	ferrite	1000	0	4600
3	Graphite	1	0	2250
4	SmCo28	1.038388959	-820000	8300
5	Alnico9	B-H curve	-119366	7300
6	Strontiumferrite	B-H curve	-312000	5100

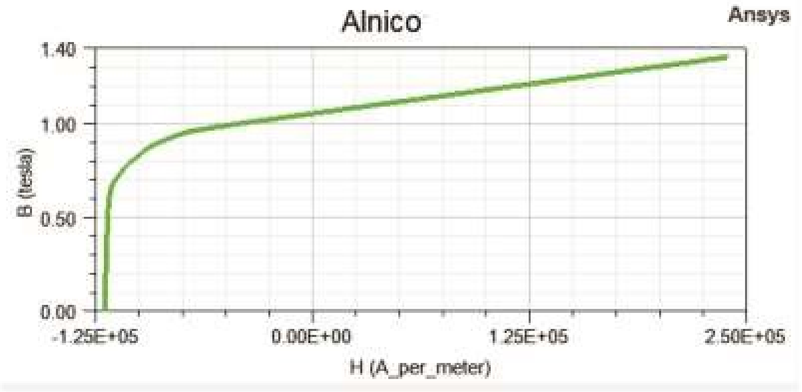


Fig. 3: Magnetic characteristics plot of Alnico (ANSYS)

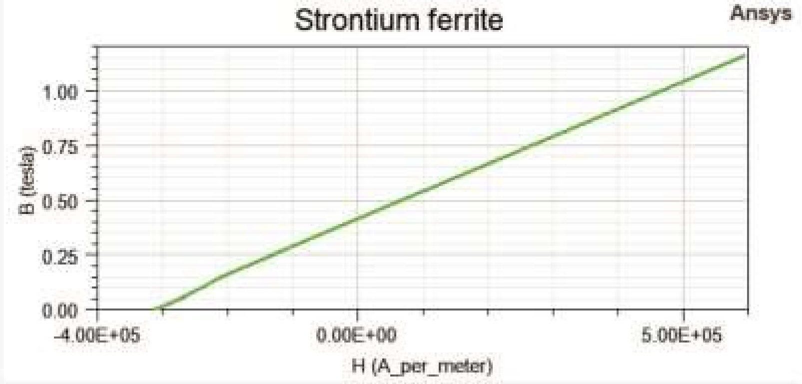


Fig. 4: Magnetic characteristics plot of Strontium ferrite [13]

4. SIMULATION OF THE DYNAMIC PROCESS

The Vector potential, speed, inductances, phase Current and Flux linkage of the machine were monitored for all the considered models. For the inductances, the a-phase self-inductance, the a-phase and b-phase mutual inductance, and the a-phase and c-phase mutual inductance were considered. The considered mutual inductance has a $\frac{2\pi}{5}$rad phase shift in a-phase and c-phase, and a $\frac{4\pi}{5}$ rad phase shift between a-phase and b-phase.

4.1 Vector Potential

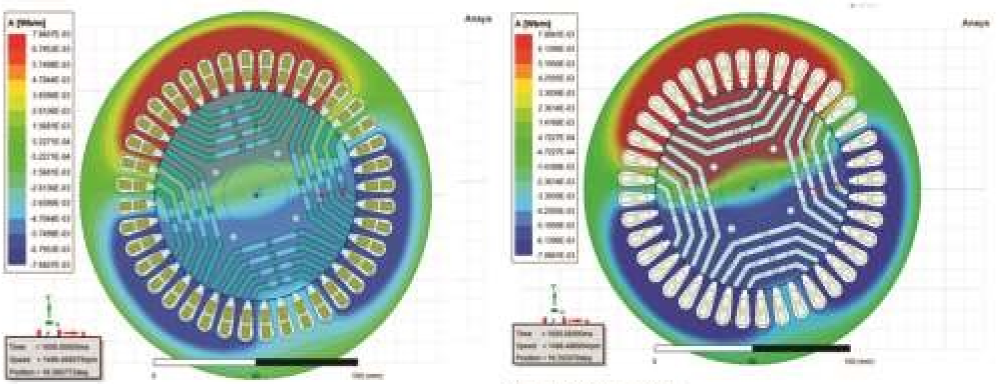
The vector potential of the models was plotted at 1 second. The permanent magnet-assisted SYNRM showed alnico distinctly split potential, while the ferrite-assisted SYNRM showed a similar vector potential layout as the SYNRM and the graphite-assisted SYNRM.

