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Finite Element Analyses of a TLA-type Synchronus Reluctance Machine

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***Abstract*— Generating energy efficient and eco-friendly electrical machines has been recently focused by researchers due to rapid decline in energy sources and increase in greenhouse gas effect. Since Inductance Machines have some drawbacks: low torque capability, low efficiency hence high energy consumption, and high carbon dioxide emission, designing Synchronous Reluctance Machines is crucial to overcome these drawbacks of Inductance Machines. Synchronous Reluctance Machines have attractive features: higher torque capability, enhanced efficiency, reduced greenhouse gas emission, longer lifetime and maintenance period comparing with Inductance Machines. In this study, flux barrier number, shape of flux barriers and rotor position effects on machine's performance is carried out by Finite Element Analyses. The analyses has concluded that the hyperbolic shaped machine with four barriers is the optimum design considering performance parameters and rotor position considerably affects torque, saliency ratio, power factor and efficiency of machines.**

Keywords*— Barrier shapes, Flux barrier number, Rotor position, SynRM.

I. Introduction

The rapidly increasing consumption of the energy has led researchers to manufacture highly efficient electrical machines both to decrease amount of consumed energy and to use electricity generating sources efficiently due to limitation of them since most of energy is expended by electrical machines which are especially utilized for conversion of energy at industry [1]. Because Induction Machines, IMs, are cheap, straightforward, and robust in construction [2], [3] as well as they can be used at comprehensive environmental conditions, these machines are highly preferred. However, IMs have some drawbacks: difficulties in speed control, overheating, high carbon dioxide emissions, poor starting torque and quite insufficient efficiency leading to increase in energy consumption [4]. Therefore, utilizing alternative machines with higher efficiencies are required to catch up with developing international efficiency standards. In this regard, designing Synchronous Reluctance Machines, SynRMs, can be considered as a reasonable alternative since they have spectacular features: low power losses hence quite high efficiency values [5], easy control of them by state-of-the-art drivers, high torque capability,[6], [7] and low temperature due to not including windings in their rotor part [8] although SynRMs are suffered from low power factor [9] and high torque ripple [10] which can be declined by different method such as proper design of flux barriers, utilizing, skewing [11], miscellaneous winding schemes [12], etc. Moreover, SynRMs reach low temperature values, they have longer maintenance intervals and increased lifetime. Additionally, the price of SynRMs is comparable with that of IMs.

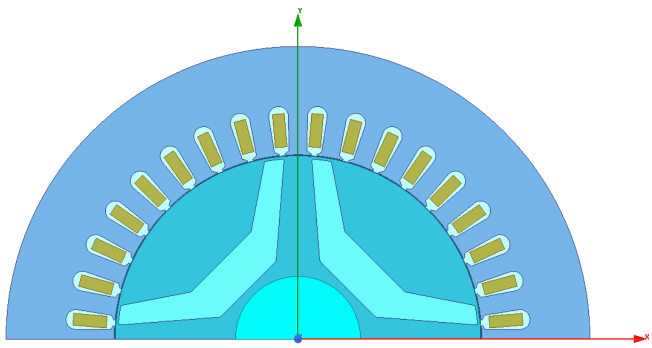
In this study, Finite Element Analyses, FEAs, of a TLA-type SynRM is carried out. Firstly, effects of changing flux barrier number on SynRMs' performance are analysed. Secondly, analyses on SynRMs with different shapes is performed. Finally, how the variation of rotor position is effective on machine performance is investigated.

II. FINITE ELEMENT ANALYZES

Effects of barrier number, barrier shape and rotor position on machine performance parameters i.e., torque, T_e, torque ripple, T_{rip}, efficiency, η, power factor, $cos\Phi$, copper and core losses, P_{copper} and P_{core}, and saliency ratio, ξ, that is the ratio of d-axis inductance to that of q-axis inductance of a Transversally Laminated Anisotropic Synchronous Reluctance Machine, TLA- SynRM, are carried out by FEAs. Each analyse accomplished lasts for 2 s and time step is arranged as 0.6 ms during analyses. Moreover, the number of stator slot and airgap length between stator and rotor are chosen as 36 and 0.5 mm, respectively. Besides, during the examination of the parameter affecting the machine performance, all other parameters such as insulation ratios, rotor slot pitch, etc., are kept constant to obtain realistic results.

