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A Study on Design of Tubular Linear Reluctance Generator Taking Account of Leakage Elements

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The focus of the work demonstrates the validation of the new shape translator taking account of leakage elements in linear oscillating generator for a series hybrid electric vehicle. By comparison and analysis using the various shapes of translator teeth, it is studied to minimization of the force ripple and increasing useful magnetic flux by equivalent magnetic circuit (EMC) and finite element method (FEM). It will be analyzed considering the leakage reluctances for a more practical and effective analysis, and design process of tubular linear reluctance generator. At last, the trapezoidal shape of translator is selected as optimal model among the proposed translator teeth in tubular linear reluctance generator. The results of this study will give elaborate information about the design rules and the performance data of linear gensets.

Keywords : equivalent magnetic circuit, finite element method, force ripple, leakage reluctance, magnetic energy

1. Introduction

Reluctance machines using the linear motion have number of advantages over machines with magnet, in terms of rugged construction and capability to operate in harsh environments and at elevated temperatures. Especially, hybrid electric vehicle taking advantages of a lightweight linear oscillating generator may be a good solution to the problems of energy crisis and environmental pollution today. Also using these gensets as an auxiliary power unit was often considered [1]. Tubular linear reluctance generator (TLRG) has much simpler bearing construction and self-supporting coils. Furthermore, this machine is easy to assemble and has a better ratio of active to total volume. It can achieve very high speeds because of the lack of conductors or magnets on the translator. However, it has essentially force ripple due to its salient structures and since the force for a given excitation current diminishes rapidly as the air-gap length increases, it is generally suitable for normal application [2, 3]. Moreover, the rapid increase in force that occurs as the translator approaches the stator means the machine is difficult to control. For applications that require longer strokes and improved controllability, it is necessary to depend on machine topologies that exploit the tangential component of force, despite the fact that they have considerably lower specific force capability [4, 5]. The machine consists of a ferromagnetic translator and stator, which carries the excitation coil. When the coil is excited, the stator and translator teeth will tend to align in order to minimize the magnetic circuit reluctance, thereby producing an axial force. The force is produced on the reluctance principle, i.e. by the tendency of the excited stator poles to align with the translator salience teeth. The tangential force that tends to align poles of the moving part with the excited poles of the static part causes the motion. Hence, the machine makes use of the inherent cogging force that contributes to the overall force.

In this paper, the comparison performance of two models with the rectangular and trapezoidal shape of translator teeth is investigated respectively through an attempt at an analytical and verification at a numerical calculation. FEM is used for numerical calculation of the inductance and force characteristic. Using characteristics flux linkage (inductance) versus position at a given current, the force characteristics is computed through the magnetic energies approach by numerical integration and differentiation.

2. Tubular Linear Reluctance Machine

The reluctance linear machine in cylindrical form with

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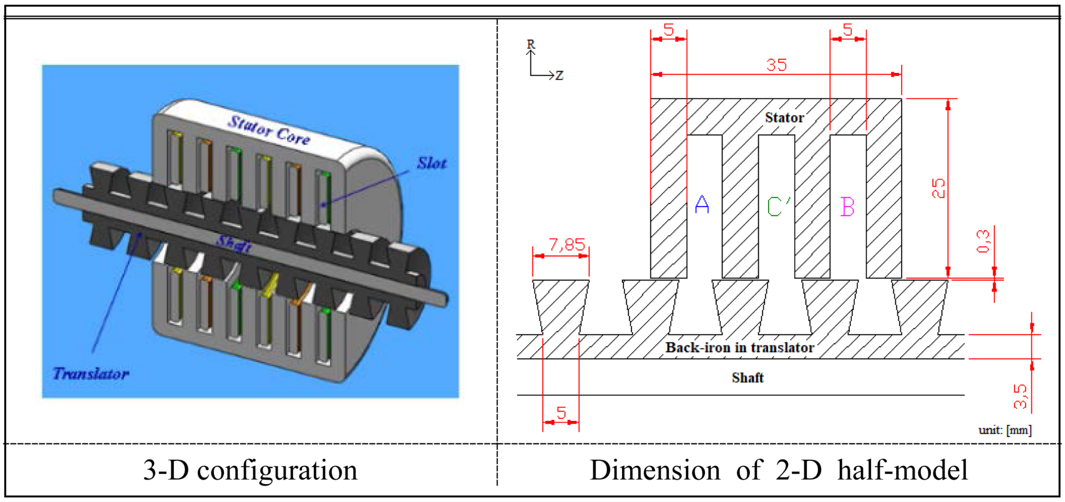

