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Optimized Permanent Magnet Assisted Synchronous Reluctance Motor Design and Comparison (PMa-SynRM) Induction Motor with Identical NEMA Stator Frame

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Abstract

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The performance of a synchronous reluctance motor (SynRM) depends on the direct axis inductance (Ld) and the square axis inductance (Ld) of the machine. To achieve a high torque density and power factor, increasing the saliency ratio Ld/Lq and making this inductance difference (Ld-Lq) large enough is a well-known method. Otherwise, the performance of the motor will remain below that of a similar induction engine using a similar stator. This study attempts to place the right amount of permanent magnet in the rotor in the right position, it will be possible to achieve a significant increase in the performance of permanent magnet-assisted SynRM (PMa-SynRM) which will be comparable to an induction machine with the same stator. The PMa-SynRM will benefit from the reduction in price due to the use of a conventional induction machine stator.

Keywords : PMa-SynRM, Induction Motor, NEMA-Frame

1. Introduction

One of the US Navy's key principles for future ships and submarines is to be electric, where electrical technology will replace the hydraulic and pneumatic fluid power systems that currently support operating equipment. The main components needed for both existing ships and future electric ships and submarines are electric motors and generators. The requirements for the development of inexpensive, flexible and reliable motor and generator systems have grown in recent years, due to the growth in electrification of ships, automobiles, etc. The development of universal stator laminate designs that can be used across a wide range of motors and generators is a way to reduce manufacturing and maintenance costs. In addition, the operation in this engine drive requires a large saliency ratio (S. Aryza et al., 2018).

Adding the right amount of permanent magnets into the SynRM rotor core is another way to improve the operating performance of this machine. In this respect, the motor is similar to an interior permanent magnet (IPM) engine. However, the number of permanent magnets used and the relationship of permanent magnetic flux is smaller than that of conventional HDI. Thus, the proposed motor can be called a permanent magnet assisted synchronous reluctance motor (PMa-SynRM) (Some et al., 2013)

In this paper, an optimized PMa-SynRM based on the same frame as a specific NEMA frame induction motor is designed. Its design and performance characteristics are compared with the special NEMA frame induction motor used for the design and conclusions are made (Asgar et al., 2016).

One of the first steps towards designing a universal stator suitable for induction machines and SynRM is the investigation of the NEMA frame laminates used in induction motors on the market. The performance characteristics of the induction machine are obtained and the operating conditions such as line voltage and winding current will be available for designing the PMa-SynRM rotor. The benefit of this method is the existence of a reference engine for comparison with (Swibawa et al., 2017) other newly designed machines. For this purpose, in this study a 7.5 HP, 4 pole, 3 phase squirrel cage induction motor was chosen. The NEMA frame of this bike is the C213T. Table I includes motor specifications with key stator information derived from the manufacturer's data sheet and from experiments. This induction motor stator laminate is used in the PMa-SynRM design. To keep the main characteristics of the new engine the same as the induction engine, the air gap width, inner diameter and outer diameter of the rotor are kept the same as the reference induction motor (Deptt & Jabalpur, 2013).

Table 1. Induction Motor Parameters

Power Output (HP)	7.5
Voltage (V)	460
Current (A)	10.5
Shaft Torque (Nm)	30.88
Efficiency (%)	89.1
Power Factor	0,81
Shaft Speed (rpm)	1730
Minimum Air Gap (inci)	0,016
Rotor Inner Diameter (inci)	1.551
Rotor Outside Diameter (inci)	4.968
Stator Inner Diameter (inci)	5.00
Stator Outside Diameter (inci)	9.00
Number of Stator Slots	36
Stator Winding Coil Pitch	8
Number of Spinning Spins per Slot	60
Number of Winding Layers Per Slot	2

2. Method

2.1 Synchronous Motor Optimization.

Synchronous reluctance motors (SynRM) have several advantages such as low cost, high speed capacity, and resistance to temperature. Since reluctance torque is the main operational source of SynRM, it is important to design optimal rotor geometry using suitable barriers [2,3]. In fact, PMa-SynRM is a permanent magnet rotor synchronous machine with multilayer flux barrier, or in other words an interior multilayer permanent magnet rotor machine. A standard interior permanent magnet machine has only one layer of permanent magnet rotor per pole, and the permanent magnet contributes to the dominant torque (Dzulfikar & Broto, 2016).

