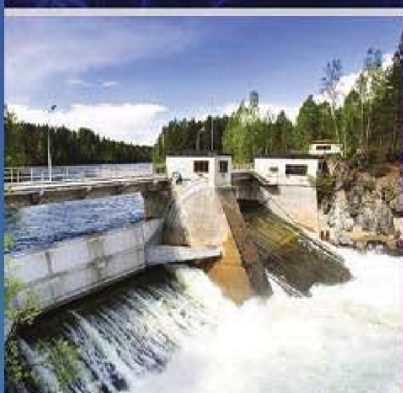
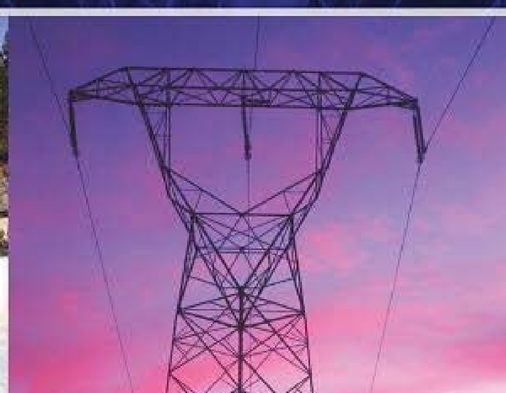
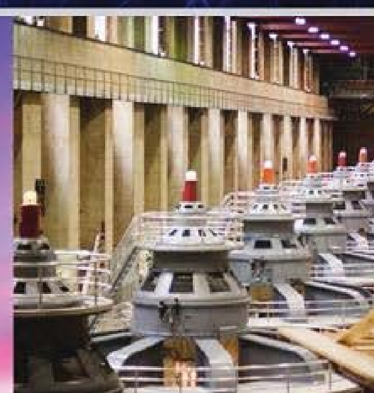
The Electric Power Engineering Handbook

ELECTRIC POWER GENERATION, TRANSMISSION, AND DISTRIBUTION

THIRD EDITION

EDITED BY **LEONARD L. GRIGSBY**

CRC Press
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Preface

The generation, delivery, and utilization of electric power and energy remain one of the most challenging and exciting fields of electrical engineering. The astounding technological developments of our age are highly dependent upon a safe, reliable, and economic supply of electric power. The objective of the Electric Power Engineering Handbook is to provide a contemporary overview of this far-reaching field as well as a useful guide and educational resource for its study. It is intended to define electric power engineering by bringing together the core of knowledge from all of the many topics encompassed by the field. The chapters are written primarily for the electric power engineering professional who seeks factual information, and secondarily for the professional from other engineering disciplines who wants an overview of the entire field or specific information on one aspect of it.

The first and second editions of this handbook were well received by readers worldwide. Based upon this reception and the many recent advances in electric power engineering technology and applications, it was decided that the time was right to produce a third edition. Because of the efforts of many individuals, the result is a major revision. There are completely new chapters covering such topics as FACTS, smart grid, energy harvesting, distribution system protection, electricity pricing, linear machines. In addition, the majority of the existing chapters have been revised and updated. Many of these are major revisions.

The handbook consists of a set of five books. Each is organized into topical parts and chapters in an attempt to provide comprehensive coverage of the generation, transformation, transmission, distribution, and utilization of electric power and energy as well as the modeling, analysis, planning, design, monitoring, and control of electric power systems. The individual chapters are different from most technical publications. They are not journal-type articles nor are they textbooks in nature. They are intended to be tutorials or overviews providing ready access to needed information while at the same time providing sufficient references for more in-depth coverage of the topic.

This book is devoted to the subjects of power system protection, power system dynamics and stability, and power system operation and control. If your particular topic of interest is not included in this list, please refer to the list of companion books referred to at the beginning.

In reading the individual chapters of this handbook, I have been most favorably impressed by how well the authors have accomplished the goals that were set. Their contributions are, of course, key to the success of the book. I gratefully acknowledge their outstanding efforts. Likewise, the expertise and dedication of the editorial board and section editors have been critical in making this handbook possible. To all of them I express my profound thanks.

They are as follows:

- Nonconventional Power Generation — Saifur Rahman
- Conventional Power Generation — Rama Ramakumar
- Transmission Systems — George G. Karady
- Distribution Systems — William H. Kersting

• Electric Power Utilization	Andrew P. Hanson
• Power Quality	S. Mark Halpin
• *Transformer Engineering* (a complete book)	James H. Harlow
• *Substations Engineering* (a complete book)	John D. McDonald
• Power System Analysis and Simulation	Andrew P. Hanson
• Power System Transients	Pritindra Chowdhuri
• Power System Planning (Reliability)	Gerry Sheblé
• Power Electronics	R. Mark Nelms
• Power System Protection	Miroslav M. Begovic*
• Power System Dynamics and Stability	Prabha S. Kundur†
• Power System Operation and Control	Bruce Wollenberg

I wish to say a special thank-you to Nora Konopka, engineering publisher for CRC Press/Taylor & Francis, whose dedication and diligence literally gave this edition life. I also express my gratitude to the other personnel at Taylor & Francis who have been involved in the production of this book, with a special word of thanks to Jessica Vakili. Their patience and perseverance have made this task most pleasant.

