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Analysis of linear motor with symmetrical EMF vector for household elevator application

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ABSTRACT

Linear permanent magnet synchronous motor (LPMSM) has emerged as a viable alternative to other linear motors for higher thrust lifting action. With the advancement of permanent magnets, LPMSM could contribute to energy conversation while also being suitable for applications requiring higher thrust, such as elevator. However, because the existing LPMSM is larger in size, it requires more space to be equipped with a household elevator. To address this issue, a new LPMSM with increased thrust capability has been proposed. The new LPMSM is modelled and analyzed in terms of back EMF and force in this paper. For improved performance, a symmetrical EMF vector is applied to the new LPMSM. In terms of back EMF and force, 4 LPMSM models are studied. According to the results, 6 slot 4 pole has the highest back EMF when compared to the others. As a suitable combination of slot and pole, a symmetrical EMF vector is the suggested LPMSM at the end of this research.

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1. INTRODUCTION

The world today is moving towards an aging society. Various places are reporting increasing rates of aging populations and its impact on the society [1]–[4]. A similar situation also happens in Malaysia [4]. Declining fertility and mortality rates have led to an improvement in the life expectancy of the population which has resulted in an aging population in Malaysia. Malaysia is expected to become an aging nation by the year 2030 where the elderly population comprises 15 % of the total population. Therefore, support system needs to be developed to help the elderly population to maintain independent living. One of the support systems that could help the elderly population is to improve the self-mobilization system. In term of horizontal movement, a wheel-chair with improved movement control has done a lot to help the elderly to move [5]. But, in terms of vertical movement, the elderly group needs to depend on the high-cost conventional elevator which is unpractical to install in their homes. Nowadays, most housing developers tend to build double-storey or even higher landed houses. Therefore, a small size and low-cost elevator system called domestic elevators is required in order to make sure it is affordable and practical to be installed at least for a double storey house to promote independent living to the elderly. Apart from the elderly group, this system will also be beneficial to disabled people [6]. In order to make the domestic elevator system friendly to this group of people, some researchers have included the Cloud and Mobile Device Control Feature specially to promote an IOT-based smart home system [7], [8]. Then, the current domestic elevator system uses either rotational type induction motors (IM) or permanent magnet synchronous motors (PMSM) as the electric motors [9]. The rotational motion produced by IM or PMSM will be converted to linear motion using gears. The linear motion is then used to move the elevator car either up or down. For instance, the use of the IM or the PMSM requires an additional room called the motor room that is located the motor and its control panel. Usually, an additional floor is required on top of the top floor, which is uneconomical in terms of space occupancy. Based on some studies, the conventional elevator system occupies about 30% of the total floor space for buildings over 250 meters tall [10]. To solve this problem, a linear motor can be used as an electric motor for the domestic elevator system. The use of the linear motor as an electric machine in a domestic elevator system not only eliminates the motor room, but it can also be used as part of the counterweight [11].

There are some candidates that are suitable for use as the domestic elevator system electric motor. The first candidate is linear induction motor (LIM) similar to its counterpart in the rotational type of the electric motor [12], [13]. In the research by Escalada *et al.* discussed the details of a linear induction motor with variable parameters [14]. The design of a linear motor requires a procedure that starts from the mechanical specifications, requirements of feeding and dimensional restrictions. The sizing of the motor determines its structure and its main magnitude. In this research, the dynamic characteristics of the linear induction motor are analyzed by finite element method (FEM). Based on the research, it is noted that the magnetizing inductance depends on the frequency and on the flux. This is due to variations in the steel reluctance and because of the material saturation, respectively. Nireekshana and Babu developed a simple linear induction motor [15]. In this research, an aluminum sheet lay over iron core, acts as the rotor and the stator is designed for Double Layer winding and having 2 poles. The material that is used for stator is silicon steel. The air gap plays an imperative role on the machine performance, and it needs to be as small as possible to have a better thrust and efficiency. Nage and Shinde had designed single sided linear induction motor to drive the elevator [13]. An exploratory model of single sided linear induction motor driven elevator has been presented in the research. The use of sided linear induction motor is the promising solution for vertical transportation. However, LIM is well known to be a low performance electric motor since it has relatively low power factor on low load and low starting thrust. On top of that, the LIM usually consumes higher currents, and hence, contributes to higher power consumption.

