Almoraya AA, Baker NJ, Smith KJ, Raihan MAH.

[An investigation of a Linear Flux Switching Machine with Tapered Ferromagnetic Poles.](#)

*In: The 20th International conference on Electrical Machines and Systems.
2017, Sydney, Australia: IEEE.*

Copyright:

© 2017 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works.

URL link to Conference Proceedings:

<https://doi.org/10.1109/ICEMS.2017.8056083>

Date deposited:

19/09/2017

An investigation of a Linear Flux Switching Machine with Tapered Ferromagnetic Poles

A. A. Almoraya¹, N. J. Baker¹, K. J. Smith¹, M. A. H. Raihan¹

Electrical Power Research Group, School of Electrical and Electronic Engineering, Newcastle University
Newcastle upon Tyne, NE17RU, UK

Email: a.a.almoraya@ncl.ac.uk

Abstract-- This paper investigates methods of magnet mass reduction in linear flux switching permanent magnet (LFSPM) machines by introducing tapered consequent poles. Based on the finite element analysis (FEA) three different models are designed, investigated and compared. The obtained results indicate that by adopting the proposed tapered ferromagnetic poles a considerable saving of material cost and weight is obtained without sacrificing the machine performance.

Index Terms-- flux switching, consequent pole, ferromagnetic poles, linear machine.

I. INTRODUCTION

This paper considers linear machines designed for low speed direct drive applications. To exploit magnetic gearing ~~structure~~, small pole permanent magnet machines have been proposed for direct drive applications such as wave energy converters[1]. Typically, topologies have adjacent ~~fully pitched magnets magnets~~ of alternating ~~adjacent~~ polarity and significant inter-pole leakage, ~~effectively fully pitched magnets suffering from leakage~~. This effect is compounded by the fact that if the magnets are located on the moving translator, a portion of the material is always inactive. The result is machines that require a large amount of permanent magnet material relative to their force output. One way of saving material is to replace alternate poles with iron pieces – consequent poles. Vernier permanent magnet machines with consequent pole of this type have been proposed[2],[3]. However, chamfered PMs have been utilized in those works, which contribute to complexity of manufacturing and raise the cost of PMs.

This paper presents a developed design with incorporation of tapered consequent poles using rectangular PMs. Resultant designs are shown to maintain reported performance and give higher no load back EMF waveforms compared to that produced by the chamfered magnet but with a relatively simple structure and lower per unit PM cost.

II. MODELS USED IN ANALYSIS ANALYSIS MODELS

Fig.1 (a) shows the baseline linear flux switching permanent magnet machine with adjacent alternating polarity (model I). Fig. 1(b) illustrates the topology with chamfered consequent poles and PMs (model II). Fig. 1(c) has tapered iron poles and rectangular PMs (model III). ~~It should be indicated that models II and III in Fig. 1(b) and (c) respectively adopt only one polarity of PM, and all PMs have the same magnetization direction. The~~

~~key difference between the proposed LFSPM machine and the baseline LFSPM machine is that one polarity of PMs is absent and substituted with tapered ferromagnetic poles. In simple words, the structure of the proposed machine possess the same magnet orientation whichever N or S, while alternating poles arrangement is utilized in the baseline LFSPM design.~~

~~For simulation comparison, Model III configuration provides a better mechanical flexibility in making regular rectangular shaped PM. All three models possess are designed to be of the same dimensions, type of materials, rated speed, rated phase armature current, winding number of turns and translator pole pitch. The key specifications of the three models are listed in table I.~~

III. DESCRIPTION OF THE MACHINE MACHINE CONFIGURATION CONFIGURATION PROPOSED TOPOLOGY

The configuration of the proposed ~~LFSPM linear flux switching permanent magnet~~ machine is shown in Fig.1 (c). The stator consists of three U-shaped iron cores with six stator teeth in which each tooth is wrapped with a concentrated winding. ~~While each stator tooth is split into four small teeth serving as multi-toothed flux modulating pole. The translator comprises of tapered salient teeth with tapered shape and rectangular PMs inserted between them. The key difference between the new model and the baseline LFSPM machine is that one polarity of PMs is absent and substituted with tapered ferromagnetic poles. In simple words, the structure of the proposed machine possess the same magnet orientation whichever N or S, while alternating poles arrangement is used in the baseline LFSPM design as shown in Fig.1 (a).~~