Fig. 1. (Color online) Three-phase Tubular Linear Reluctance Generator.

three-phase has a distinctively simple and compact construction consisting of a magnetic shaft (usually the 'translator'), and an outer cylindrical assembly (usually the 'stator') containing a number of identical phase sets. Each set consists of a magnetic core and an enclosed solenoidal winding. Fig. 1 shows the machine structure and dimension of a three-phase TLRG. The TLRG has an active stator, a passive translator and a longitudinal flux configuration.

The reluctance machine is a type of synchronous machine that induces non-permanent magnetic poles on the ferromagnetic translator. Force is generated through the phenomenon of magnetic reluctance. It has wound field coils like those of a DC motor for its stator windings and has no coils or magnets on its translator. It can be seen that both the stator and translator have salient poles; hence, the machine is a doubly salient machine.

3. Proposal of Study Models

Various methods to minimizing force ripple and increase magnetic flux has appeared in the literature. The most popular approach for this purpose has been selected to optimal teeth length and shapes of stator and translator each other. Some of the previous studies have outlined methods of parameter analysis through arrangement of stator and translator teeth [6].

The force ripple minimization and increasing magnetic flux method proposed in this study is based on shape of translator teeth in geometric aspect. It is investigated in

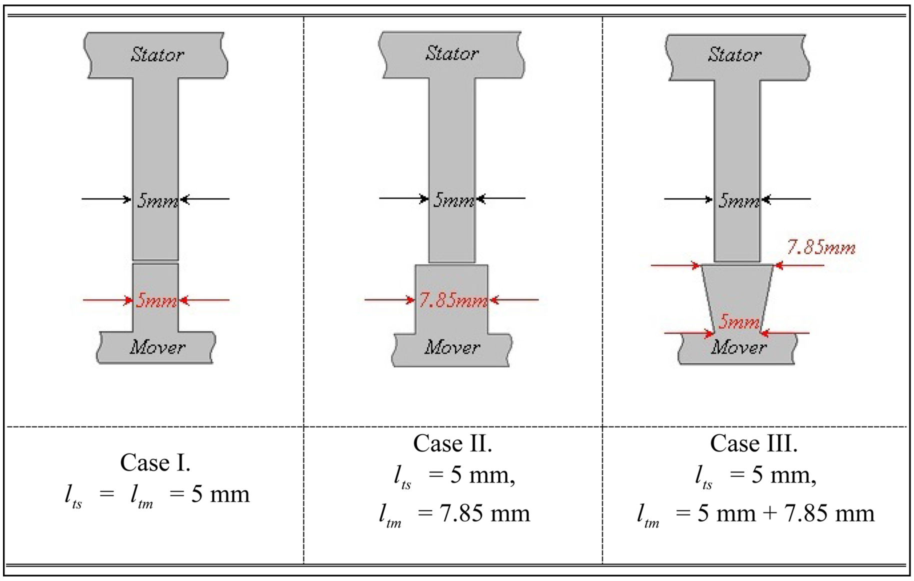

Fig. 2. (Color online) Shape of Translator Teeth.

three cases of translator shape as shown Fig. 2; in all cases, axial length of stator teeth is fixed as 5 mm and that of translator teeth is various with 5 mm, 7.85 mm, and combination of 5 mm and 7.85 mm. The significant inductance profile changes are determined in terms of the stator and translator teeth width and number of translator teeth. The reason why the translator teeth is selected in 7.85 mm that is to gain smooth force curve with increased linkage flux as the translator teeth is longer than stator teeth. Thereby, it is considered a relationship of inductance characteristic following translator shape; it is 5 mm, 7.85 mm and mixed type of 5 mm and 7.85 mm. Based on the study, the new proposed trapezoidal shape of translator teeth is focused on concentrating magnetic flux and axial length of translator connected into shaft is introduced to secure magnetic flux at least along with stator teeth.