A. Flux Barrier Number Effect

The effect of flux barrier number on machine performance is investigated by creating SynRMs with 1 to 5 barriers shown in Fig. 1.



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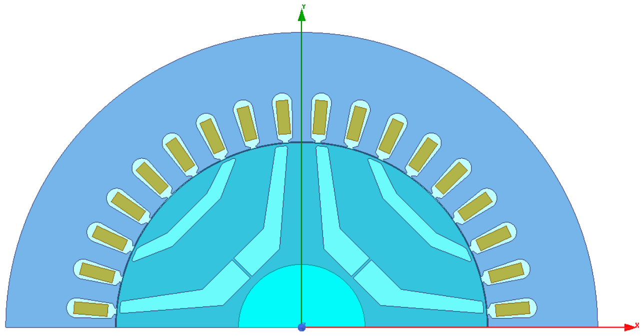

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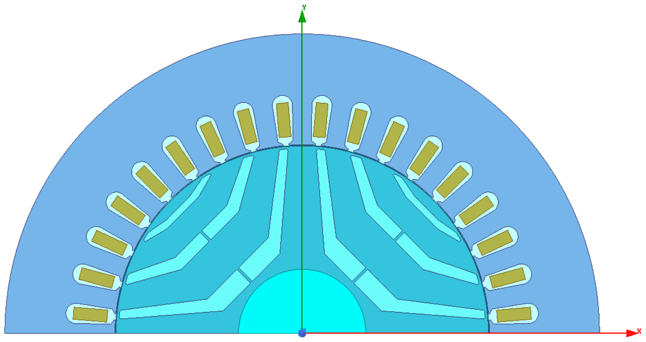

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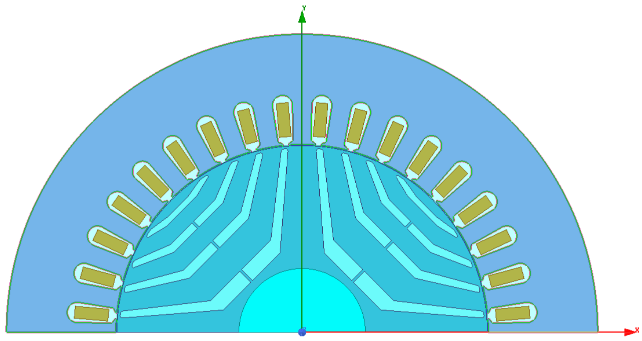

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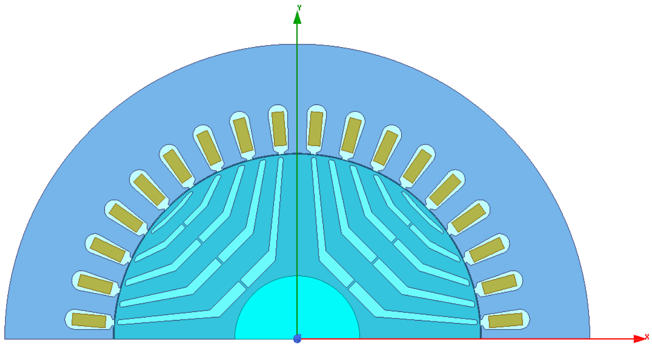