~~Since~~ The proposed LFSPM machine has almost the same configuration of the baseline LFSPM machine. The relative displacement between the teeth of the U-shaped module is 360 electrical degrees, given by

$$W_{ur} = (T+S) \tau_t / 2 + n \tau_t \quad (1)$$

where W_{ur} is the distance between the teeth belong to the U-shaped module, τ_t is the translator pole pitch and T is the number of the split teeth on one side of the U-shaped module and S is the number of ~~the stator split slots located between the split teeth~~. Moreover, the neighboring U-shaped modules are shifted by 120 electrical degrees (W_{dm}) forming a three phase machine, and that can be achieved by making this space satisfy,

$$W_{dm} = (n \pm 1/3) \tau_t \quad (2)$$

Where n is a positive integer.

Commented [NB1]: This is a repeat of section II ? you should therefore combine sections II and III

Formatted: Normal, Justified, Indent: First line: 0.4 cm, No widow/orphan control, Don't adjust space between Latin and Asian text, Don't adjust space between Asian text and numbers

Formatted: Font: 9 pt

Formatted: Superscript

TABLE I PARAMETERS OF THE THREE MODELS			
Parameters	Model I	Model II	Model III
Number of phases	3		
Rated speed, m/s	1		
Air gap length, mm	1		
PM thickness, mm	4		
Stack length, mm	100		
Secondary pole pitch, mm	24		
Number of turns	110		
Number of PMs on the translator	60	30	30
PM width, mm	12	12	11.5
Consequent pole shape	-	chamfered	tapered
Current density	5 A/mm^2		
PM remanence	1.24		
PM material	NdFeB		

PM material	NdFeB
Stator and translator core	Lamination steel

Fig. 2. No-load flux distribution (a) $\theta=0^\circ$ (b), $\theta=120^\circ$

Fig. 3. No-load field distribution (a) $x=0$ aligned position, (b) $x=1/4\tau$, unaligned position

Fig. 1. Configuration of the three models (a) alternating polarity (model I), (b) chamfered consequent pole and PMs (model II), (c) tapered consequent poles and rectangular PMs (Model III)

phase machine, and that can be achieved by making this space satisfy,

$$W_{dms} = (n \pm 1/3)\tau_t \quad (2)$$

Formatted: Indent: First line: 0 cm

IV. PRINCIPLE PRINCIPLE OF OPERATION

The proposed LFSPM machine operates upon the same principle as the baseline LFSPM machine. The proposed LFSPM machine also employs the magnetic gearing effect observed in Fig.2, where the flux distribution in

the translator varies 120 electrical degrees while the translator moves only 8mm, which is equivalent to 1/3 of the translator pole pitch. When the stator split teeth on both sides of the U-shaped core are aligned with PMs and ferromagnetic poles, the coil flux linkage reaches its maximum value as shown in Fig.3 (a). Then it decreases with the motion of the translator reaching zero at the unaligned position, as illustrated in Fig.3 (b). Again, when the translator reaches the next alignment position the flux flows in the opposite direction. Thus, the flux linkage polarity is rapidly changed over a small translator movement, which may contribute to the improve the high thrust force density. Fig.4 also demonstrates the operation principle of the proposed LFSPM machine including the flux linkage direction (either clockwise or anticlockwise), the assuming idealized flux linkage and back EMF waveforms at different four translator positions.

Based on the magnetic gear effect, the proposed LFSPM machine employs the stator split teeth to modify the static magnetic field created by PMs to the high speed magnetic field traveling in the airgap. Hence, the value and frequency of the induced back EMF, which are proportional to the rate of change of the flux linkage, can achieve relatively large values even under a very low operation speed.

