Recent Development of Linear Machine Topologies and Applications

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(Invited)

***Abstract*—Linear machines (LMs) produce linear motion without any intermediate transmission mechanisms, thus the whole electromechanical system has simple structure and its efficiency is high. Because of such merits, linear machines have been studied for a long time and rapidly developed in recent years. Due to the characteristic of open structure, linear machines have more diversity than rotary machines in terms of machine topologies. Accounting for the wide applications of linear machines, e.g. Maglev train, precision machine tools, semiconductor processing device, automatic equipment, logistic transport line, ropeless lifter, compressor, etc., this paper reviews the most applied linear machines including machine topologies, operating principle and features. In addition, the influence of end effects and the corresponding reduction methods are also summarized. Finally, several commercial applications are exemplified.**

***Index Terms*—Application, linear induction machine, linear machine, linear synchronous machine, topologies.**

I. Introduction

LINEAR motions are required in many applications, which are normally indirectly obtained by rotary machines with the auxiliary of ball screws, belts or chains. With these intermediate transmission mechanisms, not only the system efficiency is low, but also the velocity, acceleration and precision of actuators are limited. Therefore, to some applications with special requirements, this traditional method is not suitable so that linear machines (LMs) should be adopted to drive the load directly. Such system is direct drive type [1]. For example, the high speed maglev train can obtain higher operation velocity than ordinary high speed train by using linear synchronous machines (LSMs). The digital machine tools can accelerate faster than traditional ones if adopting permanent magnet linear machines (PMLMs), while the semiconductor processing equipment using these machines can also realize high speed and high precision operation. For public transportation systems, the metros driven by linear induction machines (LIMs) can realize smaller turning radius and better grade ability than traditional types.

In general, LMs can be obtained by virtually cutting and stretching the corresponding rotary machines. The part with armature winding similar to stator is called primary, and the portion corresponding to rotor is named as secondary. Since the motion is relative, either primary or secondary is fixed and the other part will move. In order to keep constant thrust force, one of two parts should be shorter than the other one, called short primary or short secondary LMs. Each type of LMs has its own advantages, therefore which topology is chosen depends on the requirement of applications.

Taking various linear machine topologies into account, this paper reviews several typical types, viz. LIMs, LSMs and linear oscillating machines (LOMs) [2]. Furthermore, several commercial applications of LMs are introduced to show the development potential of such direct drive linear machines.

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II. Linear Induction Machines

Fig.1 shows the structure of a classical short primary LIM [3]. The travelling magnetic field is produced by short primary. The long secondary is composed of electric conduction layer (copper or aluminum) and magnetic conduction layer (ferromagnetic material). Under the travelling magnetic field, the eddy current is induced in the secondary, and then the electromagnetic thrust force is produced. If the primary is fixed, the secondary will be driven by this thrust force and it moves in the same direction as this travelling magnetic field. Otherwise, the primary will move in the opposite direction to this travelling magnetic field with fixed secondary. LIMs are widely applied in industry since they have the merits of simple structure, low cost, high reliability and so on. Due to the feature of open structure, the air gap is larger than that of rotary machines, which makes the power factor and thrust force density low. Moreover, the solid secondary generates high eddy current loss resulting in low machine efficiency.

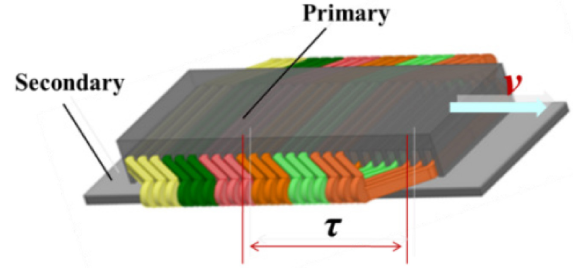


Fig. 1. Classical structure of a LIM.

The velocity of magnetic field, v_s, is determined by the armature current frequency and pole pitch. Different from rotary machines, the number of pole pairs is not related to v_s and only affects the thrust force when the pole pitch and primary lamination width are fixed. The relationship between mover velocity and travelling magnetic field velocity is shown as follows:

$$v = (1-s)2\tau f \tag{1}$$

where s is slip, τ is pole pitch and f is armature current frequency.

Due to the solid secondary structure, the slip is bigger than that of rotary machine, thus LIMs have relatively soft thrust force-current characteristics and the starting thrust force usually has the biggest value.

