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Determination of Geometric Dimensions of a Double Sided Linear Switched Reluctance Motor

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***Abstract*—In this study, a double-sided linear switched reluctance motor (LSRM) drive was investigated as an alternative actuator for vertical linear transportation applications such as a linear elevator door, hospital and subway doors which move linearly and where accurate position control and rapid response is requested. A prototype sliding elevator door that is focused on a home elevator with LSRMs is designed. The motor has 6/4 poles, 3 phases, 8A, 24V, 250 W and 250 N pull forces. Air gap between rotor and translator poles of the designed motor and phase coil's ideal inductance profile are obtained in compliance with the geometric dimensions. Operation and switching sections as motor and generator has been determined from the inductance profile.

***Keywords*—Linear switched reluctance motor, sliding door, elevator door, linear motor design.

I. Introduction

LINEAR motion with rotary motors and linear mechanical interfaces has backlash due to gears and problems such as hysteresis [1]. Linear motors eliminate the need for rotary to linear mechanical interfaces resulting in simpler and robust conversion of electrical input into linear motion. With linear motors, additional benefits of quietness and reliability are obtained. Linear motors have been applied in conveyor systems, people mover, sliding doors, and airport baggage handling, to mention a few [2].

Opening and closing time of elevator doors significantly affects the elevator's service quality and waiting time of the passengers. Due to this reason, it is need to new design of sliding door drive systems which both quickly open and close and have low failure rate and at the same time high efficiency.

Conventional elevator doors consist of an electromechanical lock and sliding door system connected to gear box, belt and pulley systems coupled with the shaft of a rotational motor. Due to these extends the accelerating time of the door since instantaneous impacts are avoided during the transfer of motion by the moving object to the subsequent power train. In addition, the increasing of element numbers in every power train, belt and pulley system causes to decrease in efficiency and increase in failure rate. Therefore, the use of high efficiency linear motors which are moving linearly in mechanical systems result in lower failure rate and high velocity responses. So, it is unavoidable to use linear motors in sliding door systems such as elevator doors.

Pasanen J. et al. designed a controller in 1991 for digital speed controlled motor to be employed first in automatic elevator doors. [3].

In 1995, J. D. Edwards and Gurdal have published their study on the subject of contactless perception of a linear LRM [4].

In 1996, Masuda T. et al. have applied the servo motor driver to panoramic multiple elevator doors [5]. In 2000, Bae HK. et al. have defined the topology of minimum power circuit for a system with linear motor [6]. In 2005, Krishnan R. has specified the employment of linear motors in linearly moving systems instead of rotational motors used throughout the history as a giant step in industry [7]. In 2006, Daldaban F. and Ustkoyuncu N. have presented the analysis of the model of linearly switched reluctance motor (LSRM) [8].

In 2007, Liu X. et al. have published their study on a new elevator door driven by a linear brushless direct current motor (PMLSM). The designed motor is used in the drive of an elevator door [9].

In 2008, YH, Wu HX et al. have used a special Brushless DC Motor servo system in the control of an elevator door [10].

In 2008, Liu X. et al. have again presented an elevator door with linear brushless motor. They have analyzed the motor by finite elements method and published various experimental and magnetic analysis and theoretical finding and the test results at the elevator door [11].

In 2010, Fenercioglu A. and Dursun M. have published the design of a double-sided linear switched reluctance motor and its 3 dimensional magnetic analysis [12]. Similar studies are encountered in the literature [13]-[23]. LSRMs have simple construction, low cost, high pull forces, and accurate position.

In this study, the geometric properties of an optimal LSRM which complies with the door systems moving linearly such as elevator, hospital, and subway and train doors were determined. Ideal and real inductance curves of the motor are obtained and the velocity control parameters of the motor are determined.

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II. Elevator Door Driver System Design with Linear Switched Reluctance

Classical door driver system block diagram is given in Fig. 1. As it is seen in given block diagram, a door moving in linear is driven by using gearbox and v-belt-pulley with a circular motor. In this way, it causes both reduction of the velocity response of door, and decrease of performance because of friction of power transmitter. In Fig. 2, it is seen that an elevator door driver system with two-sided designed LSRM. In this designed system by transferring the power of air gap directly to the sliding door mechanism, frictions to decrease minimum level it is aimed. In this system, there are not any brush and collector in motor. So, while frictions are lowered, production of motor power is increased. Furthermore, the power loss because of belt, pulley and gearbox in power transfer are prevented and the power transfer elements used more than needed are eliminated and the total cost of system is decreased.