It proposes an analytical approach that is generalized for the design of various translator teeth of TLRG based on a physical magnetic circuit model. Conventional approaches have been used to predict the behavior of electric machines but have limitations in accurate flux saturation analysis and hence machine dimensioning at the initial design stage [7, 8]. In particular, magnetic saturation is generally ignored or compensated by correction factors in simplified models since it is difficult to determine the flux in each stator tooth for machines with any slot-pole combinations [9].

As the first step in the study, the properties of this generator are investigated by machine dimensioning with help of the equivalent circuit method. Next, the comparison and evaluation based on the electrical characteristics and by various geometrical parameters. After satisfied the object, it will be investigated in terms of the energy and force. Then the model will be designed in detail considering saturation by FEM and in parallel, it will be accomplished to validate the modelling of initial design step.

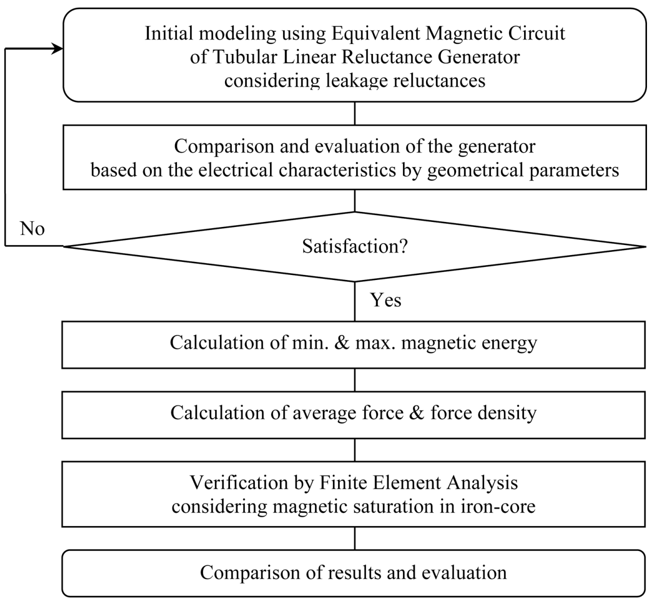

Fig. 3. Analysis Procedure.

Above all, it is assumed that turn-on angle (θon) and turn-off angle (θoff) is excited ideally for constant force generation according to the number and width of stator and translator poles. There are three different case of translator shape:

3.1. Case I (Rectangular Shape)

If the current continues beyond the positive slope region, then a negative force is produced with equal stator and translator teeth width, because there are no zero slope inductance regions. Due to the negative force generation, the average force per phase is reduced. To eliminate the negative force generation, phase current must be zero before the inductance decreases. In addition, this case generates higher force ripple by structure reason of equivalence of the stator and translator pole width.

3.2. Case II (Rectangular Shape)

When the translator teeth width is greater than the stator teeth width, there is no tangible benefit in terms of force production if ideal current switching is assumed. Furthermore, this adds to the lamination iron volume and weight. However, with the translator teeth width is greater than the stator teeth width, this will increase the average force produced in the machine much more than that with equal stator and translator teeth width, case I. Even though the force produced in case II is greater than that in case I, the current is different with the current in case II being higher than that of case I. It can be seen that it is very advantageous to have the translator teeth width greater than the stator teeth width.

Therefore, many of the practical designs have translator pole arc slightly greater or almost equal to stator pole width in the machines.