Fig. 2 shows the main classifications of LIMs [3]. In terms of machine topologies, LIMs can use single-sided planar, double-sided planar, tubular, disc or arc structures. Considering the relative length between primary and secondary, LIMs can use short primary or short secondary. Classifying LIMs based on secondary material, they can be made of steel, non-ferromagnetic metal, compound or squirrel cage. For the compound secondary, the whole solid conduction layer or ladder-slit conduction layer can be adopted. When it comes to primary, LIMs can use slotted or slotless cores. LIMs can also be distinguished according to different cooling methods, viz. natural, air-forced, water-cooled or oil-cooled. Moreover, due to inherently without the unbalanced magnetic force (UMF) problem existing in rotary machines, the primary of LIMs can have odd pole number, such as 3, 5, 7 and so on. Taking the combinations of above terms into account, LIMs can have quite a few different topologies. Since each topology has its own specialties, the specific applications will determine the adopted structure.

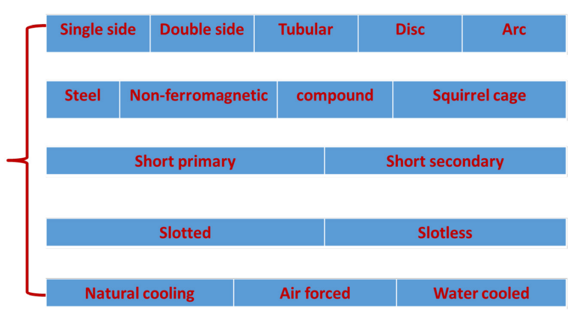


Fig. 2. LIM topology classification.

The performances of LIMs are greatly influenced by two kinds of end effects which are special issues in all of linear machines, called transverse edge effect and longitudinal end effect. The transverse edge effect is decided by the ratio of the overhang length of secondary in transverse direction to the primary pitch. If the ratio is big, normally over than 0.4, the transverse edge effect can be ignored, otherwise it should be considered in design. The longitudinal end effect is caused by two discontinuous ends due to opening iron core. With such structure, the 3-phase magnetic circuits become asymmetric. In addition, the flux densities at two ends are obviously distorted during the operation, while it decreases at the entry end and vice versa at the exit end. Apparently, the longitudinal end effect is decided by pole pair numbers and relative velocity.

Fig.3 shows the influence of transverse edge effect on a LIM at stating state, which is predicted by 2D finite element analysis (FEA) [3]. In this figure, the result without transverse edge effect is obtained by not correcting the conductivities of secondary. It clearly shows that the thrust force predicted with such method is quite different from that considering transverse edge effect. The transverse edge effect makes the thrust force decreased at low slip frequency and increased at big slip frequency. Moreover, the normal force is much increased owing to this effect. It can be concluded that the apparent transverse edge effect of this LIM is caused by the small secondary overhang length.

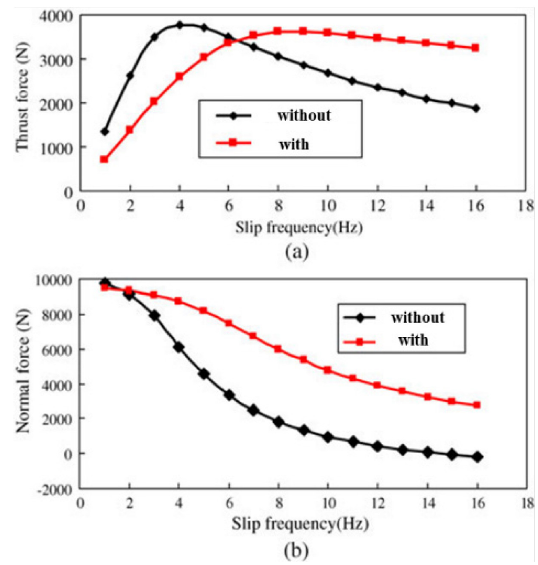


Fig. 3. Effect of transverse edge effect. (a) Thrust force. (b) Normal force.

Fig. 4 shows the influence of longitudinal end effect of the same LIM at staring state. Without considering the longitudinal end effect, both the thrust force and the normal force are increased. However, the difference is not as big as that of transverse edge effect. The reason for small longitudinal end effect is big pole pair number.