Finally, I thank my longtime friend and colleague—Mel Olken, editor, the *Power and Energy Magazine*—for graciously providing the picture for the cover of this book.

* Arun Phadke for the first and second editions.
† Richard Farmer for the first and second editions.

Editor

Leonard L. ("Leo") Grigsby received his BS and MS in electrical engineering from Texas Tech University, Lubbock, Texas and his PhD from Oklahoma State University, Stillwater, Oklahoma. He has taught electrical engineering at Texas Tech University, Oklahoma State University, and Virginia Polytechnic Institute and University. He has been at Auburn University since 1984, first as the Georgia power distinguished professor, later as the Alabama power distinguished professor, and currently as professor emeritus of electrical engineering. He also spent nine months during 1990 at the University of Tokyo as the Tokyo Electric Power Company endowed chair of electrical engineering. His teaching interests are in network analysis, control systems, and power engineering.

During his teaching career, Professor Grigsby received 13 awards for teaching excellence. These include his selection for the university-wide William E. Wine Award for Teaching Excellence at Virginia Polytechnic Institute and University in 1980, the ASEE AT&T Award for Teaching Excellence in 1986, the 1988 Edison Electric Institute Power Engineering Educator Award, the 1990–1991 Distinguished Graduate Lectureship at Auburn University, the 1995 IEEE Region 3 Joseph M. Beidenbach Outstanding Engineering Educator Award, the 1996 Birdsong Superior Teaching Award at Auburn University, and the IEEE Power Engineering Society Outstanding Power Engineering Educator Award in 2003.

Professor Grigsby is a fellow of the Institute of Electrical and Electronics Engineers (IEEE). During 1998–1999, he was a member of the board of directors of IEEE as the director of Division VII for power and energy. He has served the institute in 30 different offices at the chapter, section, regional, and international levels. For this service, he has received seven distinguished service awards, such as the IEEE Centennial Medal in 1984, the Power Engineering Society Meritorious Service Award in 1994, and the IEEE Millennium Medal in 2000.

During his academic career, Professor Grigsby has conducted research in a variety of projects related to the application of network and control theory to modeling, simulation, optimization, and control of electric power systems. He has been the major advisor for 35 MS and 21 PhD graduates. With his students and colleagues, he has published over 120 technical papers and a textbook on introductory network theory. He is currently the series editor for the Electrical Engineering Handbook Series published by CRC Press. In 1993, he was inducted into the Electrical Engineering Academy at Texas Tech University for distinguished contributions to electrical engineering.

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34

Linear Electric Motors

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Linear electric motors belong to the group of special electrical machines that convert electrical energy directly into mechanical energy of translatory motion. Linear electric motors can drive a linear-motion load without intermediate gears, screws, or crank shafts. Linear electric motors can be classified as follows:

- DC motors
- Induction motors
- Synchronous motors, including reluctance and stepping motors
- Oscillating motors
- Hybrid motors

The application of DC linear motor is marginal. The most popular are permanent magnet (PM) linear synchronous motors (LSMs) and linear induction motors (LIMs), which are manufactured commercially in several countries and are finding many applications.

A linear motor can be obtained by cutting a rotary motor along its radius from the center axis of the shaft to the external surface of the stator core and rolling it out flat (Figure 34.1).

34.1 Linear Synchronous Motors

34.1.1 Basic Geometries and Constructions

An LSM is a linear motor in which the mechanical motion is in synchronism with the magnetic field, i.e., the mechanical speed is the same as the speed of the traveling magnetic field. The thrust (propulsion force) can be generated as an action of

- Traveling magnetic field produced by a polyphase winding and an array of magnetic poles N, S, …, N, S or a variable reluctance ferromagnetic rail (LSMs with AC armature windings)
- Magnetic field produced by electronically switched DC windings and an array of magnetic poles N, S, …, N, S or variable reluctance ferromagnetic rail (linear stepping or switched reluctance motors)

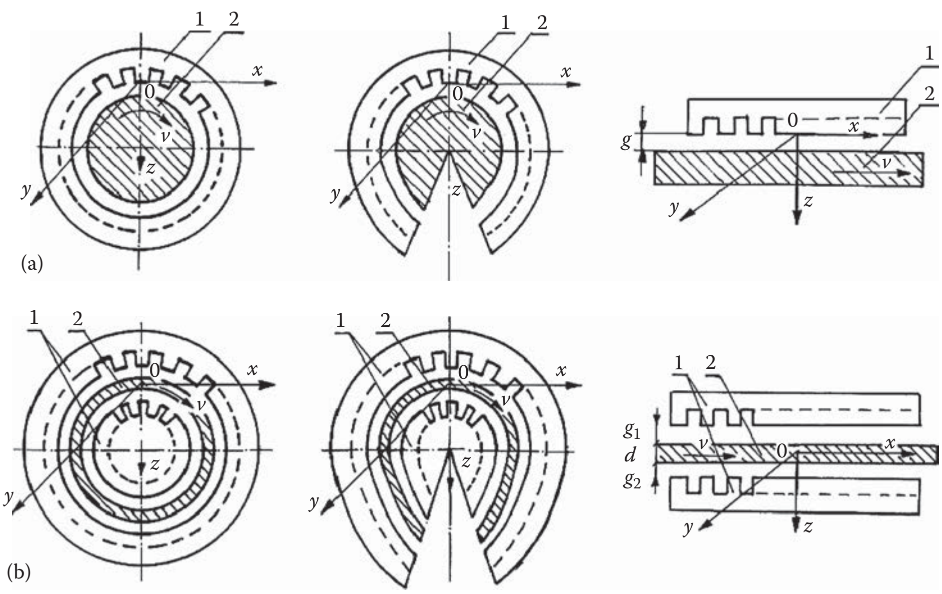


FIGURE 34.1 Evolution of a rotary induction motor: (a) solid-rotor induction motor into a flat, single-sided LIM and (b) hollow-rotor induction motor into a flat double-sided LIM. 1, primary; 2, secondary.