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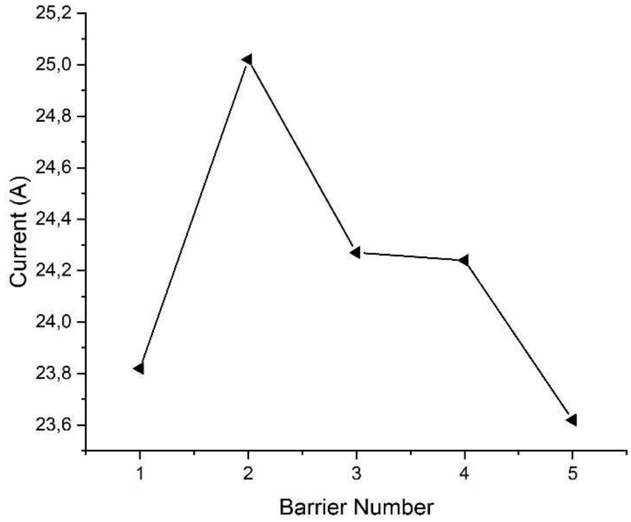
Fig. 1. SynRMs generated with a) 1-barrier, b) 2-barriers, c) 3-barriers, d) 4-barriers, and e) 5-barriers.

The figure illustrates that except for the design with 1-barrier, all designs include radial ribs along *q*-axis for barriers other than outermost barrier whereas they all have tangential ribs occurred between barrier tips through *q*-axis and the outer part of the rotor. The results of the accomplished FEAs considering the barrier number effect are demonstrated in Fig. 2.



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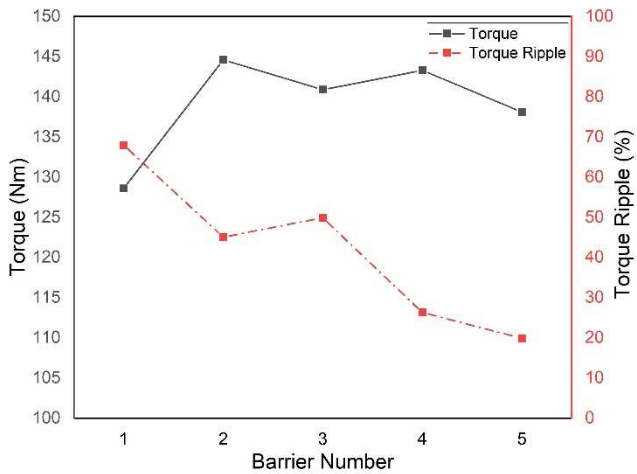

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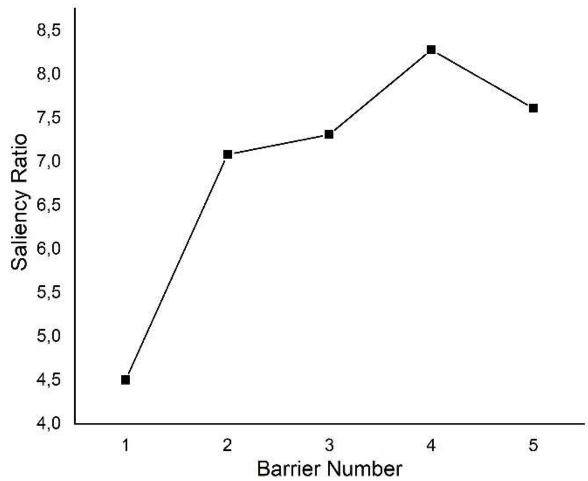

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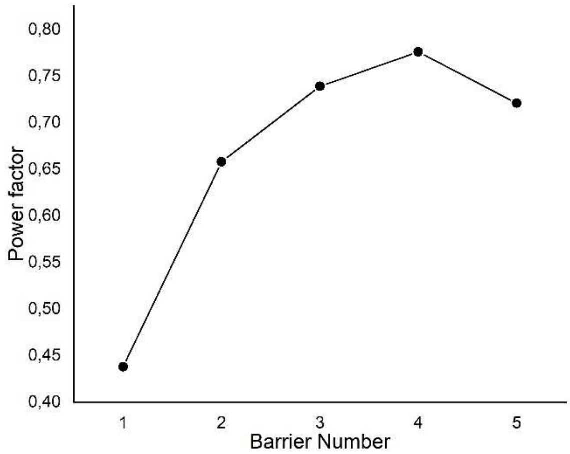