3.3. Case III (Trapezoid Shape)

Case III is similar to the case II in all aspects except weight. It has an advantage over case II in the way that the flux leakage is relatively small and the iron volume of translator is lighter. For this reason, it enables high-speed operation of the translator. In addition, this case is expected to decrease force ripple and increase average force neglecting the saturation due to the effective structure of the translator shape. The characteristics such as inductance and force will be investigated through comparing the case II.

4. Analytical Calculation

The analytical expression consists of the geometrical and physical parameter attribution. This operation requires representative modeling of the machine that is simple and fast to solve as the analytical modeling based on the reluctance network modeling. The design verification process includes an analytical calculation and FE analysis. An analysis using EMC will help to information of quantitative force and magnetic energy. Meanwhile, an analysis by FEM brings about the results comparison of characteristics; each rectangular and trapezoidal shape of translator teeth. Flux linkage (inductances) is estimated analytically at two positions of the translator relative to the stator; the position

where translator teeth and stator teeth are misaligned (minimum phase inductance) and the position where translator teeth and stator teeth are aligned (maximum phase inductance). The magnetomotive force Θ_a consumed by the air-gap is equal to the total of Ampere turns.

$$\Theta_a = N_c \cdot I \tag{1}$$

4.1. Rectangular Shape

Figure 4 and Fig. 5 shows a part of the machine's half cross-section containing adjacent phases and the translator in the aligned and unaligned position relative to the excited phase, respectively. In the method for estimating the inductance, it is assumed that the iron-core is infinitely permeable with the field lines being perpendicular to the iron-core surface. This method is based on an approximation of field lines by circular arc segment, and it accounts for the distribution of the phase winding.

• Aligned Position

The reluctance network model at aligned position is shown on the Fig. 4 takes into account the leakage effects. The aligned or so called maximum inductance position, it is dependent on the excitation current and is calculated as follows. The reluctance in air-gap and leakage in air-region is expressed as equation (2) and (3), respectively.

$$R_\delta = \frac{1}{\mu_0} \cdot \frac{\delta}{2\pi \cdot (r_o - r_i) \cdot l_{tm}} \tag{2}$$

$$R_{\sigma a} = \frac{1}{\mu_0} \cdot \frac{\pi}{1} \cdot \frac{1}{2\pi \cdot (r_o - r_i)} \cdot \frac{1}{\ln\left(\frac{l_{tm}}{\delta}\right)} \tag{3}$$

• Unaligned Position

The configuration and EMC modeling in minimum inductance position is shown Fig. 5. The leakage reluctance interacting with the stator according to the movement of translator can be separated with two categories; stator teeth and translator side (*Rσu1*), slot and translator-teeth (*Rσu2*).

$$R_{\sigma u1} = \frac{1}{\mu_0} \cdot \frac{\tau_p - l_{tm}}{2\pi \cdot (r_o - r_i) \cdot l_{tm}} + \frac{1}{\mu_0} \cdot \frac{\pi}{2} \cdot \frac{1}{2\pi \cdot (r_o - r_i)} \cdot \frac{1}{\ln\left(\frac{l_{tm}}{\tau_p - l_{tm}}\right)} \tag{4}$$