The part producing the traveling magnetic field is called the *armature* or *forcer*. The part that provides the DC magnetic flux or variable reluctance is called the *field excitation system* (if the excitation system exists) or *salient-pole rail, reaction rail*, or *variable reluctance platen*. The terms *primary* and *secondary* should rather be avoided, as they are only justified for LIMs [6] or transformers. The operation of an LSM does not depend on which part is movable and which one is stationary.

Traditionally, AC polyphase synchronous motors are motors with DC electromagnetic excitation, the propulsion force of which has two components: (1) due to the traveling magnetic field and DC current magnetic flux (synchronous component) and (2) due to the traveling magnetic field and variable reluctance in *d*- and *q*-axes (reluctance component). Replacement of DC electromagnets with PMs is common, except for LSMs for magnetically levitated vehicles. PM brushless LSMs can be divided into two groups:

- PM LSMs in which the input current waveforms are sinusoidal and produce a traveling magnetic field
- PM DC linear brushless motors (LBMs) with position feedback, in which the input rectangular or trapezoidal current waveforms are precisely synchronized with the speed and position of the moving part

Construction of magnetic and electric circuits of LSMs belonging to both groups is the same. LSMs can be designed as flat motors (Figure 34.2) or tubular motors (Figure 34.3). In DC brushless motors, the information about the position of the moving part is usually provided by an absolute position sensor. This control scheme corresponds to an *electronic commutation*, functionally equivalent to the mechanical commutation in DC commutator motors. Therefore, motors with square (trapezoidal) current waveforms are called *DC brushless motors*.

Instead of DC or PM excitation, the difference between the *d*- and *q*-axes reluctances and the traveling magnetic field can generate the reluctance component of the thrust. Such a motor is called the AC *variable reluctance* LSM. Different reluctances in the *d*- and *q*-axes can be created by making salient ferromagnetic poles using ferromagnetic and nonferromagnetic materials or using anisotropic ferromagnetic materials. The operation of LBMs can be regarded as a special case of the operation of LSMs.

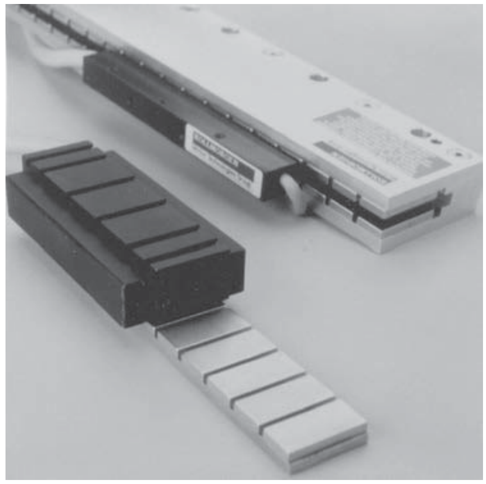


FIGURE 34.2 Flat three-phase PM linear motors. (Photo courtesy of Kollmorgen, Radford, VA.)

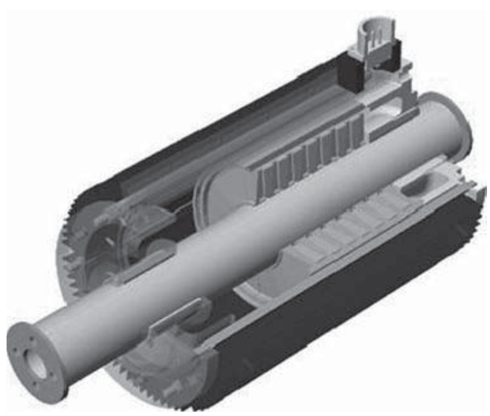


FIGURE 34.3 Tubular PM LSM. Moving rod (reaction rail) contains circular PMs (Photo courtesy of California Linear Drives, Carlsbad, CA.)

In the case of LSMs operating on the principle of the traveling magnetic field, the speed v of the moving part is equal to synchronous speed v_s, i.e.,

$$v = v_s = 2f\tau = \frac{\omega}{\pi}\tau \tag{34.1}$$

The *synchronous speed* v_s of the traveling magnetic field depends only on the input frequency f (angular input frequency $\omega = 2\pi f$) and pole pitch τ. It does not depend on the number of poles $2p$.