The second candidate is switched reluctance linear synchronous motor (SRLSM) [16], [17]. Previously, the performance of SRLSM was said to be slightly lower compared to the LPMSM. Most of the literature reported that the elevator nowadays is using SRLSM [18]–[21]. SRLSM provides a simple structure where the coil is only wound on one side, with cheaper manufacturing cost, rugged structure, temperature independence, and excellent capability of fault tolerance. A study by Hirayama *et al*. had compared the performance characteristic of linear switched reluctance linear motor (SRLM) and linear induction motor (LIM). In order to improve the efficiency, the air gap length should be shortened. The efficiency of SRLM is lower than LIM and permanent magnet linear synchronous motor [21]. However, the thrust produced by SRLM is higher than LIM of the physical size. Kawabata had designed a method for thrust ripple reduction of switched reluctance linear motor [22]. It describes a design method for thrust ripple reduction without decreasing the average thrust in the double-sided linear switched reluctance motor. The structure of the motor designed by the researcher is back-to-back mover. The spatial arrangement of stator is investigated in order to reduce thrust ripple. Meanwhile, Liu and Kuo had designed the SRLSM in longitudinal configuration. The longitudinal flux configuration is the magnetic flux, which is in the same direction as the translator movement. The moving translator configuration acts as a primary part while the stator acts as secondary part. Meanwhile, Corda *et al.* had designed their SRLSM in transverse configuration [23] whereby its configuration is parallel to each other. The transverse configuration produces more driving force compared to longitudinal configuration. The main drawback of the SRLSM is high thrust ripple that should be minimized. The thrust ripple also contributes to other problems, which are vibration and acoustic noise. This condition is less comfortable to the user and not favored by the elevator system. The thrust ripple is caused by the structure of SRLSM. In the perspective of the domestic elevator system, the thrust ripple contributes to vibration, and this makes the functionality of elevator system less efficient.

Then, the final candidate reported for elevator application is permanent magnet linear synchronous motor (LPMSM) [24], [25]. LPMSM is well known as a high-performance density electric motor since it can produce higher thrust at smaller size compared to the LIM and SRLSM. With the advancement in development of the permanent magnet (PM) material, LPMSM could contribute to energy conservation and utilization. Besides, the advantage of LPMSM is no field winding required for the motor since the permanent magnet will produce the excitation flux for the motor. Permanent magnets reduce the spaces needed for the motor. Unfortunately, there are fewer studies about LPMSM used for elevator system. Therefore, this paper will look into LPMSM in terms of symmetrical EMF vector for household elevator application. A good combination of slot and pole is studied in order to model LPMSM that needs to produce not only adequate thrust, but also minimal electromagnetic thrust ripple and cogging thrust.

2. RESEARCH METHOD
2.1. Basic structure and specification
This research focuses on the analysis of the LPMSM for elevators using finite element method (FEM). Figure 1 shows the basic structure of LPMSM for these models. Figure 1(a) shows 6 slot 4 pole. There are 6 slot of stator and 4 pieces of magnet. Meanwhile Figure 1(b) shows 12 slot 8 pole. 18 slot 12 pole and 24 slot 16 pole are shown in Figures 1(c) and 1(d), respectively. The active parameters, which are mover, permanent magnet, stator and coil are fixed. The moving parts are mover and coil whereas the other parameters are static. These models are designed for three-phase configurations.