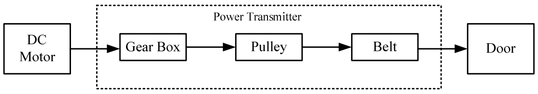

Fig. 1 Classical door driver system block diagram.

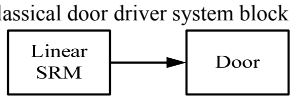

Fig. 2 Block diagram of door driver system used linear SRM.

In designed system, the elevator door is driven by translator of two-sided LSRM. The translator is mechanically connected to the sliding elevator door. To analyses and simulate the system correctly, accurate inductance curve of motor according to translator position should be known.

Therefore, the inductance curve changing with the position of the translator of motor has been partitioned into five sections. While determining the sections, the geometric dimensions of motor are taken into considerations. For the elevator door driver, considering EN81 standard, 100 N is needed to start motion and 150N is needed to accelerate the door.

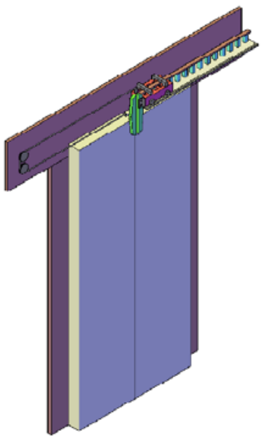

Fig. 3 Combination of designed LSRM and sliding door system

For the motor design according to this standard, a geometric dimension of LSRM which are estimated by using Ansoft Maxwel program and magnetic analysis has been made by means of finite elements method.

In design, sliding door has two symmetric parts. The weight of first part is taken as 25kg. In classical systems, the opening and closing time of sliding door is 4 seconds. The force needed to overcome static friction was experimentally founded as 100 N. Moreover, as the standard does not allow more than 150N force during the door closing, the total force to be produced by motor was determined as 250N.

III. Inductance Profile of LSRM

The ideal inductance profile according to translator position of the designed motor has 5 sections. These sections for the motor obtained versus to translator position were shown in Fig. 4. First section is found by (1). In this section, the minimum and maximum value of Phase A does not change from the initial positions to X_1. On the other hand, during the Section 2 inductance increases linearly and the length of this section is calculated by (2). Since the inductance positively changes in this section and positive pulling force occurs by ratio of the square of current which is passed through the coil. Since the inducted force varies by the square of the current, it is independent of the direction of current. Section 3 is the section where inductance is maximum and its length is calculated by (3). Since inductance variation is zero in this section, derivative of inductance is also zero. Therefore, any pulling force is not produced in this section even if current is applied to the phase coil. In order to decrease the any phase current in coil to zero, phase current should be interrupted before the end of section 2. In this section, current interruption point directly depends on the current value, inductance value and vehicle velocity.

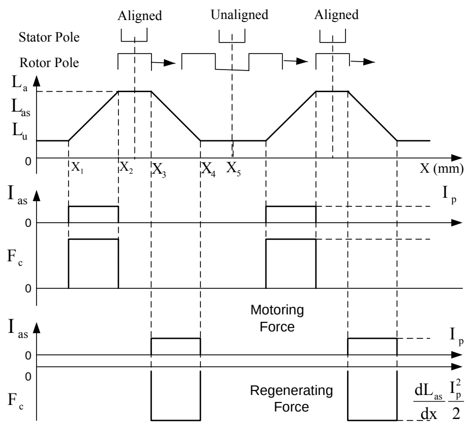

Fig. 4 Inductance profile of 5 sections for the motor versus translator position

In Section 4, the inductance decreases and length of Section 4 is calculated by (4). Since inductance variation is negative, the direction of force is also negative. So, the motor operates as a generator during this section. Properties of section 4 5 are similar to that of Section 1 and its length is calculated by (5).