As for any other linear-motion electrical machine, the useful force (thrust) F_x is directly proportional to the output power P_{out} and inversely proportional to the speed $v = v_s$, i.e.,

$$F_x = \frac{P_{out}}{v_s} \tag{34.2}$$

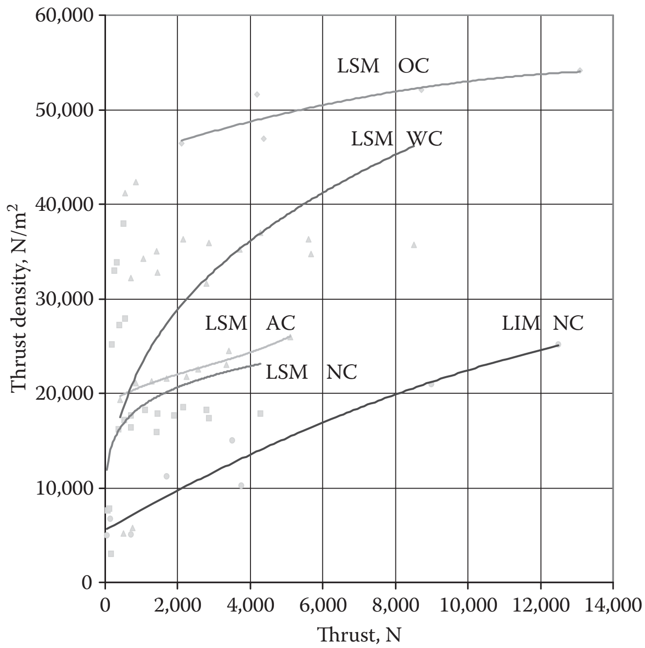


FIGURE 34.4 Comparison of thrust density for single-sided LIMs and LSMs. AC, air cooling; NC, natural cooling; OC, oil cooling; WC, water cooling. (From Gieras, J.F., Status of linear motors in the United States, *International Symposium on Linear Drives for Industry Applications (LDIA'03)*, Birmingham, U.K., pp. 169–176, 2003.)

Direct electromechanical drives with LSMs for factory automation systems can achieve speeds exceeding 600 m/min = 36 km/h and acceleration of up to 360 m/s² [7]. The thrust density, i.e., thrust per active surface $2p\tau L_i$, where L_i is the effective width of the stack.

$$f_x = \frac{F_x}{2p\tau L_i} \quad (\text{N/m}^2) \tag{34.3}$$

of LSMs is higher than that of LIMs (Figure 34.4).

The polyphase (usually three-phase) armature winding can be distributed in slots, made in the form of concentrated-parameter coils or made as a coreless (air-cored) winding layer. PMs are the most popular field excitation systems for short traveling distances (less than 10 m), for example, factory transportation or automation systems. A long PM rail would be expensive. Electromagnetic excitation is used in high-speed passenger transportation systems operating on the principle of magnetic levitation (maglev). The German system, *Transrapid*, uses vehicle-mounted steel core excitation electromagnets and stationary slotted armatures. Japanese MLX001 test train sets use onboard superconducting (SC) air-cored electromagnets and a stationary three-phase air-cored armature winding distributed along the guideway (Yamanashi Maglev Test Line).

34.1.2 Classification

LSMs can be classified according to whether they are

- Flat (planar) or tubular (cylindrical)
- Single sided or double sided
- Slotted or slotless

- Iron cored or air cored
- Transverse flux or longitudinal flux

The topologies mentioned earlier are possible for nearly all types of excitation systems. LSMs operating on the principle of the traveling magnetic field can have the following excitation systems:

- PMs in the reaction rail
- PMs in the armature (passive reaction rail)
- Electromagnetic excitation system (with winding)
- SC excitation system
- Passive reaction rail with saliency and neither PMs nor windings (variable reluctance motors)

LSMs with electronically switched DC armature windings are designed either as linear stepping motors or linear switched reluctance motors.

34.1.2.1 PM Motors with Active Reaction Rail

Figure 34.5a shows a single-sided flat LSM with the armature winding located in slots and surface PMs. Figure 34.5b shows a similar motor with buried-type PMs. In surface arrangement of PMs, the yoke (back iron) of the reaction rail is ferromagnetic, and PMs are magnetized in the normal direction (perpendicular to the active surface). Buried PMs are magnetized in the direction of the traveling magnetic field, and the yoke is nonferromagnetic, for example, made of aluminum (Al). Otherwise, the bottom leakage flux would be greater than the linkage flux, as shown in Figure 34.6. The same effect occurs in buried-type PM rotors of rotary machines in which the shaft must also be nonferromagnetic [2,3,9].

The so-called *Halbach array* of PMs also does not require any ferromagnetic yoke and excites stronger magnetic flux density and closer to the sinusoids than a conventional PM array. The key concept of the Halbach array is that the magnetization vector should rotate as a function of distance along the array (Figure 34.7).

It is recommended that a PM LSM be furnished with a *damper*. A rotary synchronous motor has a cage damper winding embedded in pole shoe slots. When the speed is different from the synchronous speed, electric currents are induced in damper circuits. The action of the armature magnetic field and damper currents allows for asynchronous starting, damps the oscillations, and helps to return to synchronous operation when the speed decreases or increases. Also, a damper circuit reduces the backward-traveling magnetic field. It would be rather difficult to furnish PMs with a cage winding so that the damper of PM LSMs has the form of an Al cover (Figure 34.8a) or solid steel pole shoes (Figure 34.8b). In addition, steel pole shoes or Al cover (shield) can protect brittle PMs against mechanical damage.