The high magnetic salience created by the double flux resistance in the rotor makes torque reluctance dominant at low speeds when the highest torque is required. The stator core of the machine is provided with uniform slots that accommodate concentrated short-pitched windings. The rotor core is manufactured from a conventional transverse laminate with a stamped double flux barrier per pole, filled with a layer of permanent magnets. Transverse laminated rotors with multiple flux barriers require induction motor magnets. Figure 2 shows the rotor optimized for this study. Using the finite element analysis of the NEMA frame stator rotor, the machine's magnetostatic and transient torques have been obtained. The main objective of optimization is to obtain the maximum average torque and minimum torque ripple which is accomplished by changing the barrier size and the position of the permanent magnet. Also, in each case the rotor geometry is modified to provide a better path for the flux lines avoiding high flux densities. This optimization method reduces the reluctance torque to a certain degree. However, due to the decrease in saturation in the PMa-SynRM core, the torque generated by the magnets increases and less core loss is expected. The stator current is in all cases the same as under the rated conditions of the original induction motor. The magnet used is NdFe30 and the data is presented in Table II [7]. Using this type of magnet causes high saturation in the ribs, but significantly improves engine performance.

2.2 Repair and investigation.

As previously mentioned, to increase the SynRM output torque, increasing the saliency ratio is an effective way. In order to demonstrate the magnetic effect on Ld and Lq SynRM and PMaSynRM, the flux relationship of the two machines in phase A was investigated.

For SynRM, it is possible to find Ld and Lq by applying the maximum current to phase A and obtaining the flux relationship of phase A when the rotor is run by an external primary drive. The maximum and minimum flux relationships will be proportional to Ld and Lq respectively [8]. Figure 3 shows the relationship of the phase A flux when the phase A excitation is maximum and the rotor rotates at 1800 RPM using transient FEM analysis in Maxwell 2-D software. Phase A is excited with maximum line current Ia=14.85 (A) and Ib=Ic= -0.5Ia (RMS line current is 10.5 (A)).

To calculate the saliency ratio of PMa-SynRM, the flux relationship due to stator excitation was obtained and the flux relationship due to permanent magnetism was subtracted from it. Figure 4 shows the waveform generated by the bridge to leave the laminate intact and provide sufficient mechanical resistance up to the maximum design speed (Taufik, 2013).

Figure 1 shows a modern transverse laminated rotor for SynRM. This rotor lamination was used for the initial design stage and was optimized for the PMa-SynRM design for maximum performance with a stator from

Figure 1. Modern Transverse Lamination Rotor for SynRM

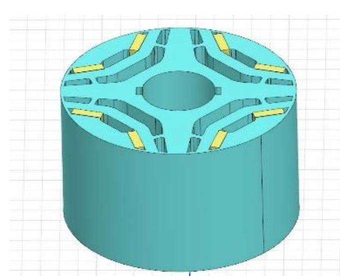

Figure 2. PMa-SynRM Rotor 3-D Model Optimized for Study

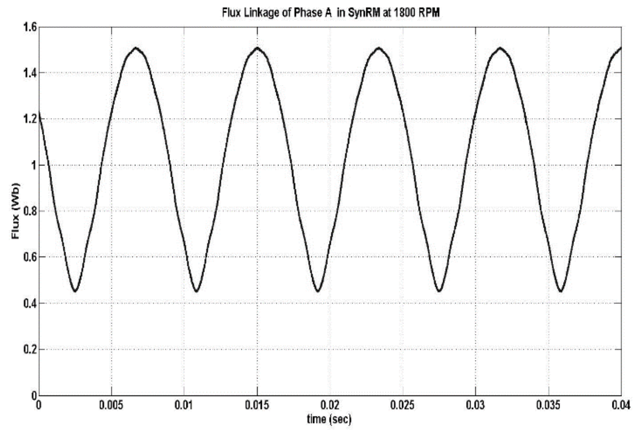

Figure 3. The flux link from SynRM (Phase A)