The minimum value of phase inductance of motor is indicated as 0.001472 mH and maximum inductance as 0.005851 mH for 8A. Consequently, electrical properties of the motor are determined as 250 W, 24V DC, 8 A.

$$x_1 = \frac{w_{ts} - w_{sp}}{2} \tag{1}$$

$$x_2 = x_1 + w_{ts} = \frac{w_{ts} + w_{sp}}{2} \tag{2}$$

$$x_3 = x_2 + (w_{tp} - w_{sp}) = w_{tp} + (\frac{w_{ts} - w_{sp}}{2}) \tag{3}$$

$$x_4 = x_3 + w_{sp} = w_{tp} + (\frac{w_{ts} + w_{sp}}{2}) \tag{4}$$

$$x_5 = x_4 + \frac{w_{ts} - w_{sp}}{2} = w_{sp} + w_{ts} \tag{5}$$

where w_{tp} is width of the translator pole , w_{ts} width of the translator slot, w_{sp} is width of the stator pole and w_{ss} is width of the stator slot.

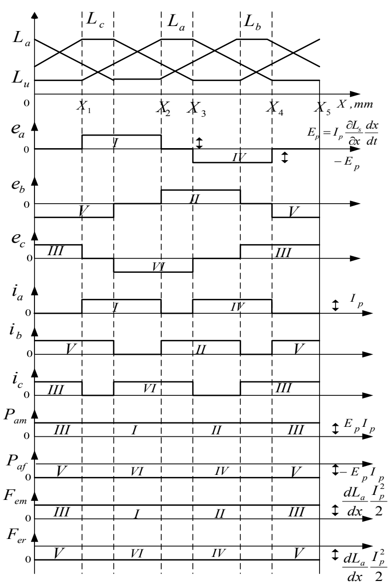

Fig. 5 Operation of LSRM versus inductance variation

In the inductance profile shown in Fig. 5, the sections between $0 - x_1$ and $X_4 - X_5$ show the unaligned position, and the section between $X_2 - X_3$ shows the aligned position.

The working principle of LSRM and the back EMF occurring, current, and power and pull force versus inductance variation are shown in Fig. 5. The force is produced along the section between $X_1 - X_2$ and the machine operates as motor. On the other hand, force is not produced in the section between $X_3 - X_4$ and the machine operates as generator.

IV. Determination Of Geometric Dimensions of a Double Sided LSRM

In the design of LSRM, the following properties are assumed:

Length of LSRM=0.8 m,

Maximum linear velocity, v_m =1.0 m/s,

Acceleration time, t_a = 0.167 s,

Maximum mass for translator=25 kg.

In fact, properties of linear motors are not much different than the electrical and geometric properties of rotational motors. Since the length of prototype of motor to be designed is 235 mm, the machine may be considered as a rotational motor with the circumferential of 235 mm and radius 37.40 mm. The motor is regarded for use in opening and closing an elevator door of weight 25 kg at a distance of 80 cm. Trapezoidal motion profile speed-time and speed-position curve of the door during opening and closing is given in Fig. 6. In addition, a trapezoidal motion profile is used to drive the vehicle smoothly and without jerky motion and to control the positions of the vehicle while its ascent and descent.

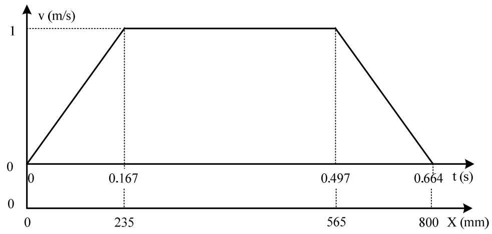

Fig. 6 Reference speed of elevator door versus position and time

Mass of the door (m) is 25 kg, acceleration time (t_a) is selected as 0.167 second and velocity of the door (v_m) is selected as 1.0 m/s. According to these values, the acceleration of the door (a) is found by (6) and the pull force to accelerate the door is found by (7), respectively as

$$a = \frac{v_m}{t_a} = \frac{1.0}{0.167} = 6\ m/s^2 \tag{6}$$

$$F_a = ma = 25.6 = 150\,N \tag{7}$$

F_a was selected as 250 N by adding the 100 N force required for the static friction. F_a is the force which the motor should apply to door, m is mass of door (kg) and a is the acceleration determined from (6). Deceleration of the door to stop is equal to its acceleration, but has reverse sign. Accordingly, the LSRM's power (P) is calculated by (8) as:

$$P = F_a v_m = 250.1 = 250W \tag{8}$$

Minimum translator pole width is selected for continuous pull force. Thus, the length of this yoke pole is found by (9) with aid of the circumferential length of the rotating motor:

$$\min[\beta_s] = \frac{4\pi}{P_t P_r} = \frac{4\pi}{6x4} = 0.5236\,rad = 30^\circ \tag{9}$$