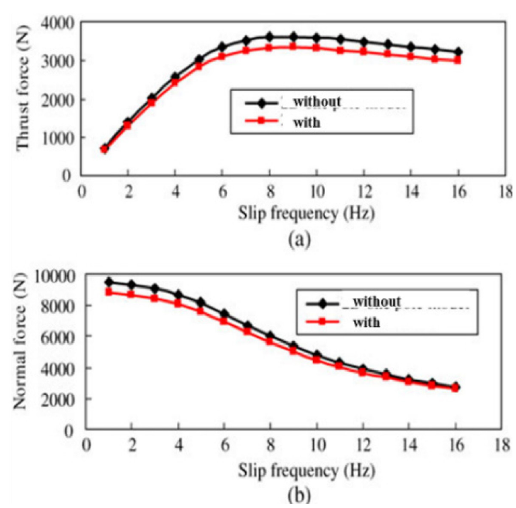
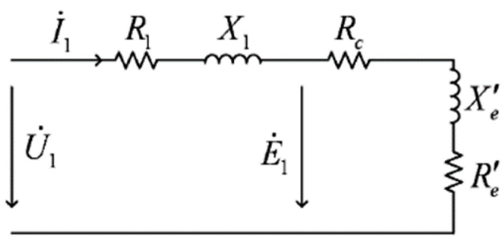
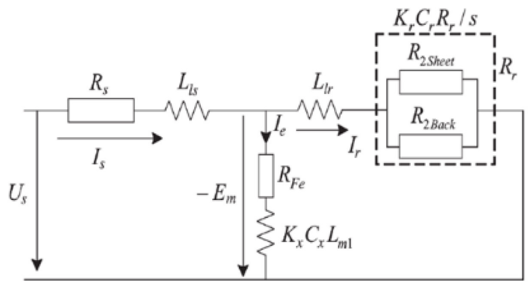


Fig. 4. Effect of longitudinal end effect. (a) Thrust force. (b) Normal force.

During the design and analysis process by equivalent circuit model, the end effects are considered by using correction factors. Generally speaking, the equivalent circuit adopts series type or T-type, as shown in Fig. 5 [4]. In series type, two impedances are added. One is for transverse edge effect and the other is for longitudinal end effect, and then equivalent impedance (R_e'+jX_e') is used. In T-type, there are two correction factors for transverse edge effect and two factors for longitudinal end effect. It can be seen that the correction factors are very important to the performance calculation.



(a)



(b)

Fig. 5. Typical equivalent circuits. (a) Series type. (b) T-type.

For LIMs, the investigations mainly focus on new secondary structure, precise calculation method of end effects, loss analysis, performance prediction under special conditions, control methods and special applications [5-7], including electromagnetic launch, low speed maglev train, intelligent stereo garage and so on.

III. Linear Synchronous Machines

Compared with LIMs, the merits of LSMs have higher thrust density, higher efficiency and higher power factor, though the manufacture cost is higher. The travelling magnetic field is also produced by primary currents and its velocity is only depends on the pole pitch and current frequency.

$$v_s = 2\tau f \tag{2}$$

The mover velocity is same to magnetic field velocity, and the moving direction can be determined in the same way as LIMs. The LSMs have more alternative topologies than LIMs, as shown in Fig. 6. They are research hot spots in recent years. According to the operating principle, LSMs can be divided into four groups: conventional, flux-switching, flux-reversal and Vernier type, respectively. The latter three categories are also called primary PM structure and have lower cost than conventional one.

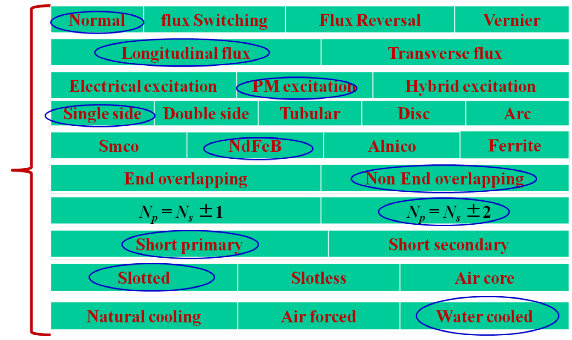


Fig. 6. LSM topology classification.

A. Conventional LSMs

The electrically excited conventional LSMs have almost the same primary as LIMs, but the secondary needs to adopt electromagnets with DC current excitation to produce the magnetic field. Since the secondary structure is complicated, they are normally used for large power devices, such as high speed maglev train [8], as shown in Fig. 7. The long primary, called long stator, mounted on the rail are powered with ground switch stations, while the electromagnets fixed in the train body are supplied with DC current from the train power supply instrument. With these LSMs, the thrust force and levitation force are produced together. In the same time, the linear generators located on the surface of electromagnets will collect energy for the sake of realizing the contactless power supply of the vehicle.