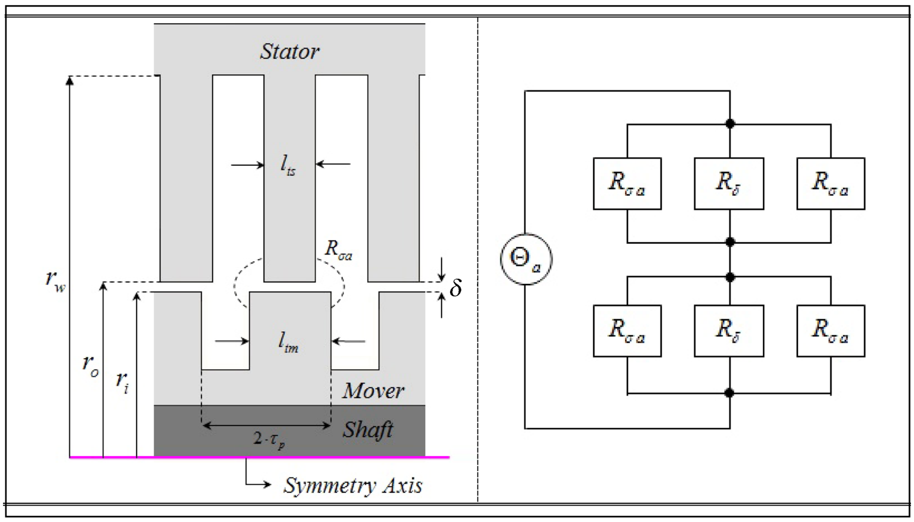

Fig. 4. Aligned Position of Rectangular Shape.

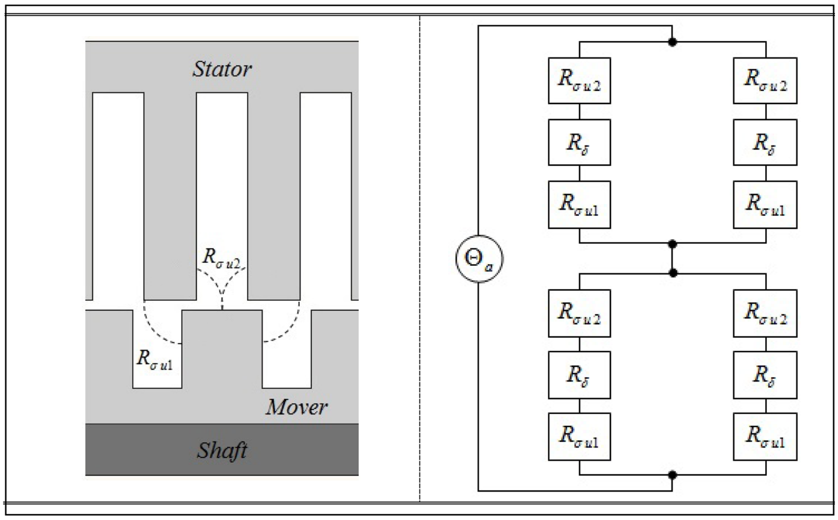

Fig. 5. Unaligned Position of Rectangular Shape.

$$R_{\sigma u2} = \frac{1}{\mu_0}\cdot\frac{\frac{l_{ts}}{2}}{2\pi\cdot(r_w-r_o)\cdot\frac{l_{tm}}{2}} + \left[\frac{1}{\mu_0}\cdot\frac{\tau_p-\frac{l_{tm}}{2}}{2\pi\cdot(r_o-r_i)\cdot\frac{l_{tm}}{2}} + \frac{1}{\mu_0}\cdot\frac{\pi}{2}\cdot\frac{1}{2\pi\cdot(r_o-r_i)}\cdot\frac{1}{\ln\left(\frac{l_{tm}}{\tau_p-\frac{l_{tm}}{2}}\right)}\right] \quad (5)$$

Rσu1 indicates the leakage reluctance which occurs between stator teeth and translator side.

Rσu2 represents the leakage reluctance which occurs between slot and translator-teeth.

4.2. Trapezoidal Shape

The EMC of trapezoidal translator shape is same to that of rectangular translator shape. Since the width of translator teeth is equal to that of rectangular shape of translator, the reluctance in air-gap is also identical with that of rectangular shape of translator. The configuration for maximum and minimum magnetic energy calculation is drawn in Fig. 6.