The *detent force*, i.e., attractive force between PMs and the armature ferromagnetic teeth, force ripple, and some higher-space harmonics, can be reduced with the aid of skewed assembly of PMs. Skewed PMs can be arranged in one row (Figure 34.9a), two rows (Figure 34.9b), or even more rows.

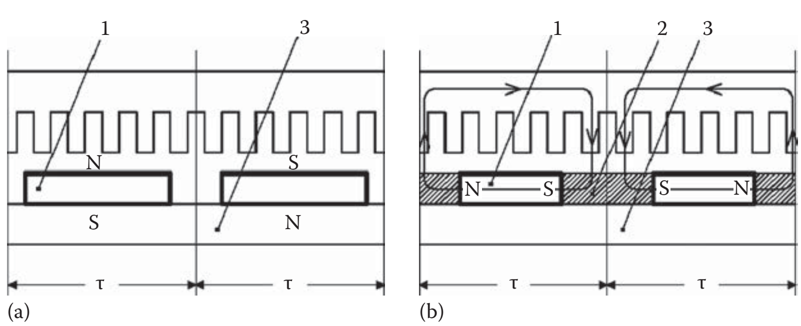


FIGURE 34.5 Single-sided flat PM LSMs with slotted armature core and (a) surface PMs and (b) buried PMs. 1, PM; 2, mild steel pole; 3, yoke.

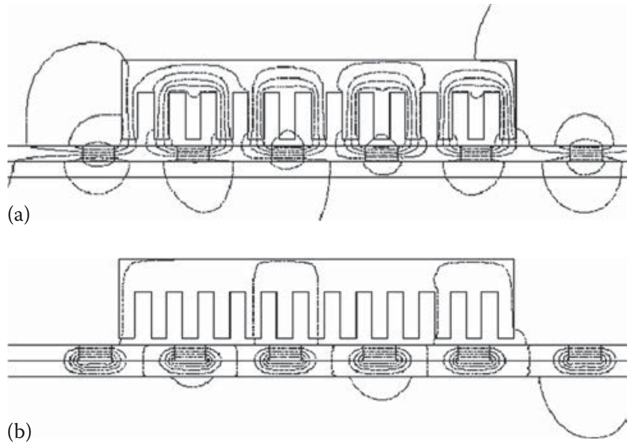


FIGURE 34.6 Magnetic flux distribution in the longitudinal sections of buried-type PM LSMs: (a) nonferromagnetic yoke and (b) ferromagnetic yoke (back iron).

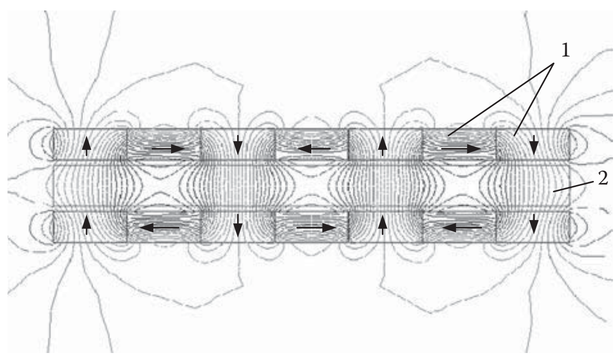


FIGURE 34.7 Double-sided LSM with Halbach array of PMs. 1, PMs; 2, coreless armature winding.

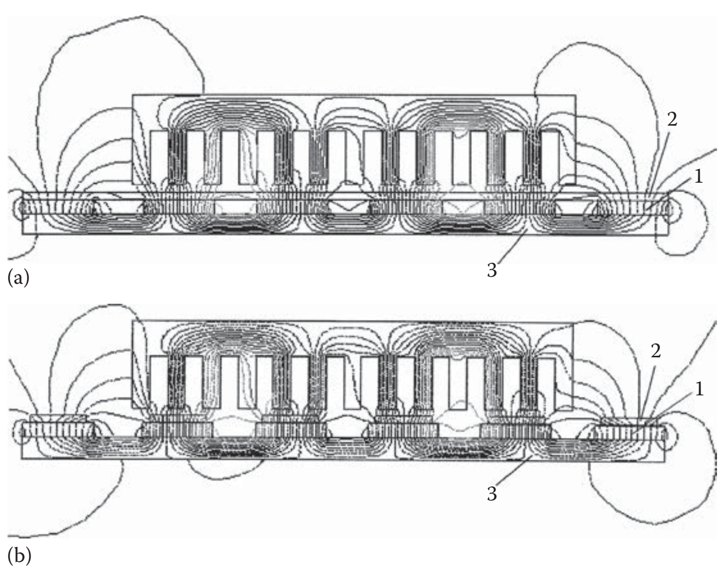


FIGURE 34.8 Dampers of surface-type PM LSMs: (a) Al cover (shield) and (b) solid steel pole shoes. 1, PM; 2, damper; 3, yoke.

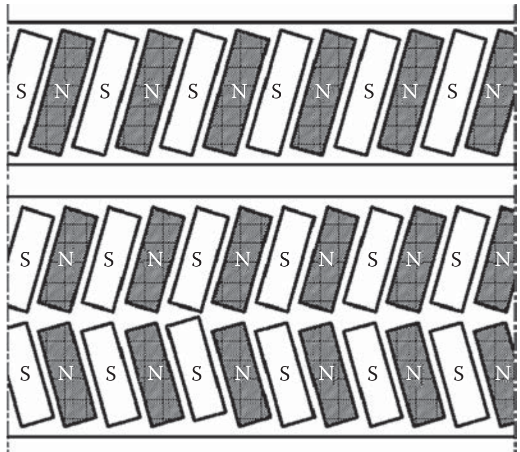


FIGURE 34.9 Skewed PMs in flat LSMs: (a) one row and (b) two rows.