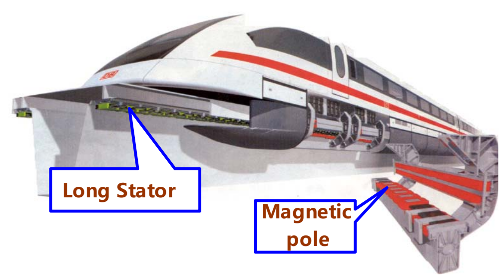


Fig. 7. Electrically excited LSMs.

PMLM is one of the most popular LSMs due to the merits of simple structure, high thrust density and high efficiency [9]. However, they also have disadvantages, such as large normal force, secondary ferromagnetic material impurity and large thrust ripple. Along with the development of PM materials, control methods and sensor techniques, PMLMs have already been widely used in precision machine tools and semiconductor device production.

When the slot pitch is close to pole pitch in PMLMs, their primaries can adopt end non-overlapping windings, as shown in Fig. 8, which is classical iron-core structure. As a consequence of small pole pitch, the frequency of primary current is obviously increased if keep the same velocity as the situation in large pole pitch PMLMs. In order to improve the thrust force density, the water-cooled systems are often installed on the primary back-iron. In general, thrust force density can be improved near three times under such circumstance.

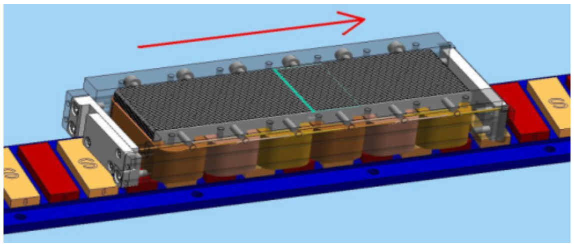


Fig. 8. PMLM with end non-overlapping windings.

The primary slot number and secondary pole number of the PMLM shown in Fig. 8 are close, viz. just differed by one or two. More specifically, if the primary slot number is 6, then the combinations of primary slot number and PM pole number can be 6-slot/4-pole (6s/4p), 6s/5p, 6s/7p, 6s/8p. Within these combinations, the 6s/5p, 6s/7p can have higher force density and lower thrust ripple. Moreover, they are only suitable for linear format due to intrinsically getting rid of unbalanced magnetic force (UMF) for LMs. Besides, the slot number can be odd as well. For example, the adoption of 9-slot primary can utilize 9s/7p, 9s/8p, 9s/10p and 9s/11p combinations. Therefore, the slot/pole combinations of PMLMs have more choices than rotary PM machines.

The issue in PMLMs is the large detent force, which includes the end force and cogging force. If the fractional-slot winding is used, the cogging force is relatively smaller than end force. That is why the research of reducing end force is one of most important things in the PMLM design. In general, the reduction of detent force due to end effect can adopt these methods: suitable slot/pole combination, optimal primary lamination length, skewed PMs or step skewed PMs, skewed slots, optimal width and position of end teeth, shaping end teeth, adding assistant teeth, and so forth. For double-sided PMLMs, the two primary sides can have a shifted angle to reduce the end effect force [10], as shown in Fig. 9.

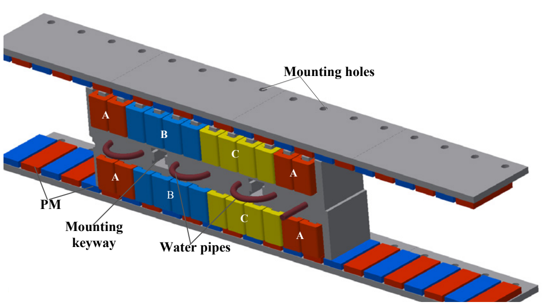
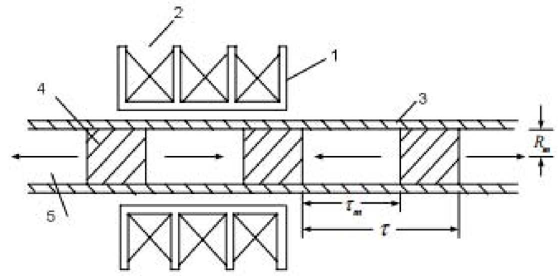


Fig. 9. Double-sided PMLMs with shifted ends.