- Aligned Position

The leakage reluctance in aligned position is expressed

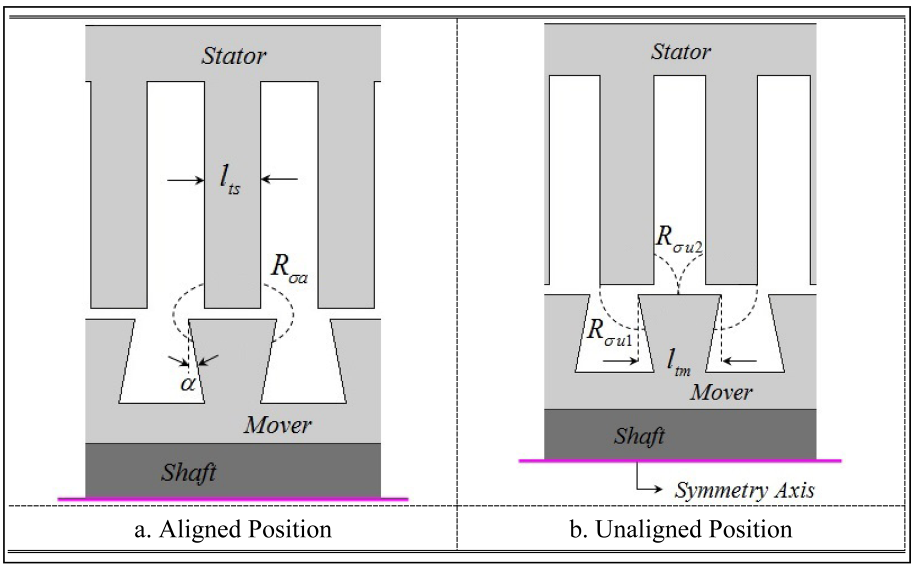

Fig. 6. (Color online) Trapezoidal Shape.

in equation (6). Meanwhile, the *Rσu1* and *Rσu2* represent the leakage reluctances in unaligned position as shown Fig. 6(b).

$$R_{\sigma a} = \frac{1}{\mu_0}\cdot\left(\pi+\frac{\pi}{k}\right)\cdot\frac{1}{2\pi\cdot(r_o-r_i)}\cdot\frac{1}{\ln\left(\frac{l_{tm}}{\delta}\right)} \tag{6}$$

where, coefficient k is expressed as $\frac{180\,Deg.}{\alpha}$.

$$\begin{aligned} R_{\sigma u1} &= \frac{1}{\mu_0}\cdot\frac{l_{tm}-l_{ts}}{2\pi\cdot(r_o-r_i)\cdot l_{tm}} \\ &+\frac{1}{\mu_0}\cdot\left(\frac{\pi}{2}+\frac{\pi}{k}\right)\cdot\frac{1}{2\pi\cdot(r_o-r_i)}\cdot\frac{1}{\ln\left(\frac{l_{ts}}{l_{tm}-l_{ts}}\right)} \end{aligned} \tag{7}$$

$$\begin{aligned} R_{\sigma u2} &= \frac{1}{\mu_0}\cdot\frac{\frac{l_{ts}}{2}}{2\pi\cdot(r_w-r_o)\cdot\frac{l_{tm}}{2}} \\ &+\left[\frac{1}{\mu_0}\cdot\frac{\frac{l_{tm}-l_{ts}}{2}}{2\pi\cdot(r_o-r_i)\cdot\frac{l_{tm}}{2}}+\frac{1}{\mu_0}\cdot\frac{\pi}{2}\cdot\frac{1}{2\pi\cdot(r_o-r_i)}\cdot\frac{1}{\ln\left(\frac{l_{ts}}{l_{tm}-l_{ts}}\right)}\right] \end{aligned} \tag{8}$$

Based on the above calculated reluctances, the average force is developed over an elementary axial displacement τp, can be calculated starting from the energy variation ΔW, by difference between maximum ($W_{\max}$) and minimum magnetic energy ($W_{\min}$).

$$W_{\max} = 2\cdot\Theta_a^2\cdot R_{\max} \tag{9}$$

$$W_{\min} = 2\cdot\Theta_a^2\cdot R_{\min} \tag{10}$$

where, $R_{\max}$ and $R_{\min}$ indicates the synthetic reluctance at aligned and unaligned position respectively.