TABLE 34.1 Flat Three-Phase, Single-Sided PM LBMs with Natural Cooling Systems Manufactured by Anorad, Hauppauge, NY

Parameter	LCD-T-1	LCD-T-2-P	LCD-T-3-P	LCD-T-4-P
Continuous thrust at 25°C, N	163	245	327	490
Continuous current at 25°C, A	4.2	6.3	8.5	12.7
Continuous thrust at 125°C, N	139	208	277	416
Continuous current at 125°C, A	3.6	5.4	7.2	10.8
Peak thrust (0.25 s), N	303	455	606	909
Peak current (0.25 s), A	9.2	13.8	18.4	27.6
Peak force (1.0 s), N	248	373	497	745
Peak current (1.0 s), A	7.3	11.0	14.7	22.0
Continuous power losses at 125°C, W	58	87	115	173
Armature constant, k_E, Vs/m	12.9			
Thrust constant (three phases), k_F, N/A	38.6			
Resistance per phase at 25°C, Ω	3.2	2.2	1.6	1.1
Inductance, mH	14.3	9.5	7.1	4.8
PM pole pitch, mm	23.45			
Maximum winding temperature, °C	125			
Armature assembly mass, kg	1.8	2.4	3.6	4.8
PM assembly mass, kg/m	6.4			
Normal attractive force, N	1036	1555	2073	3109

Specification data of flat, single-sided PM LBMs manufactured by Anorad are shown in Table 34.1 [1], and motors manufactured by Kollmorgen are shown in Table 34.2 [11]. The temperature 25°C, 125°C, or 130°C for the thrust, current, resistance, and power loss is the temperature of the armature winding.

The electromotive force (EMF) constant k_E in Tables 34.1 and 34.2 for sinusoidal operation is defined according to the equation expressing the EMF (induced voltage) excited by PMs without the armature reaction, i.e.,

$$E_f = k_E v_s \tag{34.4}$$

where v_s is the synchronous speed according to Equation 34.1. Thus, the armature constant k_E multiplied by the synchronous speed v_s gives the EMF E_f.

TABLE 34.2 Flat Three-Phase, Single-Sided PM LBMs with Natural Cooling Systems Manufactured by Kollmorgen, Radford, VA

Parameter	IC11-030	IC11-050	IC11-100	IC11-200
Continuous thrust at 130°C, N	150	275	600	1260
Continuous current at 130°C, A	4.0	4.4	4.8	5.0
Peak thrust, N	300	500	1000	2000
Peak current, A	7.9	7.9	7.9	7.9
Continuous power losses at 130°C, W	64	106	210	418
Armature constant, at 25°C, k_E, Vs/m	30.9	51.4	102.8	205.7
Thrust constant (three phases) at 25°C, k_F, N/A	37.8	62.9	125.9	251.9
Resistance, line to line, at 25°C, Ω	1.9	2.6	4.4	8.0
Inductance, line to line, mH	17.3	27.8	54.1	106.6
Electrical time constant, ms	8.9	10.5	12.3	13.4
Thermal resistance winding to external structure, °C/W	1.64	0.99	0.50	0.25
Maximum winding temperature, °C	130			
Armature assembly mass, kg	2.0	3.2	6.2	12.2
PM assembly mass, kg/m	5.5	7.6	12.8	26.9
Normal attractive force, N	1440	2430	4900	9850

The thrust constant k_F in Tables 34.1 and 34.2 is defined according to the simplified equation for the developed electromagnetic thrust, i.e.,

$$F_{dx} = k_F I_a \cos \Psi \tag{34.5}$$

for a sinusoidally excited LSM with equal reluctances in the *d*- and *q*-axes and for the angle between the armature current I_a and the *q*-axis $\Psi = 0°$ ($\cos \Psi = 1$). Thus, the thrust constant k_F times the armature current I_a gives the electromagnetic thrust developed by the LSM.

Double-sided, flat PM LSMs consist of two external armature systems and one internal excitation system (Figure 34.10a), or one internal armature system and two external excitation systems (Figure 34.10b). In the second case, a linear Gramme's armature winding can be used.

In *slotless motors*, the primary winding is uniformly distributed on a smooth armature core or does not have any armature core. Slotless PM LSMs are detent force–free motors, provide lower torque ripple, and, at high input frequency, can achieve higher efficiency than slotted LSMs. On the other hand, larger nonferromagnetic air gap requires more PM material, and the thrust density (thrust per mass or volume) is lower than that of slotted motors (Table 34.3). The input current is higher as synchronous reactances

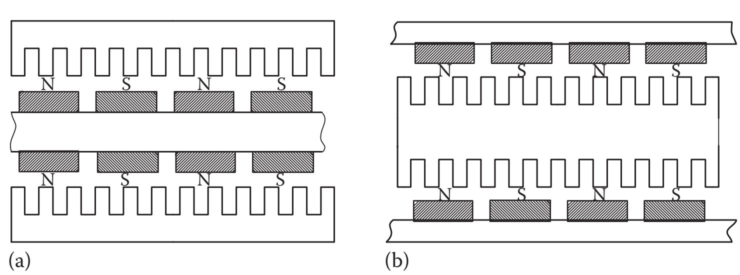


FIGURE 34.10 Double-sided flat PM LSMs with (a) two external armature systems and (b) one internal armature system.