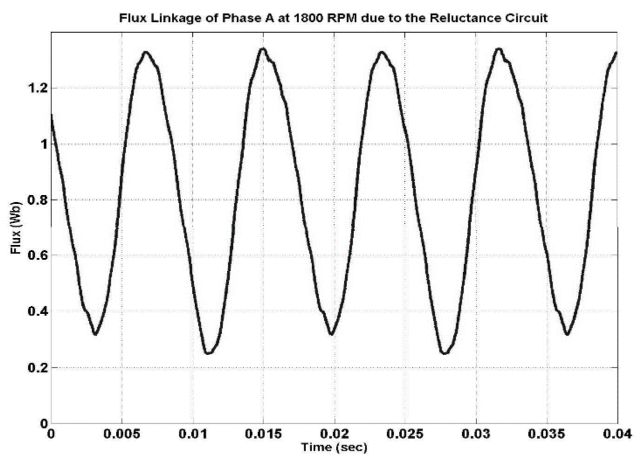

Figure 4. Link flux from PMaSynRM Due to Stator Excitation

It is clear that the saliency ratio is not very high for SynRM because the rotor geometry has been improved by using permanent magnets. The maximum and minimum ratio of the waveform in Figure 4 is about 5.4 which indicates a significant increase of the SynRM saliency ratio using permanent magnets. Also, it is interesting to see that the maximum linkage flux waveform in Fig. 4 is less than the maximum waveform in Fig. 3. Image. 5 and Fig. 6 shows the distribution of flux lines for the maximum torque angle. In SynRM, flux lines are more and density is higher in some teeth whereas in PMa-SynRM it is reduced. As a result, less core loss is expected compared to SynRM.

The decrease in the d-axis flux relationship in PMa-SynRM is caused by saturation of the stator teeth and rotor ribs. This is caused by permanent magnets. Table III compares the saliency ratios of SynRM and PMa-SynRM and the improvements obtained using permanent magnets.

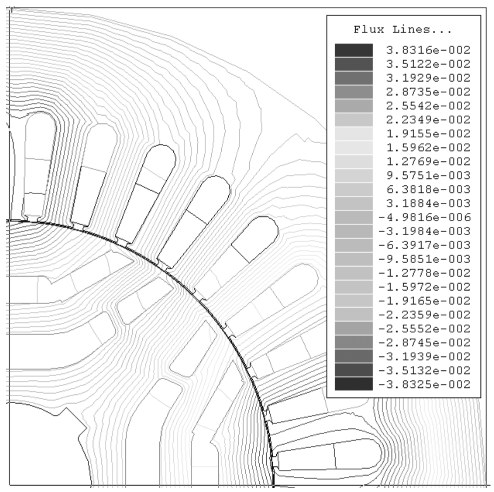

Figure 5. Flux Channel Distribution in SynRM

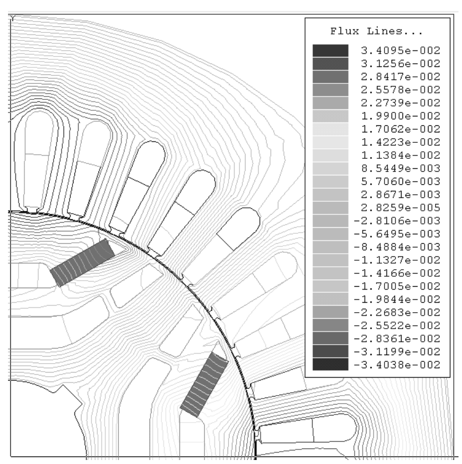

Figure 6. Flux Path Distribution in PmaSynRM

3. Result And Discussion

3.1 Analysis of a syncron motor and comparison with induction motor

After finding the maximum torque angle of the rotor on the magnetostatic analysis in Maxwell 2-D, then a transient analysis was carried out to obtain the transient torque and return EMF of the engine. Because the stator is the same as the induction motor, the current used for excitation is 10.5A. PMa-SynRM speed is considered as synchronous speed which is 1800 RPM for 4 pole engine supplied at 60Hz.

The stator current is the same to keep the copper losses the same as the reference induction motor and ensure the windings are properly loaded. In addition, to compare the performance of the motor, transient analysis of the induction motor was carried out at the rated operating point.

Figure 7 shows the transient torque for both a synchronous machine and a reference induction motor with the same stator current. It is interesting to note that the average torque and ripple torque of the SynRM is more than that of the induction motor. However, it is clear that SynRM's power factor will be low. The optimized PMa-SynRM delivers more torque compared to SynRM and induction motors. PMa-SynRM torque ripple is higher due to cogging torque caused by permanent magnet but still smaller than induction motor. Table IV contains the results of the FEM analysis.