$$R_{\max} = \frac{2\cdot R_\delta + R_{\sigma a}}{R_\delta\cdot R_{\sigma a}} \tag{11}$$

$$R_{\min} = \frac{2}{R_\delta + R_{\sigma u1} + R_{\sigma u2}} \tag{12}$$

Eventually, the average force and force density can be obtained as below equations:

$$\Delta W = W_{\max} - W_{\min} \tag{13}$$

$$F_{ave} = \frac{\Delta W}{\tau_p} \tag{14}$$

$$F_{den} = \frac{F_{ave}}{2\cdot\pi\cdot r_i\cdot\tau_p} \tag{15}$$

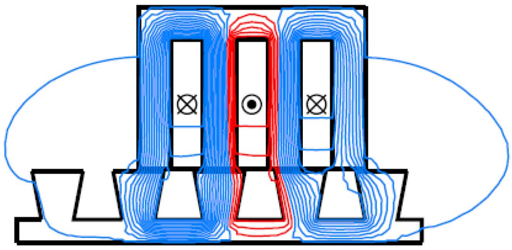

Fig. 7. (Color online) Magnetic Flux Characteristics.

5. Numerical Calculation

The design of machine using analytical magnetic circuit techniques enables it to access easily understanding of characteristics. In addition, FE analysis is used to verify the result from analytical calculation by EMC. Fig. 7 represents the flux characteristics by FE analysis as the result of the numerical calculation in trapezoidal shape of translator. It taken the saturation effect of iron core into consideration in given magnetomotive force. The flux density in iron-core should be not more than 1.6-1.7 T. Different materials have different saturation levels. For example, high permeability iron alloys used in electrical machines reach magnetic saturation at 1.6-2.2 T, whereas ferrites saturate at 0.2-0.5 T. Some amorphous alloys saturate at 1.2-1.3 T.http://en.wikipedia.org/wiki/Saturation_(magnetic) - cite_note-6 This study set a goal of approximately 1.6 ~ 1.7 T of the magnetic flux density in the iron core under a given input value [2].

With this result, the inductance curves versus position for a given current show the characteristic of two different shapes with rectangular and trapezoidal translator. The force in the machine is produced when its' stator winding

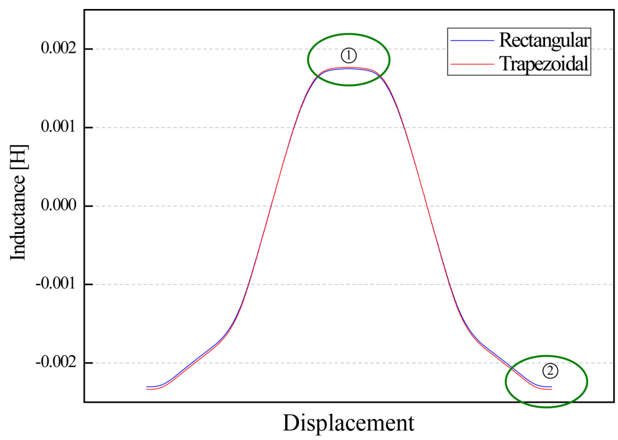

Fig. 8. (Color online) Inductance Curve of One-cycle.

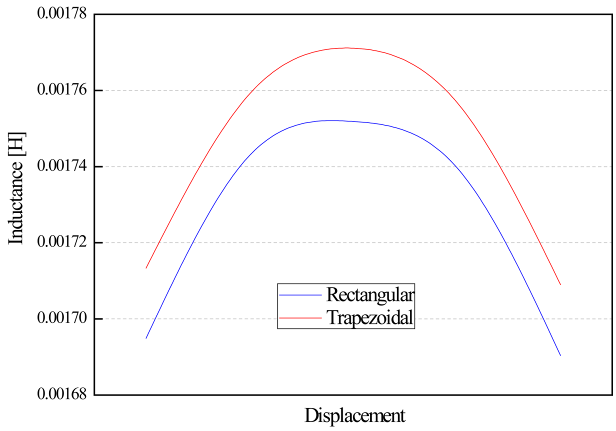

Fig. 9. (Color online) Maximum Inductance, ① in Fig. 6.