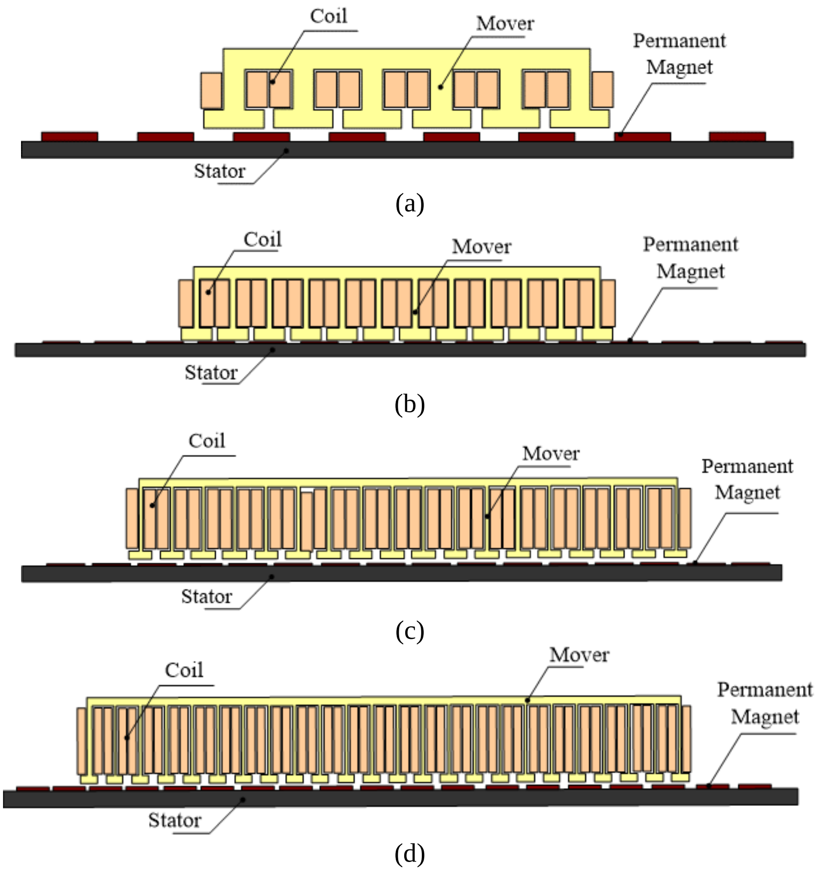

Figure 1. Basic structure: (a) 6 slot 4 pole, (b) 12 slot 8 pole, (c) 18 slot 12 pole, and (d) 24 slot 16 pole

The analysis on the production of thrust is using FEM. FEM is employed to predict the electromagnetic performance of the motors such as back EMF, cogging force, flux density and force. This approach begins with the creation of the electrical machine model. Depending on the software package, this step probably takes the same time to suit the software requirement. The calculation process continues with the creation of mesh of the electrical machine model. The mesh is used specifically to calculate the element in the modelling structure. The accuracy of the FEM calculation depends on the mesh of the structure. The more detailed the mesh is created, the more accurate model of the result. However, a high amount of details of the mesh will require high specification of the computer processor and large memory consumption. The final stage in FEM calculation is magnetic analysis. In this stage, several iterative calculations are involved to produce a flux flow path, flux strength value, magnetic flux density of the structure and value of thrust and torque. By using the FEM technique, it is possible to obtain the magnetic forces and other characteristics of electromagnetic equipment with a high degree of accuracy because it gives an approximation of the magnetic flux distribution on a microscopic scale.

The target specification of the LPMSM is based on the conventional elevator in the market. Table 1 shows the target specification of conventional and also new LPMSM for lab scale. In this research, lab scale is used because it is easier to validate the simulation result for further action. The target force needed for lab scale is 400 N.

There are three different initial models of linear permanent magnet synchronous motor (LPMSM) which are 6 slot 4 pole, 12 slot 8 pole, 18 slot 12 pole and 24 slot 16 pole. All the active parameters, such as size of mover, yoke, volume of permanent magnet and number of turns are fixed. The magnetomotive force (mmf) for each model is also fixed. Table 2 shows the parameter of LPMSM.

Table 1. Target Specification

Parameter	Conventional	New LPMSM (Lab Scale)
Length of mover [mm]	1400	700
Stack length [mm]	800	100
Capacity [kg≈N]	300kg ≈ 3kN	40kg ≈ 400N

Table 2. Parameter of LPMSM

Parameter	Value
Total length of mover [mm]	710
Volume of permanent magnet [m^{-3}]	0.03×10^{-3}
Number of turns	2400
Air gap [mm]	3
Stack length [mm]	100

2.2. Overall research methodology

This research analyses the linear motor in order to achieve higher thrust characteristic for household elevator application. Several steps have been carried out to fulfil the requirement in achieving the required specification. This research starts with the calculation of back EMF phase vector configuration. In this stage, a suitable combination of slot and pole is chosen for further action. Then, the structure of selected LPMSM is modelled using Solid work software followed by importing to Ansys Maxwell software to analyze its performance. The length of mover for all LPMSM model is fixed to 710 mm. Then, other parameters are calculated elements such as number of turns and volume of permanent magnet. After all elements are determined, the back EMF and cogging force are analyzed. There are two types of analyses for force are static force and dynamic force. To get this force, it needs two types of current source namely DC current and AC current. An AC current source is for dynamic force and DC currents is for static force for determining the magnetic flux density. Next, the analysis is carried out further on magnetic flux density and dynamic thrust for all value of current. Lastly, the back EMF constant, k_e and torque constant, k_t is calculated for all LPMSM model. If the current does not reach 6 A, the step will be repeated. Figure 2 shows the flowchart of overall methodology for this research.