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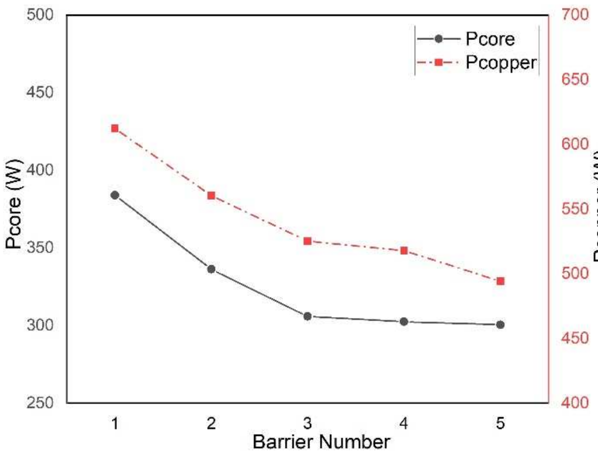

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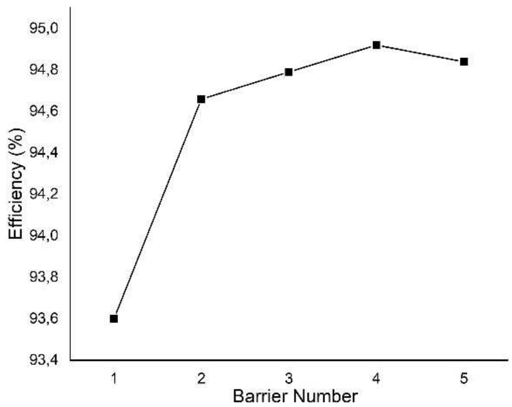

f)

Fig. 2. The results of FEAs on barrier number effects: a) Current, b) Torque, c) Saliency ratio, d) Power factor, e) Core loss and copper loss, and f) Efficiency.

During the design of SynRMs, the lower value of the current drawn by the machine is required. Because higher current values cause to increase in temperature and hence power losses of the machine. The variation of flux barrier number does not significantly affect the root mean squared, RMS, values of currents varying in between 23.6 A and 25 A seen in Fig. 2.a.

As declared previously, torque capability of SynRMs is better than that of IMs. While designing of SynRMs, maximizing T_e, and minimizing T_{rip} is aimed. The obtaining these two objectives simultaneously is challenging and therefore a trade-off must be done. The results of FEAs depict that the highest T_e is obtained for 2-barrier design approximately 145 Nm; however, T_{rip} of that design is around 45 % shown in Fig. 2.b. On the other hand, the 5-barrier design has the lowest T_{rip} among them, but its T_e is lower than that for 4- barrier design.

Obtaining higher saliency ratio is desired during the design of SynRMs since it leads to improvement in $cos\Phi$ and facilitates the detection of the angular position of the rotor by sensorless control providing cost benefits. As number of flux barriers increase, ξ also augments up to 4-barrier and the highest ratio is obtained as 8.28 for 4-barrier design illustrated in Fig. 2.c.

The power factor of SynRMs is lower than that for IMs because of the nature of SynRMs, its inherent *q*- axis reactance and cross-coupling between *d*- and *q*- axes fluxes. Therefore, $cos\Phi$ must be obtained as high as possible in the design of SynRMs. Because the poor value of $cos\Phi$ causes to higher kVA rating and oversizing of the inverter for SynRMs leading to cost disadvantages. The Fig. 2.d demonstrates that the highest $cos\Phi$ among given five designs belongs to SynRM with 4 barriers, 0.776.

Power losses are also effective on the performance of SynRMs and increasing them brings about decline in their efficiency. The most prominent power losses, P_{copper} and P_{core}, are considered during FEAs of this study. The Fig. 2.e clearly states that P_{copper} and P_{core} both decrease as number of flux barrier increases. Though 5-barrier design has the lowest power losses, it cannot be considered as the best design since it is more plausible to consider these losses proportionally with input and output powers.