It can also be recorded that none of the machines has recorded the same position at 1 second even though they all started at a standstill at the same position.

The Alnico, Strontiumferrite (Str ferrite), samarium-cobalt (smco) and NdFe35 (Nde) magnets assisted SYNRM vector potential plot at 1 second are shown in Figure 5. The speed and rotational position values are shown in Table 3.

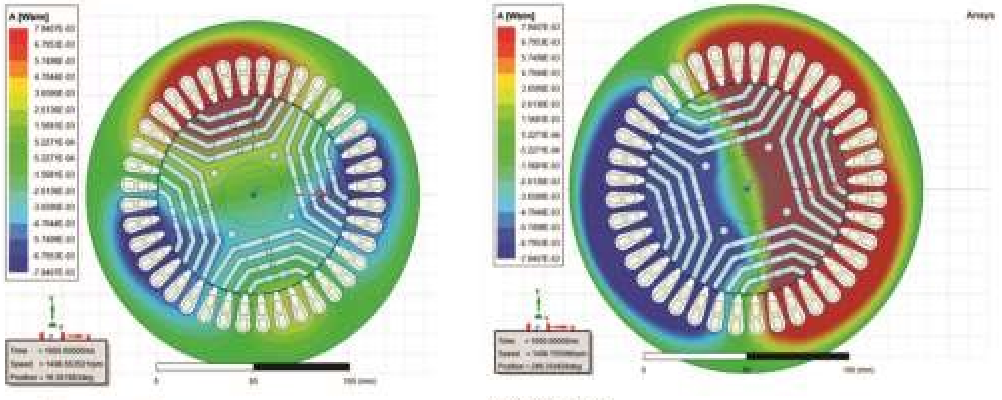
Table 3: Material Assisted SynRM position and Speed value at 1 sec.

Material Assisted SynRM position and speed at 1 second		
SYNRM TYPE	Speed (rpm)	Position (deg)
SynRm	1484.2679	99.2545
PMA ferrite	1484.8702	84.6306
PMA Nde	1496.7555	286.3546
PMA Smco	1496.4869	16.3521
PMA Alinco	1496.4691	16.3608
Graphite	1496.3966	16.3624
PMA Str ferrite	1496.5535	16.3819



(a) Alnico

(c): Samarium-cobalt

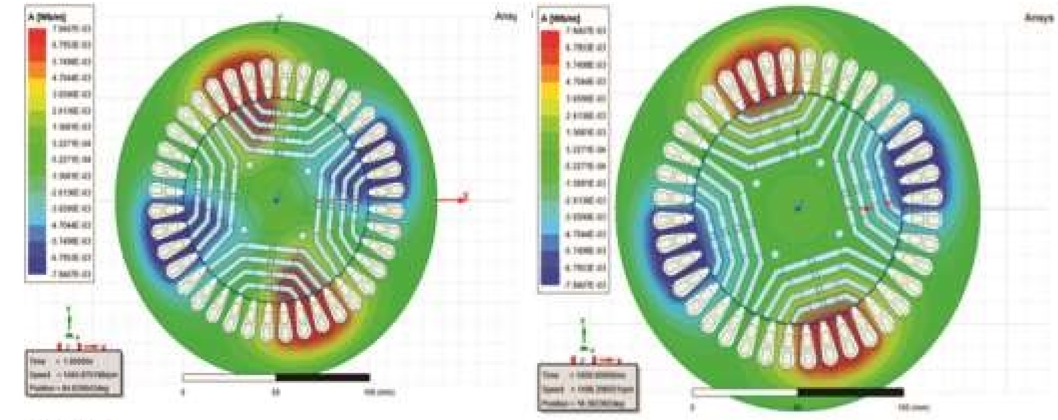


(b) Strontium-ferrite

(d) Nd-Fe35

Fig.5: Vector potential plot for PMA SynRM

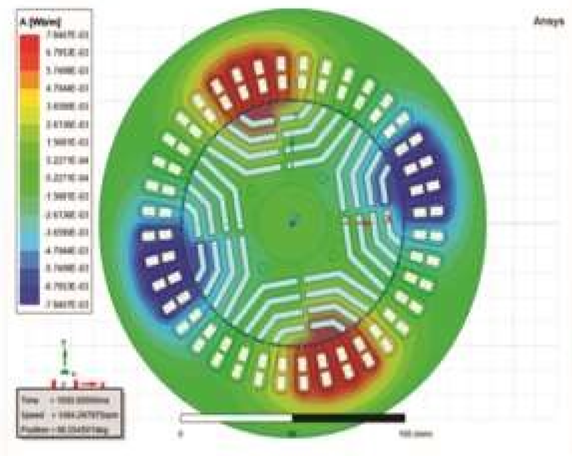
The vector potential plot of ferrite, graphite and non-material assisted SynRM is shown in Figure 6. Their speed and rotational position values are shown in Table 3.