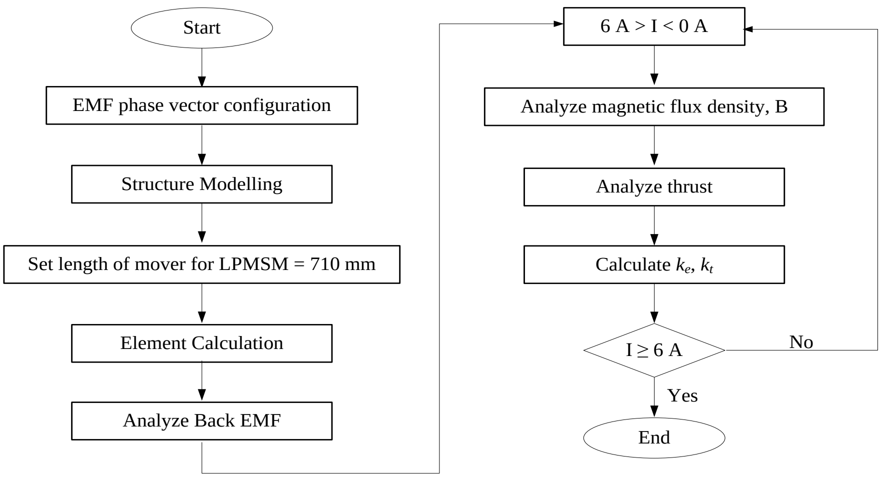

Figure 2. Overall research methodology

2.3. Back EMF phase vector configuration

Back emf is the induced voltage develop in the opposite current flow direction across the enclosed are of the magnetic conductor. It is also stated as the rate of change of magnetic flux as mathematically formulated in (1) while the ratio of the voltage generated in the winding to the rotor speed is stated as back emf constant as formulated in (2). In addition, back emf can be measured when the motors operate as the generator in no load condition.

$$e = \frac{d\varphi}{dt} \tag{1}$$

$$k_e = \frac{V}{\omega} \tag{2}$$

Where e is the back emf, ϕ is the magnetic flux, dt is the rated of change of time, k_e is back emf constant, V is the supplied voltage and ω is the rotational speed.

In term of winding coil, influence between the slot number and pole number on electromagnetic behavior are reviewed. In many cases, the three-phase motors are constructed with wye connected for balance phase excitation of 120° electrical degree. The coil vector arrangement for LPMSM was defined by the electrical degree of emf induced in the coil of each slot. The determination of winding connection in LPMSM used EMF coil vector. Each phase was displayed by a mechanical displacement can be calculated using (3). In this design, $360/Q_s$ refers to the mechanical degree of LPMSM.

$$\theta_{mech} = \frac{360}{Q_s} \tag{3}$$

The coil vector arrangements for this LPMSM are defined by electrical degree, θ_{elect} of the EMF induced in the coil side of each slot. The angle between the phasor of two consecutive slots is shown in (4).

$$\theta_{elect} = \frac{360}{Q_s} \times P_p \tag{4}$$

Where P_p is number of pole pairs and Qs is the number of slots. The electrical degree of three-phase LPMSM is 120°.

2.4. Symmetrical back EMF vector

When the coil arrangement in balance conditions it will call as symmetrical phase winding. It means that, the phase angle difference between each coil is 120°. Meanwhile, if the angle difference between one coil to another coil is not equal 120°, it is in unbalance condition as well as unsymmetrical phase winding. Figure 3 shows the coil vector for LPMSM for 6 slot 4 pole. The coil arrangement is designed in symmetrical phase winding. The symmetrical winding means the phase different from one coil to another coil is same. Since this LPMSM is designed in three phases, 6 slot will have 6 coil and every phase will have two coils. Therefore, coil 1 and 4, (C1 and C4) will be located in phase A, coil 2 and 5, (C2 and C5) in phase B and phase C will be coil 3 and 6 (C3 and C6). The phasor inside the same winding sector belongs to same phase. The coils in each phase are connected in series. Table 3 shows the coils arrangement and phase for each model that studied in this research.