Efficiency, η, is one the most important performance parameter that needs to be considered during the design of electrical machines since it is directly related to performance and lifetime of them. Besides, high efficiency causes to lower energy consumption. The design with 4 barriers has the highest η value, 94.92 %, which is 1.32 % higher than 1-barrier design.

To sum up, the highest T_e is obtained for 2-barrier structure at the same position. However, this design cannot be considered as optimum one since T_{rip} of this design is much more than that of four and five barrier designs. Additionally, ξ, $cos\Phi$ and η of that design is worse than the last three designs. Among these three designs, although the one with 5 barriers has the lowest T_{rip}, and lower power losses than the SynRM with four barriers, the latter can be considered as optimum design since it has the highest ξ, $cos\Phi$ and η.

B. Barrier Shape Effect

Having decided that four barrier is the optimal number of flux barrier for the design, analyses are carried out to see the effect of the shape of flux barriers. Three types of rotor barriers that are rectangular, circular, and hyperbolic shaped barriers shown in Fig. 3 are considered in this section. From the figure, SynRMs with different shaped have 3 innermost radial ribs and 8 radial ribs in their quarter part.

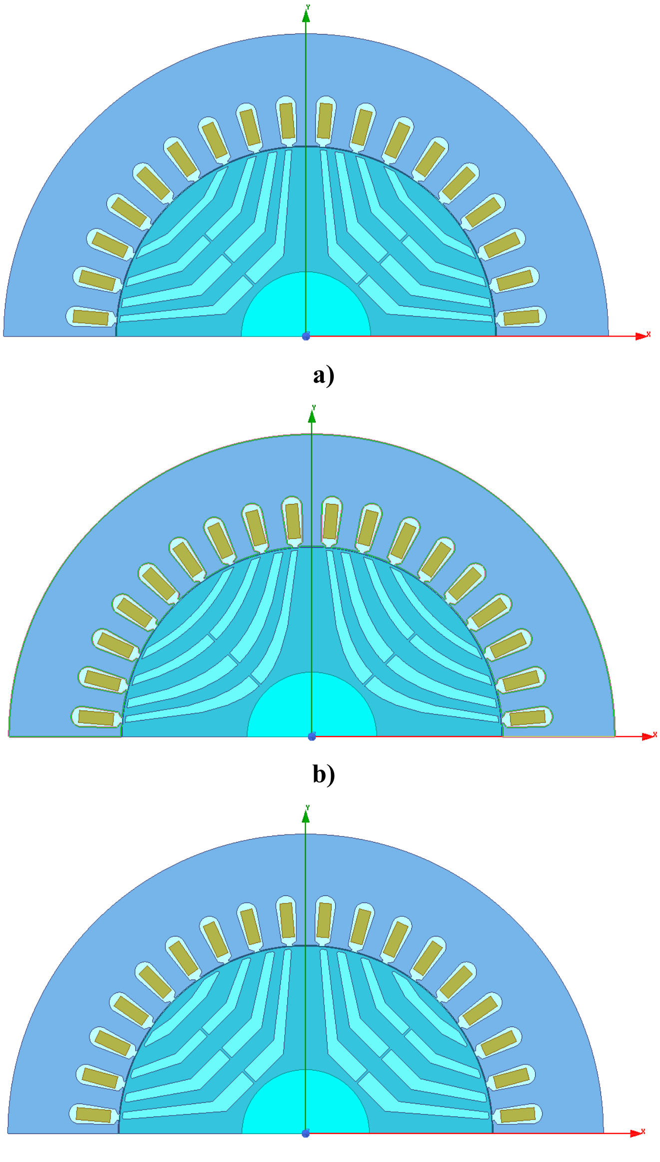

Fig. 3. Barrier shapes: a) Rectangular, b) Circular, and c) Hyperbolic.