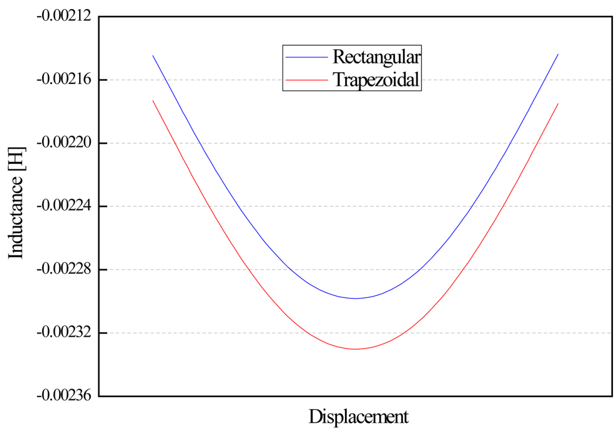

Fig. 10. (Color online) Minimum Inductance, ② in Fig. 6.

is energized; in result the stator pole pulls the nearest translator pole to align in the region where reluctance is minimum and inductance maximum. The inductance starts increasing with relative approach of translator pole to energized stator poles. Different inductance profile within the one-cycle by the translator shapes is indicated in Fig. 8; it shows inductance line distribution at a rated current in case rectangular and trapezoidal shape of translator teeth by FEM. As translator teeth travels towards stator teeth, inductance increases until completely aligned each other.

The trapezoidal shape of translator teeth leads to improved results than rectangular shape in inductance respects. It is actually the fact that this translator shape further expands an effective magnetic flux. As a result, trapezoidal shape brings better results in both of energy and force characteristics than rectangular shape as shown Fig. 11.

Through above graph, their arithmetic values are listed in Table 1. The characteristics of trapezoidal translator

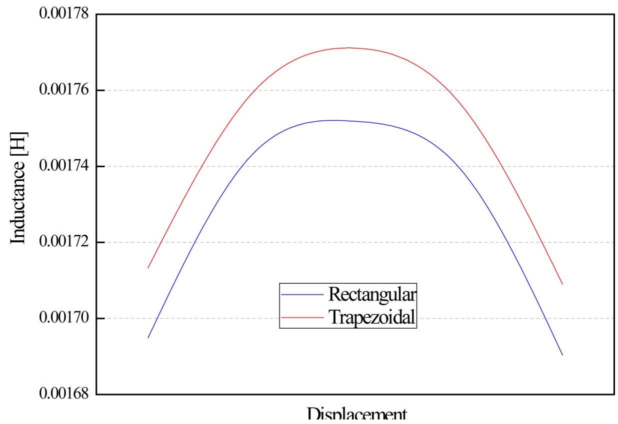

Fig. 11. (Color online) Comparison by Translator Shape.

Table 1. Comparison Energy and Force.

	Magnetic Energy [J]	Average Force [N]	Force Density [N/mm^2]
Rectangular	0.034	5.502	7.784
Trapezoidal	0.053	8.404	11.89

shape show better results than that of rectangular one as a whole; average force, force density and magnetic energy. This means that the trapezoidal type is capable of producing high force and decreasing force ripple.

6. Conclusion

This study has investigated the characteristics of three models by translator teeth shape in tubular linear reluctance machine. The motion is caused by the tangential force which tends to align poles of the moving part with the excited poles of the static part. Theoretically it enables neutralization of normal forces, by this allowing a smaller air-gap and better use of active material. The process of analysis and evaluation has been performed by analytical design by EMC and verification by FEM. These methods enable to obtaining an approximate insight into the value of force and magnetic energy. The calculation results show the possibilities of improving the force and magnetic energy of the machine by modification of the tubular translator teeth.

As a result, it is made clear that the trapezoidal shape of translator teeth could be improved by approximately 65[%] from the rectangular shape of that in magnetic energy, average force and force density. It will be helpful to study various shape of geometric parameters which are not only tubular linear machine.

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