PMLMs also can adopt air-core structure in order to improve the dynamic response ability [11]. Fig. 10(a) shows the planar structure, often called U-channel PMLMs. Fig.10(b) shows the tubular structure. In this kind of PMLM, the mover is only composed by windings. That is why the weight of mover is low and the thrust force is almost linearly proportional to the current. These PMLMs have already been widely used in automatic manufacture equipment and are the most common PMLM products.

(a)



(b)

Fig. 10. Air-core PMLMs. (a) Planar structure. (b) Tubular structure.

B. Linear Flux-switching Machines

For the conventional LSMs, they have either long armature or long PMs, since the armature and PMs are separated. Consequently, the cost is high. In order to lower the cost, flux-switching linear machines (FSLMs) which place both PMs and armature in short primary have attracted increasing attention [12], where PMs are sandwiched inserted in the middle of primary teeth. This type of LSMs can adopt single-sided, double-sided with yoke, yokeless double-sided format, etc. [13]. In order to overcome the high temperature rise of PMs which is caused by direct contact between PMs and armature windings, the structure of FSLMs can be further improved by separating the primary into two parts, which is called primary-partitioned FSLM (PPFSLM). PPFSLM can also adopt planar and tubular format, as shown in Fig. 11 [14-15].

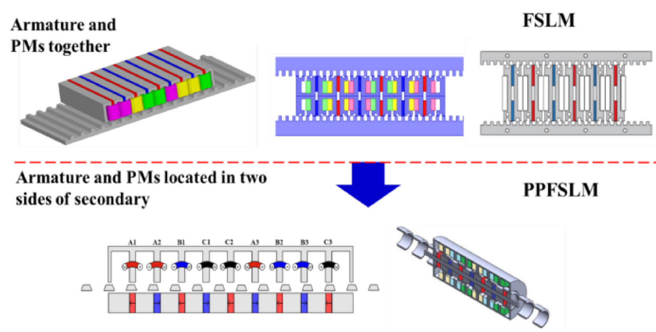


Fig. 11. Topologies of FSLMs.

The cost is much lower for FSLMs, especially in long stroke applications. However, the primary is consisted of many separated parts, thus the manufacture becomes difficult and the performance is easy to be affected by manufacture tolerance. For PPFSLM, since the armature and PMs are located in separate side referring to secondary, the armature structure is the same as that of conventional traditional PMLM and the manufacture will be easy. The long secondary only consists of separated iron pieces. From this point of view, PPFSLM is not only low cost, but also easily to be manufactured.

C. Linear Flux-reversal Machines

Flux-reversal linear machines (FRLMs) are also low cost structure. They suit long stroke application as well. The secondaries of FRLMs have the similar structures as FSLMs, whereas the position of PMs on the primary is different [16].

Normally, the PMs are surface-mounted on the primary tooth or inserted in the primary tooth surface with opposite polarity pairs. Single-sided, double-sided with yoke, transverse flux format, etc. can be adopted. Since the PMs are easily affected by armature current resulting in irreversible demagnetization, the primary-partitioned FRLM (PPFRLM) is also proposed by separating the primary into two parts. Both planar and tubular format can be adopted, as shown in Fig. 12 [17].

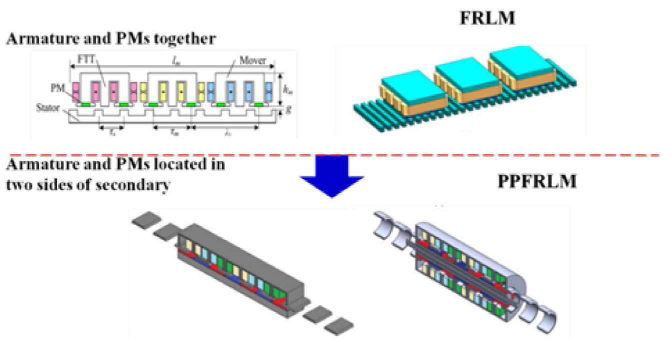


Fig. 12. Topologies of FRLMs.

For such kind of LSMs, both the armature structure and PMs are the same as those of conventional PMLMs. The difference is the long secondary which is composed by many separated iron segments between partitioned primaries. Therefore, the manufacture is much easier than that of FRLM.