By considering, the pole width of the rotational motor is the same as the linear version; the length of a translator pole is calculated as 19.58 mm. With considering production problems, the pole width was chosen as 20 mm and the total length of motor was determined as 235 mm for 360. Since $\beta_{r>}\beta_s$ the value of β_r is chosen as $36°$. Therefore, stator pole angle of rotary SRM, $\beta_s = 30^{\circ} = 0.5236\,rad$, rotor pole angle of rotary SRM, $\beta_r = 36^{\circ} = 0.6283\,rad$. Then to get the maximum power developed, current conduction angle θ_i must be equal the stator pole arc β_s,

$$k_d = \frac{\theta_i.q.P_r}{360} = \frac{30x3x4}{360} = 1 \tag{10}$$

$$\mathrm{k}_1 = \frac{\pi^2}{120} \tag{11}$$

$$\mathrm{k}_2 = 1 - \frac{\mathrm{L_u}}{\mathrm{L}_a^s} \tag{12}$$

where θ_i is current generating angle , β_t translator pole width q is number of phase.

Maximum translator current should be calculated for k_2 constant in order to draw the maximum power. In this case, magnetic characteristics of the core used give the ratio of inductance value of the unaligned position to the inductance value at the aligned position. This ratio is found as $L_u / L_a = 0.1$ from the sheet steel core used. Thus k_2=1-0.1=0.9. The magnetic parameters of M 1010 steel used for core are B=1.7 and A_t=24400. For applications without servo systems, k is chosen as 0.65. After the unknown parameters are determined as:

$$ke = 0.4, kd = 1, k_1 = \frac{\pi^2}{120}, k_2 = 0.9, B = 1.7T,$$

The hole diameter (D) of rotary counterpart of motor is calculated by (13) as:

$$D = \sqrt{\frac{P\pi}{60xk_e k_d k_1 k_2 kBA_s v_m}} \tag{13}$$

$$= \sqrt{\frac{250\pi}{60x0.4x1x\dfrac{\pi^2}{120}x0.9x0.65x1.7x24400x1}} = 0.076 \cong 76mm$$

If the velocity of LSRM is relevant to rotational velocity, it is found by (14);

$$N_r = \frac{v_m}{0.5D} \times \frac{60}{2\pi} = \frac{1\times10^3}{37} \times \frac{60}{2\pi} = 258.09\,rpm \tag{14}$$

Switching frequency ($\mathrm{f_{sw}}$) of the current applied to the coils is calculated by (15) and length of pole pitch τ is calculated by (16).

$$f_{sw} = 2P_r \frac{N}{60} = 2\times4\times\frac{360}{60} = 48 \approx 50\,Hz \tag{15}$$

$$\tau = \frac{v}{f_{sw}} = \frac{1.0}{50} = 20\,mm \tag{16}$$

Stack length (L)of rotary LSRM is found by (17).

$$\mathrm{L = kD = 0.65 \times 0.76 = 0.494\ mm} \tag{17}$$

Thickness of stator yoke, b_{sy} is found as by (18),

$$b_{sy} = \frac{D\beta_s}{2} = \frac{76\times0.5236}{2} = 19.90\,mm \tag{18}$$

and taken approximately as 20. Assuming that outer diameter of stator is 118 mm, height of stator pole (h_s) is found by (19).

$$h_s = \frac{D_o}{2} - \frac{D}{2} - b_{sy} = \frac{118}{2} - \frac{76}{2} - 24 = 20\,mm \tag{19}$$

Rear copper width of the rotor, b_{ry} is by (20) and top of rotor pole are found, h_r is by (21);

$$b_{ry} = (\frac{D}{2})\beta_r = (\frac{76}{2})\times0.6283 \approx 23.88mm \tag{20}$$

$$h_r = 2\left(\frac{D}{2} - 2\lambda_g - b_{ry}\right) = \left(\frac{76}{2} - 2\times0.6 - 23.88\right) = 26mm \tag{21}$$

Magnetic field intensity in the air gap (H_g) is calculated and found by (22) as

$$H_g = \frac{B}{\mu_r} = \frac{1.7}{4\times\pi\times10^{-7}} = 1352817.016A/mm \tag{22}$$