TABLE 34.3 Slotted versus Slotless LSMs

Quantity	Slotted LSM	Slotless LSM
Higher thrust density	X	
Higher efficiency in the lower speed range	X	
Higher efficiency in the higher speed range		x
Lower input current	X	
Less PM material	X	
Lower winding cost		x
Lower thrust pulsations		x
Lower acoustic noise		x

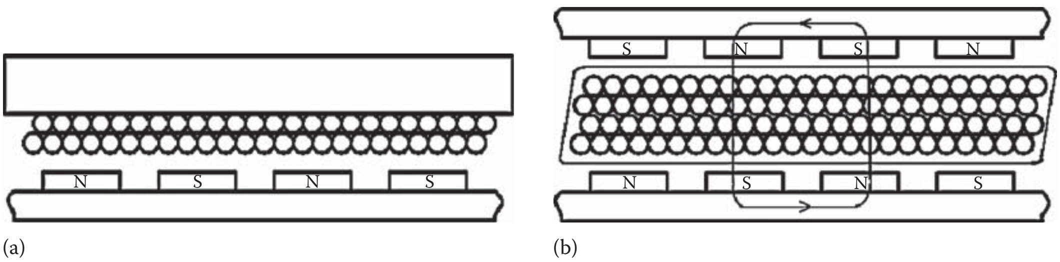


FIGURE 34.11 Flat slotless PM LSMs: (a) single-sided with armature core and (b) double-sided with inner air-cored armature winding.

in the *d*- and *q*-axes can decrease to a low undesired value due to the absence of teeth. Figure 34.11a shows a single-sided flat slotless motor with armature core, and Figure 34.11b shows a double-sided slotless motor with inner air-cored armature winding (moving coil motor).

Table 34.4 contains performance specifications of double-sided PM LBMs with inner three-phase air-cored armature winding manufactured by Trilogy Systems Corporation, Webster, TX (Figure 34.12).

TABLE 34.4 Flat Double-Sided PM LBMs with Inner Three-Phase Air-Cored Series-Coil Armature Winding Manufactured by Trilogy Systems Corporation, Webster, TX

Parameter	310-2	310-4	310-6
Continuous thrust, N	111.2	209.1	314.9
Continuous power for sinusoidal operation, W	87	152	230
Peak thrust, N	356	712	1068
Peak power, W	900	1800	2700
Peak/continuous current, A	10.0/2.8	10.0/2.6	10.0/2.6
Thrust constant k_F for sinusoidal operation, N/A	40.0	80.0	120.0
Thrust constant k_F for trapezoidal operation with Hall sensors, N/A	35.1	72.5	109.5
Resistance per phase, Ω	8.6	17.2	25.8
Inductance ±0.5 mH	6.0	12.0	18.0
Heat dissipation constant for natural cooling, W/°C	1.10	2.01	3.01
Heat dissipation constant for forced air cooling, W/°C	1.30	2.40	3.55
Heat dissipation constant for liquid cooling, W/°C	1.54	2.85	4.21
Number of poles	2	4	6
Coil length, mm	142.2	264.2	386.1
Coil mass, kg	0.55	1.03	1.53
Mass of PM excitation systems, kg/m	12.67 or 8.38		

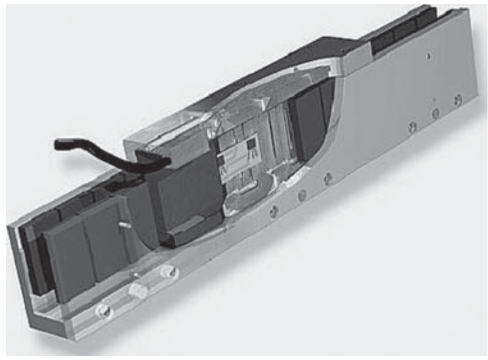


FIGURE 34.12 Flat double-sided PM LSM with inner moving coil. (Photo courtesy of Trilogy Systems, Webster, TX.)

By rolling a flat LSM around the axis parallel to the direction of the traveling magnetic field, i.e., parallel to the direction of thrust, a tubular (cylindrical) LSM can be obtained (Figure 34.13). A tubular PM LSM can also be designed as a double-sided motor or slotless motor.

Tubular single-sided LSMs LinMoT®* with movable internal PM excitation system (slider) and stationary external armature are manufactured by Sulzer Electronics AG, Zurich, Switzerland (Table 34.5). All active motor parts, bearings, position sensors, and electronics have been integrated into a rigid metal cylinder [14].