D.Linear Vernier Machines

Vernier linear machines (VLMs) are put forward to improve the thrust force density at low velocity, which can separate the armature and PMs into two parts or put them together in the same primary [18]. The former topology is similar to conventional PMLM, while the number of PMs is much higher than slot number. The latter one arranges both armature and PMs in the short primary, where PMs are surface-mounted on teeth or inserted in the teeth surface. The structures are similar to those of FRLMs. Nevertheless, the number of PMs is larger. That is to say, each PM has small volume. Apparently, only the latter one can keep the advantage of low cost. VLMs can also adopt single-sided, double-sided, and tubular format, as shown in Fig. 13.

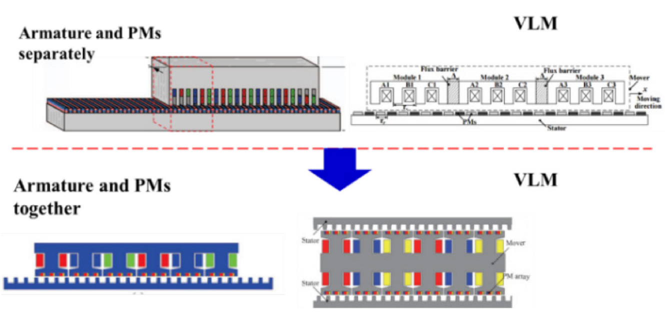


Fig. 13. Topologies of VLMs.

Besides the FSLMs, FRLMs and VLMs, the variable-flux linear machines (VFLMs) with PMs located in slot openings, viz. slot opening PM linear machines (SOPMLMs), are also investigated [19], as show in Fig. 14. Compared with conventional PMLMs, the difference is putting PMs in the slot openings. As a consequence, the structure is simple and the manufacture is easy. Moreover, there is no open-circuit attractive force, which can make the installation easy and improves the fault tolerance at high velocity. This is due to no back-EMF if there is no armature current under inverter faults.

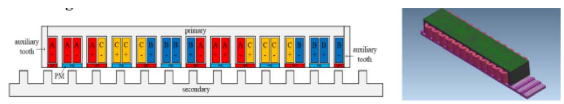


Fig. 14. Topology of SOPMLM.

E. Hybrid excitation LMs

The hybrid excitation LMs (HELMs) are proposed in order to combine the advantages of PM excitation and electrical excitation. Since each PMLM or electrically excited LM has its own corresponding HELMs, a vast number of topologies exist.

When electrically excited LMs are applied in high speed maglev train, the HELMs can insert PMs into electromagnet teeth to lower the levitation power supply. Since the shape and position of PMs can be different, there are several alternative topologies.

In FSLMs, the E-core 3-phase HEFSLM, E-core 9-phase HEFSLM and double-sided yokeless HEFSLM are presented in [19] and [20], as shown in Fig. 15. In E-core hybrid excitation structure, both DC and armature winding are located in the primary slot, thus they should be optimized for maximal thrust force. In double-sided HEFSLM, the DC winding occupies some space which PMs should use in the conventional PMLMs. The thrust density is lower, though the speed range is extended.

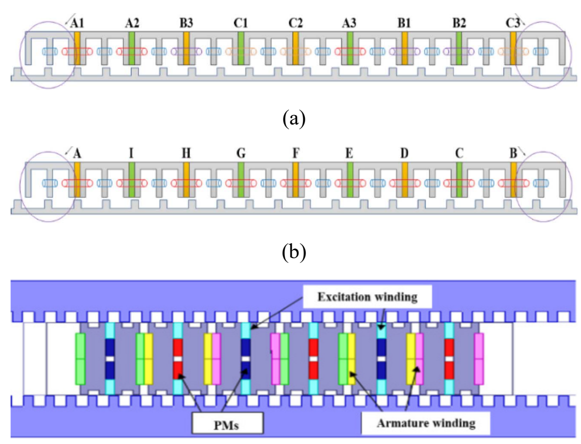


Fig. 15. Different HEFSLMs. (a) E-core 3-phase HEFSLM. (b) E-core 9-phase HEFSLM. (c) Double-sided HEFSLM.

The investigations of LSMs mainly focus on new topologies, end effect analysis and reduction techniques, thermal performance improvement and accurate loss calculation, high performance control methods and so on [21-23].

IV. Linear Oscillating Machines

LOMs directly produce the short stroke linear oscillating motion, which can be applied in compressor, lens and phone camera. Usually, the magnetic field of LOMs is established by

PMs, while armature coils are supplied with DC or AC currents to produce thrust force [24]. According to the mover type, there are four kinds of classical structures: moving coil, moving iron, moving coil and iron, and moving PM type, as shown in Fig. 16.