For a peak phase current of Ip = 8 A allowable in the machine, the number of turns per phase is by (23).

$$T_{ph} = \frac{H_g(2\lambda_g)}{I_p} = \frac{1352.817(2\times0.6)}{8} = 203\,turn/phase \tag{23}$$

Assuming the current density as 5 A/mm^2, the area of the conductor is found by(24).

$$a_c = \frac{I_p}{J\sqrt{q}} = \frac{8}{5\sqrt{3}} = 0.92\,mm^2 \tag{24}$$

a_c was selected 1 mm^2. The number of total sectors of LSRM is found by (25) and the resultant total number of stator poles (n) are by (26)

$$\mathrm{N_{sc}} = \frac{\mathrm{L_t}}{\pi \mathrm{D}} = \frac{0.8}{\pi\times76\times10^{-3}} \approx 4 \tag{25}$$

$$n = P_s N_{sc} = 6\times4 = 24 \tag{26}$$

Active operation of stator of LSRM and passive operation of its translator reflects the stator and translator of LSRM versus the stator and rotor of rotating SRM. The width of the stator pole is by (27) and the width of the stator slot are obtained as (28)

$$w_{sp} = b_{sy} = \frac{D\beta_s}{2} = \frac{76 \times 0.5236}{2} = 19.90 \approx 20mm \quad (27)$$

$$w_{ss} = \frac{(\pi D - P_s w_{sp})}{P_s} = \frac{(\pi \times 76 - 6 \times 20)}{6} = 19.79 \approx 20mm \quad (28)$$

The width of the translator pole is by (29) and the width of the translator slot are calculated as (30)

$$w_{tp} = b_{ry} = 20mm \quad (29)$$

$$w_{ts} = \frac{(\pi D - P_r w_{tp})}{P_r} = \frac{(\pi \times 76 - 4 \times 20)}{4} = 39.69 \approx 40mm \quad (30)$$

The core stack width of the LSRM is obtained by (31)

$$L_w = L = kD = 0.65 \times 76 = 49.4mm \quad (31)$$

Translator slot window area is by (32)

$$d_c = \sqrt{\frac{4a_c}{\pi}} = \sqrt{\frac{4 \times 0.92}{\pi}} = 1.08mm \quad (32)$$

The total stator length is found by (37)

$$P_s \times W_{sp} + P_g \times W_{ss} = 6 \times 20 + 5 \times 23 = 235mm \quad (37)$$

where P_s is stator pole number and it is 6, P_g is stator slot number and it is 5. In conclusion, it is observed that the above equation is satisfied with the LSRM design.

TABLE I
DATA SHEET OF CALCULATED DESIGN PARAMETERS

Symbol	Design Parameter	Value
L	Length of LSRM	0.8 m
v_m	Maxsimum Linear Velocity	1 m/sec
t_a	Acceleration time	0.167 sec
m	Maximum mass for translator	25 kg
F	Pull force	250 N
P	Power of LSRM	250 W
I	Current	8 A
w_{tp}	Width of translator pole	23 mm
w_{sp}	Width of stator pole	20mm
w_{ss}	Width of stator slot	20mm
w_{ts}	Width of translator slot	40mm
q	Number of phase ()	3
f_{sw}	Switching frequency	50 Hz
τ	Pole pitch	20 mm
P_g	Stator slot number	5
D	The hole diameter	76 mm
λ_g	Stator and translator slot	0.6 mm

V. MAGNETIC ANALYZES OF MOTOR

The appropriate mechanical and electrical parameters was designed the motor has been visualized as 3 dimensional upon these parameters.3-d Figure of the motor as been drawn with a computer aided design software, and it is shown in Fig.8.

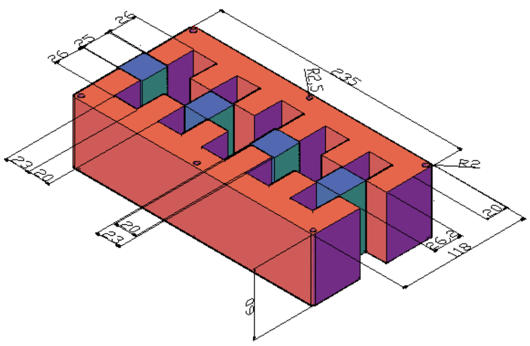

Fig. 8 3-d model of the LSR motor

The induced electro magnetic torque, magnetic flux and magnetic flux with flux density, magnetic flux with flux density vectors are obtained for this design. The obtained values are non-linear functions because they are changed according to the location of the rotor and flux.