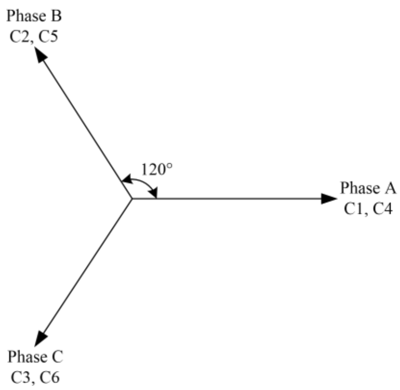

Figure 3. Coil vectors of LPMSM for 6 slot 4 pole in electrical degree

Table 3. LPMSM coil arrangement

Model	Phase A	Phase B	Phase C
6 slot 4 pole	C1, C4	C2, C5	C3, C6
12 slot 8 pole	C1, C4, C7, C10	C2, C5, C8, C11	C3, C6, C9, C12
18 slot 12 pole	C1, C4, C7, C10, C13, C16	C2, C5, C8, C11, C14, C17	C3, C6, C9, C12, C15, C18
24 slot 16 pole	C1, C4, C7, C10, C13, C16, C19, C22	C2, C5, C8, C11, C14, C17, C20, C23	C3, C6, C9, C12, C15, C18, C21, C24

3. RESULT AND DISCUSSION

The models of the segmented LPMSM were simulated using FEM software. FEM can provide magnetic analysis with high accuracy because it gives an approximation on a microscopic scale. However, it requires structural modelling and high memory capacities of computer, which in the end give more computational time drawbacks. It is clear that the adequacy of meshing directly affects the precision of computation. These drawbacks are taken into account in this research to ensure reliability and accuracy. Therefore, FEM is not essential for repetitive calculation such as for optimization or structure analysis. The simulation process will be focused on its magnetic analysis. Examples of magnetic performances that will be observed are magnetic flux path, magnetic flux density, inductance profile and thrust characteristics. On top of that, the effect of structural parameters for the thrust characteristics will be examined. The thrust characteristics are covered in terms of thrust profile to ensure achievement of the design target and thrust ripple so that the segmented LPMSM can produce constant thrust.

3.1. Analysis using FEM

Figure 4 shows the characteristics of back EMF, cogging force, transient force and magnetic flux density simulated from FEM. There are 4 types of LPMSM model that are studied in this research. However, this results for 24 slot 16 pole model. Figure 4(a) shows the back EMF of the LPMSM for 24 slot 16 pole model. The back EMF is obtained when there is no current supply to the LPMSM. Later, the average of the back EMF will be discussed. To calculate the average of back emf, only one phase is selected since other phases produce the same pattern.

Figure 4(c) shows the characteristic of transient force for LPMSM from FEM simulation. This is when the AC current is injected to the motor. Transient force refers to the amount of force that is produced at certain speed with load applied. At the end, only the average of force is being discussed further. This is because the force produced in the transient mode has ripple, thus the area under the graph is required in order to estimate force of the motor. The flux density of the energized phase A is shown in Figure 4(d). The marked value shows the maximum flux density produced by LPMSM. The value of flux density is taken at fixed point for every change of current value.