V. DESIGN OPTIMIZATION

Tapered ferromagnetic poles are utilized in the proposed LFSPM machine which have an obvious influence on the fringing flux and undesirable harmonics reduction such as 5th harmonic. Consequently, the performance of the proposed LFSPM machine including thrust force, cogging force and no-load back EMF and its waveform shape can be affected. Thus, the optimization of ferromagnetic pole ratio shown in Fig.5, which is defined as the ratio of the translator tooth tip to the translator pole pitch is an important stage of the machine design.

Fig.6 illustrates the impact of varying ferromagnetic pole ratio on the thrust force, no-load back EMF and cogging force. It can be seen that the maximum no-load

back EMF and thrust force can be achieved when the ferromagnetic pole ratio equals 0.31. However, 0.33 was selected where the minimum cogging force can be obtained. In addition, by choosing the ratio of 0.33 the translator mass can be saved.

Fig. 5. Module of translator

ferromagnetic pole tip equals 8mm or 11mm. However, 8mm was selected where the minimum cogging force can be obtained. In addition, by choosing 8mm the translator mass can be saved.

Three models of LFSPM machine are designed, analyzed and compared using finite element analysis 2D-FEA.

A. Flux linkage and back EMF

In [4] and [5] the effect of the consequent poles on the flux leakage suppression and flux linkage improvement was deeply analyzed and proved by analyzing the reluctance path. Therefore, since the proposed design implements the tapered consequent poles the fringing flux can be further decreased, and hence the effective flux is increased. Fig.7 compares the no-load flux linkage waveforms of all the three models. It can be observed that model III generates the highest peak flux linkage followed by model II and model I respectively. Fig.8 compares the induced no-load back EMF of all three

Fig. 4. Operation principle: (a) $\theta=0^\circ$, (b) $\theta=90^\circ$, (c) $\theta=180^\circ$, (d) $\theta=270^\circ$ and (e) flux linkage and back EMF

Formatted: Normal, Keep with next

Fig. 9. Thrust force waveforms of the three models

models under the same conditions of speed, electric loading and number of turns. It can be seen that among the three designs the proposed LFSPM machine produces the highest no-load back EMF with the value of 123 V followed by 110.5 V generated by model II, while 86.5 V which is the lowest value of the no-load back EMF is produced by model I. Namely the induced voltage is 29.6% and 10.2% higher than model I and model II respectively.

Fig. 7. Flux linkage waveforms for three models

Fig. 7. Flux linkage waveforms for three models

which is the lowest value of the no-load back EMF is produced by model I.

Moreover, it can be seen that the no-load back EMF waveforms of the proposed LFSPM machine are pure sinusoidal. The induced back EMF can be defined as:

$$e = \frac{d\psi_m}{dt} = \frac{d\psi_m}{dx} \cdot \frac{dx}{dt} = \frac{d\psi_m}{dt} \cdot v \quad (3)$$

B. Force capability

Fig.9 shows the thrust force waveforms for all three machines under the rated condition. As shown in the former section, the back EMF waveforms of the model III are very approximately sinusoidal. Thus, the injected current is assumed to be pure sinusoidal which smoothes the obtained thrust force waveforms. In this publication, the force ripple is defined as the ratio of the peak to peak

force to the average force which can be given as:

$$\text{Force ripple} = \frac{F_{\max} - F_{\min}}{F_{\text{avg}}} \times 100 \quad (4)$$

where $F_{\max}$ is the maximum force, $F_{\min}$ is the minimum force and F_{avg} is the average value of the thrust force respectively.