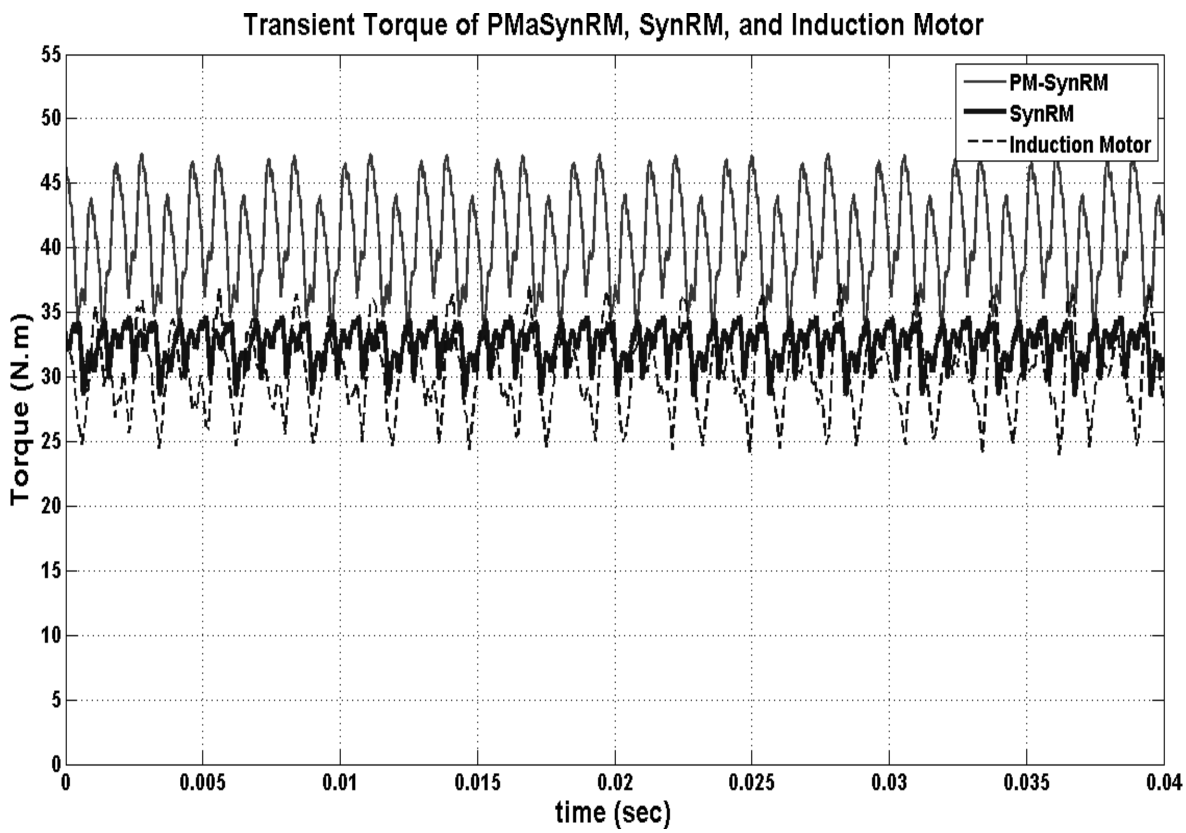

Figure 7. Comparison of PMa-SynRM, SynRM, and Induction Motor Transient Torques

Table 2. Parameters Of Induction Motor

Parameter	Induksi	PMa-SynRM	SynRM
Kecepatan Operasi (rpm)	1730	1800	1800
Nilai Arus Fase RMS (A)	10.5	10.5	10.5
Nilai Torsi (Nm)	30.88	39.8	32
Torsi Riak (%)	20	16	8
Nilai Daya Keluaran (kW)	5.6	7.5	6.0
Faktor kekuatan	0.8	0,85	0,55

The results showed that the output power of PMa-SynRM was 33% greater than the induction machine. These results indicate that the PMa-SynRM input voltage must be higher because the input current is the same even though the efficiency and power factor estimates of PMa-SynRM are larger than those of the induction machine. One solution can be to reduce the length of the stator and rotor stack or reduce the input current to have the same power as an induction motor.

After finding the average torque for the new design, the flux density in the rotor and stator cores should be checked to ensure that there are no highly saturated areas in the core. In this study, the material used for SynRM and PMa-SynRM was M-45 steel (the same material as used in induction motors) with a knee point of approximately 1.4 Tesla.