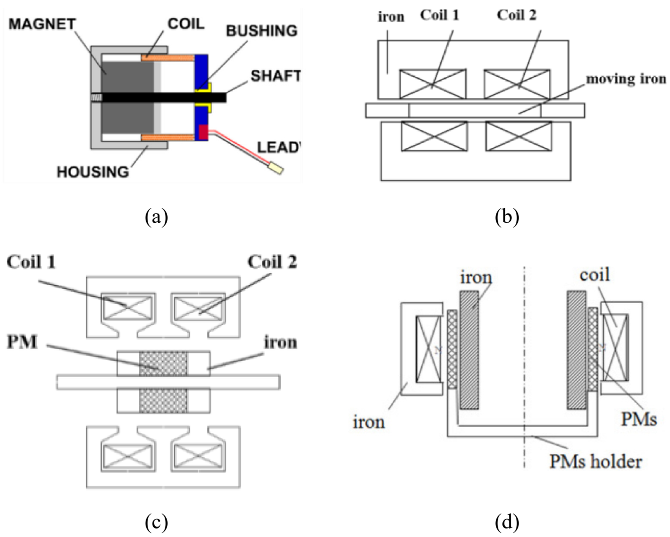


Fig. 16. Different topologies of LOMs. (a) Moving coil type. (b) Moving iron type. (c) Moving coil and iron type. (d) Moving PM type.

The moving coil LOM is called voice coil machine whose oscillating frequency is high due to light mass of mover. However, the fast moving coil needs to be powered, thus the reliability is low. For moving iron structure, the moving part is heavy and the oscillating frequency is low, whereas the reliability is high. The mass of mover is much heavy for moving coil and iron type, and the frequency is also low. In order to obtain both high oscillating frequency and high reliability, the moving PM structure is proposed, which is focused by many researchers. Similar to above mentioned LMs, each LOM topology has its own suitable applications accounting for the special characteristics. Based on these classical structures, there are several new topologies being proposed, for instance, double-stator transverse flux structure, flux-switching structure, E-core structure [24]-[25].

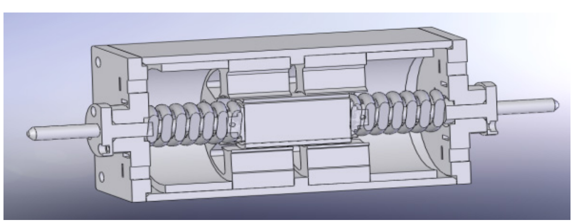


Fig. 17. Double-stator transverse-flux LOM.

In terms of LOM investigations, research topics focus on new structures, optimal design, sensorless control, intelligent control, high efficiency control and so forth.

V. Linear Machine Applications

LMs are widely applied due to the advantages of direct drive. Among the commercial applications, low speed and high speed maglev trains, linear metro, machine tools, semiconductor devices and refrigerators attract much attention.

Fig. 18 shows a commercial transportation line in China and the corresponding applied LIMs. In one carriage, there are ten LIMs and ten levitation magnets.

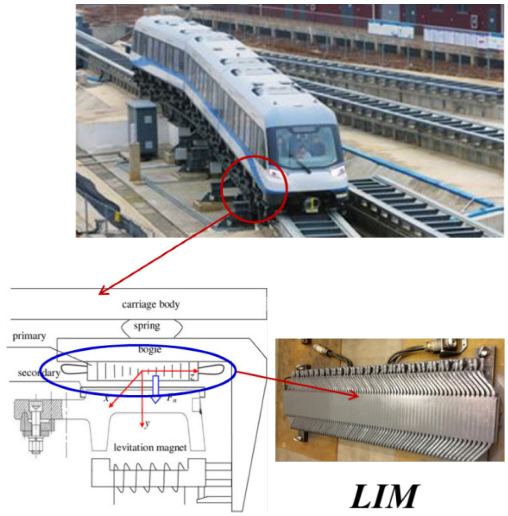


Fig. 18. Commercial transportation line and applied LIMs.

In order to lower the weight, the armature windings of LIMs and excitation windings of levitation magnets are made of aluminum. For these ten LIMs, every five LIMs are located in one side of carriage and connected in series as a branch. Therefore, the rated line voltage is only 220V. The short primaries of linear induction motors are fixed under the bogie in the train, and the long secondary is fixed on the surface of F-shaped rail. When the train is suspended by levitation magnets and LIMs are supplied with variable frequency power supply, the thrust force is produced to drive the train without friction.