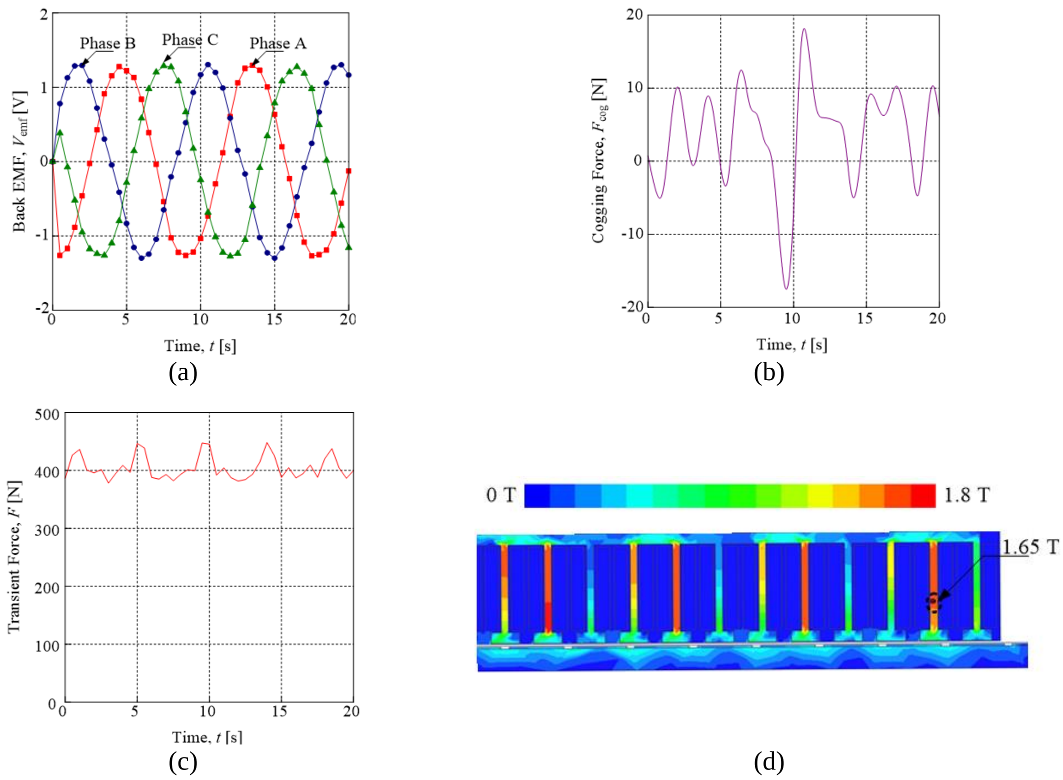

Figure 4. FEM result for 24 slot 16 pole model: (a) back EMF, (b) cogging force, (c) transient force, and (d) magnetic flux density

The cogging force for LPMSM is displayed in Figure 4(b). Cogging force is the force generated due to the interaction between the permanent magnet and the stator. It is also known as detent or 'no-current' force. Cogging force is an undesirable component for the operation of a motor. It is especially prominent at lower speeds, with the symptom of jerkiness. Cogging force results in the force, as well as force ripple.

Figure 5 shows the characteristic of average back EMF, cogging force, transient force and maximum flux density. All the values plotted at this graph were taken for 6 slot 4 pole, 12 slot 8 pole, 18 slot 12 pole and

24 slot 16 pole. Figure 5(a) shows the average back EMF for LPMSM. The 6 slot 4 pole produced the highest back EMF when the speed recorded at 30 mm/sec compared to other model of LPMSM which is 2.7 V while the 18 slot 12 pole produced the lowest back EMF. The back EMF is directly proportional to the speed. When the speed increases the back EMF will increase. Based on Figure 5(b) the highest and the lowest cogging force are 6 slot 4 pole and 24 slot 16 pole, respectively. The highest cogging force is 30 N and the lowest is 6 N.

Based on Figure 5(c), the average transient force is gradually increased as the current increases. The magnetomotive force (mmf) is fixed for each model of LPMSM. The force is simulated under various current values. For this research, the AC current is set from 1 A to 6 A. The highest force is obtained by 6 slot 4 pole which is 550 N at 6 A. Meanwhile, the 18 slot 12 pole produces the lowest transient force. The 18 slot 12 pole produced lower than 6 slot 4 pole, resulting in about 24 %.

The maximum flux density produced by LPMSM is shown in Figure 5(d). Magnetic flux density is defined as the ratio of magnetic flux per area. It is denoted as *B* and the unit is Tesla or Wb square meter. The flux density is directly proportional to the current. When the current increases, the flux density will be increased until it reaches the saturation value. The highest flux density produced almost 2.0 T for 6 slot 4 pole. Since in this research, the material used for mover is made from SS400, the saturation value is about 1.8 T. Thus, this model has reached the saturation value for flux density.