The variables in the magnetic analyses of the motor are the location of the armature and winding currents. The software composes the finite elements surface of the motor depending upon the location of the armature and then calculates the basic outlet parameters like phase inductions.

During the magnetic analyzing of the motor designed, 8A current is applied. In this case, the force obtained in the state of armature is given as force in Fig. 9. The graphic in the Fig. 10 shows the force alteration of the stator and armature from the total detached status to the coincident status.

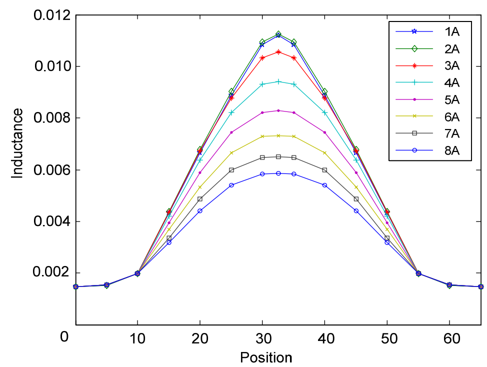

Fig. 9 Inductance change

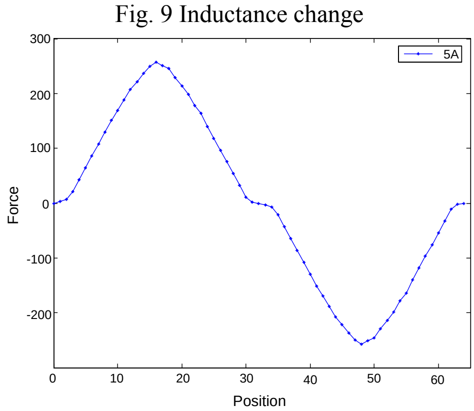

Fig. 10 Rotor position-force change

VI. CONCLUSION

In this study, the method of geometric dimensioning method for a double sided, 6/4 poled, 3 phase LSRM of 250 W power to be used in places such as elevator, hospital and subway doors where accurate position control and rapid response are requested and the parameters obtained by this method are calculated. Operation and switching sections as motor and generator are determined by obtaining the ideal inductance profile according to the geometric dimensions of air gap, stator and translator in compliance with the power of motor.

As seen, the power of air gap is directly transferred to the sliding door and friction is minimized in the system. Since in this system friction is reduced because there is not any brush and collector in the motor, the motor efficiency is high. In addition, the losses arising from belt, pulley and reducer in power transfer are prevented and cost is reduced by removing the power transfer elements used in excess.

APPENDIX

a	Acceleration (m/s^2)
a_c	The area of the conductor (mm^2)
b_{sy}	The stator yoke thickness (mm)
b_{ry}	Rear copper width of the rotor (mm)
β_r	Rotor pole angle of rotary (degree)
β_s	Stator pole angle of rotary $^\circ$ (degree)
D	The bore diameter (mm)
d_c	The diameter of the conductor (mm)
f_{sw}	Switching frequency (Hz)
$F_{a:}$	Force of LSRM (N)
H_g	Magnetic field intensity in the air gap $A/mm)$
h_r	Top of rotor pole (mm)
h_s	Height of stator pole (mm)
h_t	height of translator pole
I_p	Peak phase current (A)
L	Stack length of rotary SRM (mm)
L_a	Aligned inductance (H)
L_u	Unaligned inductance (H)
L_{tr}	The total length of the translator (mm)
L_w	The core stack width of the LSRM (mm)
m	Maximum mass for translator (kg)
n	The resultant total number of stator poles
N_r	Rotational velocity (rpm)
N_{sc}	The number of total sectors of LSRM
P	Power of LSRM (W)
t_a	Acceleration time (s)
θ_i	Current generating angle (degree)
τ	Pole pitch
P_f	Packing factor
P_s	Stator pole number
P_r	Rotor pole number
T_{ph}	The number of turns per phase
q	Number of phase
v_m	Maximum linear velocity
w	Width of the wedges
w_{tp}	Width of the translator pole
w_{ts}	Width of the translator slot
w_{sp}	Width of the stator pole
w_{ss}	Width of the stator slot

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