Fig. 19 is the linear metro and the employed LIMs [4]. The short primaries of LIMs are fixed with the bogie under the train. There are two bogies at two ends of carriage, thus there are two LIMs in one carriage. Thus, the output power per LIM is much bigger than that in low speed maglev train. The two LIMs are connected in parallel, so that the rated line voltage is 1100V. The long compound secondary is located in the middle of the rail, which includes aluminum layer and steel layer.

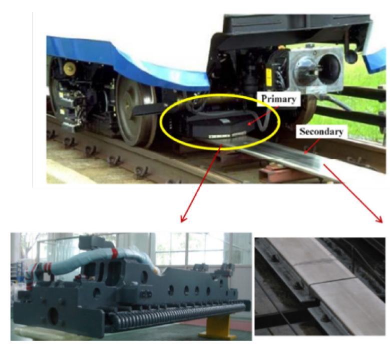


Fig. 19. Linear metro and the employed LIMs.

LIMs are also successfully applied in the logistics transport lines of airports, post services, car parking devices, factories, electromagnetic launch systems, etc.

The high speed maglev train and corresponding LSMs have been shown in Fig. 8. For this LSM, since the long stator is primary, the subsection power supply technology is adopted to improve the system efficiency.

Fig. 21 shows the high speed precise 3D machine tool and the used iron-core PMLMs [26]-[27]. The iron-core PMLMs have the merits of high acceleration, high velocity and high thrust force density. In this application, the linear bearing is adopted to keep small uniform air gap, and the linear grating is used to measure the mover position. When PMLMs are supplied with controllable power source, the load is driven according to the given motion track. This PMLM should not only output large thrust force, but keep high precision motion as well. Apart from Sodick Ltd., several companies also successfully develop machine tools driven by PMLMs, including DMG, Siemens, Fanuc, Ingersoll, Mazak, MAG / Ex-Cell-O and so on.

Fig. 20. The machining tool driven by PMLMs and iron-core PMLMs.

Fig. 21 shows the semiconductor device which is driven by air-core PMLMs [28]. The air-core PMLMs have the advantages of high acceleration, high velocity and high dynamic response ability, which are the most common LM products. Compared with iron-core PMLMs, the size of linear bearing is small because of small normal force. Super high precise sensor may be adopted due to the requirement of high accuracy position, such as photoetching machine. Besides photoetching machine, the semiconductor devices also include electronic processing equipment, LCD processing equipment, wafer cutting equipment, etc.

Fig. 21. Semiconductor device.

Fig. 22 shows the linear compressor and the corresponding LOMs produced by LG company [29]-[30]. As can be seen, this LOM has out stator and inner stator, and the moving PMs mounted on a light non-ferromagnetic frame between two stators. Since the moving part only includes PMs and light non-ferromagnetic frame, the moving mass is low, therefore the oscillating frequency is improved. LG company successfully applies this LOM in refrigerator to realize low noise and high efficiency operation. However, this LOM with moving PMs has double air gaps, which reduces the thrust force density. What is more, the manufacture of lamination is relatively difficult owing to adopting radial laminated method.

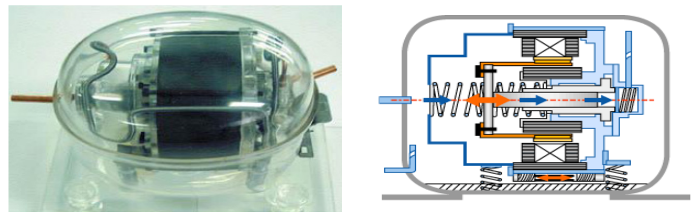


Fig. 22. Linear compressor and its diagram.

VI. Conclusions

Linear machines can directly drive the load without any indirect transmission instruments. Due to the features of open structures, LMs have many different topologies. Each topology has its own advantages, and is suitable to different applications. In recent years, the research mainly focuses on new topologies, optimal design, end effect calculation method and depression technology, the thermal management, high performance control method. Among all of LMs, PMLMs are most concerned and developed quickly.

LMs have already been applied in maglev train, precision machine tools, semiconductor processing device, automatic equipment, logistic transport line, ropeless lifter, linear compressor, phone cameras etc. It can be expected that more applications of LMs will be found in the future with the development of this kind of promising direct drive electrical machines.

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