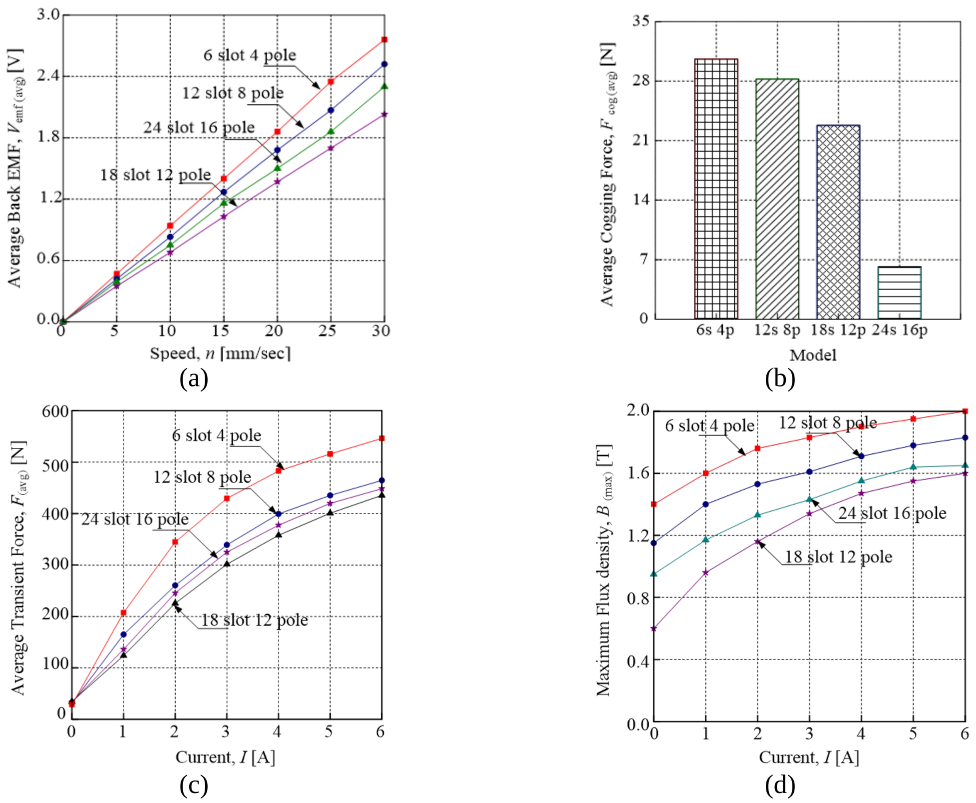

Figure 5. Characteristic of LPMSM: (a) back EMF, (b) cogging force, (c) transient force, and (d) magnetic flux density

3.2. Constants of LPMSM

There are two types of constants that are analyzed in this research. There are back emf constant and force constant. The back emf constant is the ratio of voltage generated in the winding to the speed of the mover. The (6) shows the relationship between back emf and speed. Meanwhile, the force constant is defined as the ratio of the force delivered by a motor to the current supplied. This ratio can be found by determining the slope (7) of the relationship between the torque value and the current.

$$k_e = \frac{V_{emf}}{n} \qquad [\text{V/m/sec}] \tag{6}$$

$$k_t = \frac{F}{I} \qquad [\text{N/A}] \tag{7}$$

Where k_e is the back emf constant in [V/mm/sec], k_t is the force constant in [N/A], V_{emf} is the back emf in [V], n is the speed in [m/sec], F is the force in [N] and I is the current in [A].

Table 4 shows k_e and k_t for all model of LPMSM. Based on Table 4, 6 slot 4 pole has the highest back emf constant compared to others which is 0.00916 V/m/sec. The percentage between the highest and the lowest back emf constant is 26.63 %. Meanwhile, the highest and the lowest force constant is 6 slot 4 pole and 12 slot 8 pole, respectively. Each of them produced 67.742 N/A and 59.944 N/A. From this analysis, it can be synthesis that the the higher the number of slot and pole, the higher the back emf constant and force constant.

Table 4. Summarization of LPMSM constant in this research

Model	Back EMF constant, k_e [V/m/sec]	Force constant, k_t [N/A]
6 slot 4 pole	0.00916	67.742
12 slot 8 pole	0.0084	59.944
18 slot 12 pole	0.00672	62.468
24 slot 16 pole	0.00764	62.28

4. CONCLUSION

In this study, there are 4 types of LPMSM that are studied in terms of their structure and analyze its performance, including back emf, cogging force, transient force and magnetic flux density. The symmetrical of the back emf vector should be used to select the combination slot and pole. The back emf constant and force constant are highest in the 6 slot 4 pole configuration. Meanwhile, the 24 slot 16 pole has the lowest back emf constant and force constant. The combination of slot and pole is important in the design of the LPMSM. This LPMSM will be used in the application of a household elevator. Because a small LPMSM will be used as a motor for the household elevator, this LPMSM will take up less space.

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