(a) Ferrite

(b) Graphite

(a) Ferrite



(c) SynRM

Fig.6: Vector potential plot for non-PMA SynRM

4.2 Speed Characteristics

All the models reach synchronism after starting with graphite graphite-assisted model recording the greatest oscillation but dampened on the introduction of load. The load is introduced as a ramp load at 0.9 seconds, with a gradient value of 10 Nm/s.

At 0.98 seconds. The ferrite model lost synchronism followed by the non-assisted model of the SynRM, recording a drop in speed, and maintaining the speed until 1.4 seconds Figure 8. The speed characteristics plots of the models are shown in Figure 7, with an enlarged plot showing the lost of synchronism of SynRM and ferrite-assisted models in Figure 8, while the PMA SynRM and graphite-assisted models enlarged plot showing loss of synchronism in Figure 9.

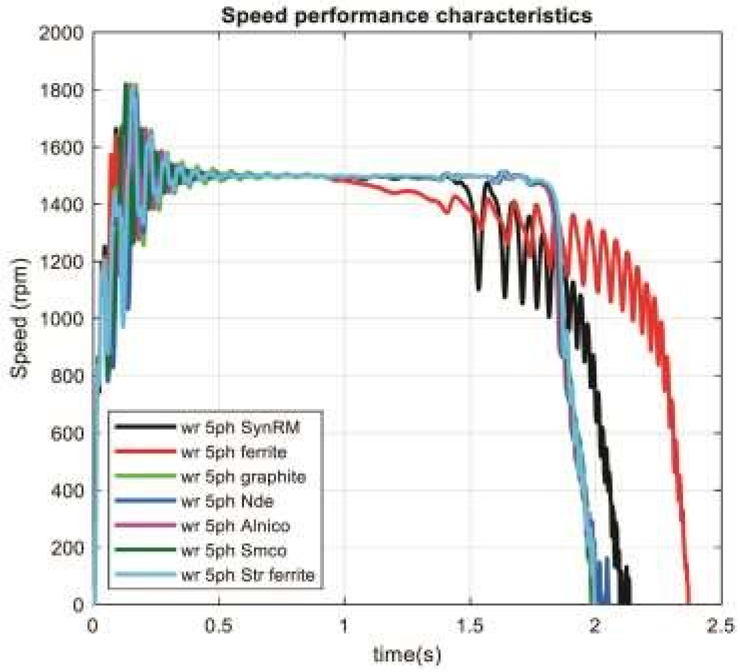


Figure 7: Speed Performance Characteristics

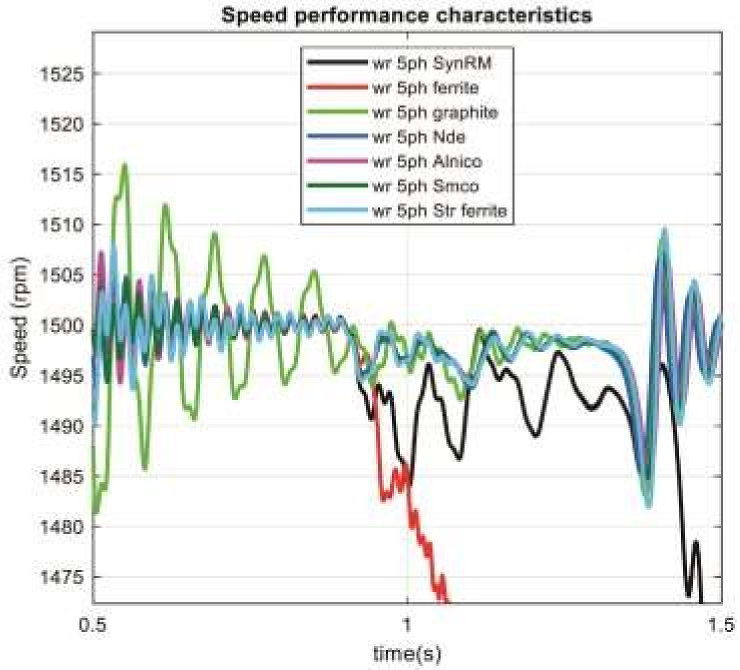


Fig. 8: Enlarged plot showing loss of synchronism of SynRM and Ferrite-SynRM