At the rated operating point, the flux density has been measured in a radial path in the PMa-SynRM and induction machines. The path has been selected in such a way as to contain the maximum flux line in the stator yoke. For a better comparison of flux density across the three engines, flux density was measured at the stator gear, stator yoke, and air gap and compared in Table V. The results show that the flux density in the PMa -SynRM stator gear is high due to the magnets used in the rotor core but not local or permanent. Also, in the air gap SynRM and PMa-SynRM have higher flux densities compared to induction motors. The flux density in PMa-SynRM is higher than that of an induction machine but because it produces a larger torque, this flux density can be reduced by reducing the stator current. Since the PMa-SynRM rotor has low core losses and no copper losses, the increased power losses in the stator are negligible.

Figure 3. Comparison of All Motor's Flux Density

Object	**Induction**	**PM-SynRM**
Stator Copper Weight (lb)	14.7	14.7
Weight of copper rotor (lb)	5.13	T/A
Rotor End Ring Material Weight (lb)	3.50	T/A
Stator Core Steel Weight (lb)	37.75	37.75
Rotor Core Steel Weight (lb)	15.42	12.56
NdFe30 Weight (lb)	T/A	1.14
Net weight		
Stator (lb)	52.45	52.45
Rotors (lb)	24.05	13.70
Total weight (lb)	76.50	66.15

Since the permanent magnets used in the rotor core produce a high flux density, it is important to find the return EMF generated by the motor. For this purpose, the rotor of the PMa-SynRM was rotated at a rated speed of 1800 RPM in a transient analysis to find the induced voltages in the stator windings. A single-phase stator waveform and a three-phase rms value of about 275 V. It also shows that the machine is suitable for high-speed operation.

By comparing the figures in Table VI, it is clear that the PMa-SynRM rotor is lighter than the induction motor rotor because it does not have copper rods and end rings making it 43% lighter. This means that it will have a faster dynamic response and better transient operation. This result is for a 4 inch stack length but since the PMa-SynRM torque is about 25% greater than the reference induction engine rated torque, we can reduce the PMa-SynRM stack length to 3 inches and the output torque will be the same as the induction engine. Material consumption in PMa-SynRM will be reduced by 25%. Table VII contains material consumption and machine weight for PMa- SynRM pile length reduction

This new stack length results in a 32% lighter motor with the same torque at rated speeds. But the main point is that the rotor is 57% lighter in this respect which means faster response times and transient dynamics. Also the stator copper is reduced by 10% which means 10% less power loss in the stator (considering the stator current is the same in both motors). The reduction of iron losses in the stator and very small power losses in the PMa-SynRM rotor due to rotating at synchronous speed results in high efficiency PMa-SynRM motors.

These results indicate that the price of PMa-SynRM is only 8.5% higher but PMa-SynRM has a higher efficiency. Also, iron and copper prices are increasing but permanent magnet manufacturing technology is developing and PM prices may be falling (This comparison is made for motors only, and the price of power electronics required to drive PMa-SynRM is not included).

4. Conclusion

This study shows that stators designed for induction motors can be used in PMa-SynRM. The PMa-SynRM output torque is higher than that of an induction motor with the above analysis showing that a 3 inch stack length for PMa-SynRM will produce the same torque as an induction motor. However, using a permanent magnet NdFe30 which is classified as an expensive type of magnet. Taking into account that the cost of steel is $1/kg, copper is $5/kg and permanent magnet NdFe30 is $96/kg, the estimated cost of the materials used in PMa-SynRM will be $90.32 and in the induction motor it will be $83.24.

The stator winding configuration is the same and the current and flux density in the stator is slightly higher. The high torque generated by this engine indicates that it is possible to use a shorter stack length to obtain the same power from a higher efficiency engine. In both simulations, tilt effect was not considered and without tilting rotor, PMa-SynRM showed less torque ripple than induction motor and one can expect less torque ripple in actual experiment. Less rotor weight will allow the motor to respond to dynamic transients more quickly than an induction motor and this will be another advantage. Comparison of material costs shows that this type of machine can compete with traditional induction motors as the cost of power electronics and permanent magnets decreases. In this study, the price of power electronics is not included. Taking into account applications where power electronic drives are required for induction engines, the use of PMa-SynRM is fully justified especially for naval applications where weight and volume are critical

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