Fig. 8. No-load back EMF waveforms for three models

From the aforementioned figure it can be found that the averaged steady state force of the proposed LFSPM machine is 3.14 kN, while model I is 2.8kN and model II is 2.94kN. In other words, the force handling capability of the proposed LFSPM machine is therefore 12.5% and 8.8% higher than that of model I and model II respectively. It also exhibits the minimum force ripple of 6%, while a much largern-excessive force ripple of 17.3 % and 11.7 % is produced by model I and model II respectively when all machines are operated at the same speed and electric loading. It should be noted that the force ripple of these machines are-is mostly due to the cogging force, which happens at the different positions of the stator split teeth with different airgap lengths. Additional observation discloses that cogging force mainly causes force ripple [6].

Fig.10 shows the variation of the thrust force with respect to the applied phase current for the three models. It can be seen that model I shows a perfect thrust linearity. However, in consequent pole models (model II and model III) non-linear characteristics occurs as the

applied current increases beyond the rated current and consequent poles are saturated as a result. It should be indicated that the proposed LFSPM machine possess a

Commented [NB2]: Quite odd to talk about electric loading when you are analyzing open circuit data!

better capability of thrust variation than that of model II, while the baseline LFSPM has the best overloading capability. In the alternate magnet machine, overload capability will be limited by demagnetisation of the magnets, whereas in the consequent pole machine it is limited by saturation in the poles.

Fig.10. Variation of the thrust force with respect to the applied current

Fig. 11. Cogging force waveforms for three models

C. Cogging force

Cogging force is an unwanted mechanical pulsation in linear electrical machines which caused by the interaction between magnets and stator slots. Therefore, cogging force reduction is a significant goal in PM machines design. Fig.11 shows the cogging force waveforms for three models. It can be seen that the proposed LFSPM machine produces lower peak to peak cogging force with the value of 160N, while the baseline and chamfered PM exhibits 449N and 280N respectively. It should be also indicated that the cogging force and force ripple can be further minimized in linear machine by implementing skewing approach [3],[7],[8]. In this work, the effect of skewing on the cogging force was investigated. From Fig.11 it can be observed that the resultant cogging force produced by each phase is simply a summation of each component, i.e. U and $-U$, where the resultant cogging force waveform repeats every $1/3 \tau_p$. Therefore, the cogging force can be reduced by implementing further skewing of $1/3 \tau_p$ (48mm) as shown in Fig.13. However, Therefore, The cogging force of the proposed LFSPM machine offeris s-5% of the rated thrust, which is considered an acceptable valueas a normal level for of the cogging force and force ripple without skewing compared with model I and model IIelectrical machines. That is due to the adoption of the tapered ferromagnetic poles which have a significant impact on the cogging force as debated in section VI. Therefore, the new LFSPM machine possess the merit of simplicity of manufacturing.

$$F_d = \frac{F}{V} \quad (5)$$

where F_d is the force density, F is the average thrust force and V is the active machine volume. The results show that

the proposed LFSPM machine can achieve the highest thrust force density with the value of 541 kN/m³, which is about 10.7% and 6% higher than that of model I and model II respectively. Table III summarizes the comparison analysis between the three designs.

TABLE II. PERFORMANCE COMPARISON

Item	Model I	Model II	Model III
Magnet mass [kg]	1.94	0.93	0.91
Peak back EMF [V]	86.5	110.5	123
Thrust force [kN]	2.8	2.94	3.14
Force ripple [%]	17.3	11.7	6
Cogging force [N]	449	248	160
Force/ Magnet mass[kN/kg]	1.44	3.2	3.45
Thrust force density [kN/m ³]	483	507	541

VIII.

B.D. Power Factor

LFSPM machines are similar to other direct drive machines where the poor power factor is considered as a critical problem [7]. Although a double amount of PM material is utilized in the baseline LFSPM machine (model I) compared with model II and III, its PF is relatively low, 0.3. This is mainly caused by the excessive leakage between the adjacent magnets. In model II and model III the consequent poles are employed, which also affect the PF. However, due to the utilization of the tapered ferromagnetic poles in the proposed LFSPM machine the PF can be improved up to 0.27 compared with only 0.23 achieved by model II. Using trapezoidal consequent pole would vary the field distribution very slightly in the airgap but would allow up to 12% much flux to be directed to the airgap before saturation happens leading to an increase in the airgap flux density. It should be mentioned that the proposed LFSPM can achieve the PF of 0.27, while the baseline LFSPM machine reaches the PF of 0.3 but with 52% more magnet material. Therefore, the proposed LFSPM machine is the most cost effective.