The comparison of the effect of shape of flux barriers on machine performance parameters are detailed in Table I.

The table depicts that the rotor position is mostly effective on T_e, increasing 1 deg. cause to 15.42 % decline in that parameter. However, T_{rip} and *cosΦ* of the analysed SynRM slightly differs given in the table. The saliency ratio at 52 deg. is approximately 10 % higher than that for others. Moreover, the efficiency of the machine gradually decreases with the enhancement of rotor position from 52 deg. to 53 deg. It can be indicated considering the applied analyses that the ideal rotor position is 52 deg. since it has the highest T_e, *ξ, cosΦ,* and *η* with comparable T_{rip}

III. CONCLUSION

In this study, FEAs including effects of flux barrier number, barrier shape and rotor position on machine performance parameters i.e., torque, torque ripple, saliency ratio, power factor and efficiency are carried out. The results of analyses declare that the optimum flux barrier number among analysed ones is four since it has the highest values for

TABLE I. EFFECTS OF BARRIER SHAPE

Barrier Shape	Parameters Affected by Barrier Shape				
	Torque (Nm)	*Torque Ripple (%)*	*Saliency Ratio*	*Power Factor*	*Efficiency (%)*
Rectangular	140.2	32.71	8.17	0.701	94.97
Circular	140.6	25.25	8.09	0.709	94.98
Hyperbolic	142.8	20.84	8.68	0.777	94.92

Table I depicts that though T_e of three designs is around 140 Nm, that for hyperbolic-shaped SynRM is slightly higher. Besides, *ξ* of this design is enhanced by 6.24% and 7.29 % comparing with rectangular and circular types, respectively. Additionally, *cosΦ* of the hyperbolic design is 10.84 % and 9.59 % better than that of the other SynRMs. Moreover, T_{rip} of this design is 11.87 % and 4.41 % less than that of rectangular and the circular designs, respectively. Furthermore, *η* of hyperbolic-shaped SynRM is quite comparable with the other designs, varying in the 0.05 % range. Considering all performance parameters given in the table, it can be stated that SynRM with hyperbolic shaped barriers is the optimum one amongst them.

C. Rotor Position Effect

Rotor position is also effective on performance parameters of SynRMs. After concluded that, SynRM with hyperbolic shaped and 4 barriers is the optimum among analysed SynRMs, the effect of rotor position is Finite Elementally analysed in the range between 52 deg. and 53 deg., and results of this analysis is given in Table II.

TABLE II. EFFECTS OF ROTOR POSITION

Rotor Position (deg.)	Parameters Affected by Rotor Position				
	Torque (Nm)	*Torque Ripple (%)*	*Saliency Ratio*	*Power Factor*	*Efficiency (%)*
52	143.3	26.35	8.28	0.776	94.92
52.2	136.4	24.06	7.61	0.774	94.68
52.4	131.9	25.25	7.59	0.77	94.37
52.6	127.4	25.79	7.57	0.767	94.1
52.8	123	26.1	7.54	0.762	93.83
53	121.2	29.34	7.49	0.76	93.71

ξ, cosΦ, and *η* as 94.92 %, 0.776, and 8.28, respectively. Besides, T_{rip} of this design is quite compatible with its lowest value, 6.47 % higher than its lowest value belongs to 5-barrier design. Among SynRMs with different shapes, hyperbolic-shaped SynRM is chosen as the optimal design since *ξ,* and *cosΦ* of it is much better than rectangular and circular SynRMs. Additionally, *η* of hyperbolic SynRM only differs from the others by 0.05 %. Moreover, this design has the lowest T_{rip},20.84 %, among three analysed SynRMs. As a final analyse the effect of changing rotor position on SynRMs' performance is accomplished and results indicate that T_e, *ξ, cosΦ,* and *η* gradually decrease with the enhancement of rotor position by 1 deg. whereas changing the position is not highly effective on T_{rip}.

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