IX.VII. CONCLUSIONS

In this paper, three different topologies of LFSPM machines have been designed, analyzed and compared. The analysis results show that the proposed LFSPM machine which incorporates a combination of trapezoidal consequent poles and rectangular PMs is capable of offering the highest no-load back EMF and thrust force handling capability compared with model I and model II, while it exhibits the lowest cogging force and force ripple. Therefore, model III, which is the proposed machine possess the best performance and the most cost-effective since the regular PMs are adopted. In addition, the translator of the proposed LFSPM machine is $\approx$ 54.7% and 2.7% lighter than that of model I and model II respectively. Hence verifying that it is very promising for low speed and high thrust direct drive applications.

Formatted: Font: 8 pt

Formatted: No bullets or numbering

Formatted Table

Formatted: Indent: First line: 0.51 cm

Formatted: Don't adjust space between Latin and Asian text, Don't adjust space between Asian text and numbers

ACKNOWLEDGMENT

This work was financially supported by Technical and Vocational Training Corporation, Saudi Arabia.

REFERENCES

- [1] M. A. Mueller and N. J. Baker, "Modelling the performance of the vernier hybrid machine," *IEE Proceedings-Electric Power Applications*, vol. 150, pp. 647-654, 2003.
- [2] S.-U. Chung, J.-W. Kim, B.-C. Woo, D.-K. Hong, J.-Y. Lee, and D.-H. Koo, "A novel design of modular three-phase permanent magnet vernier machine with consequent pole rotor," *IEEE Transactions on Magnetics*, vol. 47, pp. 4215-4218, 2011.
- [3] S.-U. Chung, Y.-D. Chun, B.-C. Woo, D.-K. Hong, and J.-Y. Lee, "Design considerations and validation of permanent magnet vernier machine with consequent pole rotor for low speed servo applications," *Journal of Electrical Engineering and Technology*, vol. 8, pp. 1146-1151, 2013.
- [4] Y. Gao, R. Qu, D. Li, J. Li, and G. Zhou, "Consequent-pole flux-reversal permanent-magnet machine for electric vehicle propulsion," *IEEE Transactions on Applied Superconductivity*, vol. 26, pp. 1-5, 2016.
- [5] A. A. Almoraya, N. J. Baker, K. J. Smith and M. A. H. Riahian, "Development of a Double Sided Linear Vernier Hybrid Permanent Magnet Machine for Wave Energy Converters," *International Electric Machines and Drives Conference, Miami, FL, USA, 2017*.
- [6] J. Ji, S. Yan, W. Zhao, G. Liu, and X. Zhu, "Minimization of cogging force in a novel linear permanent-magnet motor for artificial hearts," *IEEE Transactions on Magnetics*, vol. 49, pp. 3901-3904, 2013.
- [7] T. W. Ching, K. T. Chau, and W. Li, "Power factor improvement of a linear vernier permanent-magnet machine using auxiliary dc field excitation," *IEEE Transactions on Magnetics*, vol. 52, pp. 1-4, 2016.
- [4] Y. Gao, R. Qu, D. Li, J. Li, and G. Zhou, "Consequent-pole flux-reversal permanent-magnet machine for electric vehicle propulsion," *IEEE Transactions on Applied Superconductivity*, vol. 26, pp. 1-5, 2016.
- [2] S.-U. Chung, J.-W. Kim, B.-C. Woo, D.-K. Hong, J.-Y. Lee, and D.-H. Koo, "A novel design of modular three-phase permanent magnet vernier machine with consequent pole rotor," *IEEE Transactions on Magnetics*, vol. 47, pp. 4215-4218, 2011.