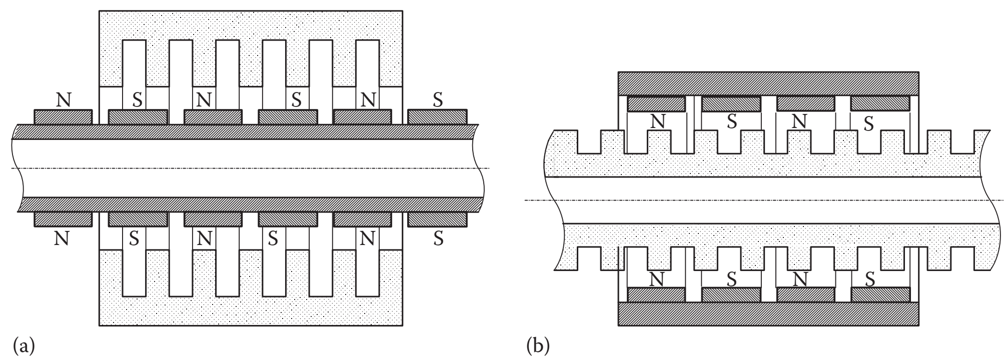
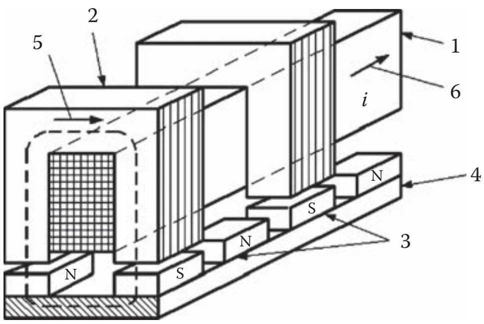


FIGURE 34.13 Single-sided slotted tubular PM LSMs: (a) with external armature system and (b) with external excitation system.

TABLE 34.5 Data of Tubular LSMs LinMot® Manufactured by Sulzer Electronics AG, Zürich, Switzerland

Parameter	P01 23 × 80	P01 23 × 160	P01 37 × 120	P01 37 × 240
Number of phases	2			
PMs	NdFeB			
Maximum stroke, m	0.210	0.340	1.400	1.460
Maximum force, N	33	60	122	204
Maximum acceleration, m/s^2	280	350	247	268
Maximum speed, m/s	2.4	4.2	4.0	3.1
Stator (armature) length, m	0.177	0.257	0.227	0.347
Stator outer diameter, mm	23	23	37	37
Stator mass, kg	0.265	0.450	0.740	1.385
Slider diameter, mm	12	12	20	20
Maximum temperature of the armature winding, °C	90			

* LinMot® is a registered trademark of Sulzer Electronics AG, Zürich, Switzerland.



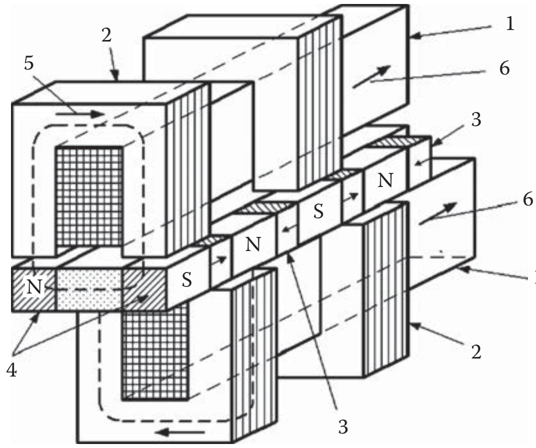


FIGURE 34.14 Transverse flux PM LSM: (a) single-sided and (b) double-sided. 1, armature winding; 2, armature laminated core; 3, PM; 4, back ferromagnetic core; 5, magnetic flux; 6, armature current.

All the aforementioned PM LSMs are motors with *longitudinal magnetic flux*, the lines of which lie in the plane parallel to the direction of the traveling magnetic field. LSMs can also be designed as *transverse magnetic flux* motors, in which the lines of magnetic flux are perpendicular to the direction of the traveling field. Figure 34.14a shows a single-sided transverse flux LSM in which PMs are arranged in two rows. A pair of parallel PMs creates a two pole flux excitation system. A double-sided configuration of transverse flux motor is possible; however, it is complicated and expensive (Figure 34.14b).

34.1.2.2 PM Motors with Passive Reaction Rail

The drawback of PM LSMs is the large amount of PM material that must be used to design the excitation system. Normally, expensive rare-earth PMs are requested. If a small PM LSM uses, say, 10 kg of NdFeB per 1 m of the reaction rail, and 1 kg of good-quality NdFeB costs U.S.$ 130, the cost of the reaction rail without assembly amounts to U.S.$ 1300 per 1 m. This price cannot be acceptable, for example, in passenger transportation systems.

A cheaper solution is to apply the PM excitation system to the short armature that magnetizes the long reaction rail and creates magnetic poles in it. Such a linear motor is called the *homopolar* LSM.

The homopolar LSM as described in [5,17] is a double-sided AC linear motor that consists of two polyphase armature systems connected mechanically and magnetically by a ferromagnetic U-type yoke (Figure 34.15). Each armature consists of a typical slotted linear motor stack with polyphase armature winding and PMs located between the stack and U-type yoke. Since the armature and excitation systems are combined together, the armature stack is oversized as compared with a conventional steel-cored LSM. The PMs can also be replaced by electromagnets [17,19]. The variable reluctance reaction rail is passive. The saliency is created by using ferromagnetic (solid or laminated) cubes separated by a nonferromagnetic material. The reaction rail poles are magnetized by the armature PMs through the air gap. The traveling magnetic field of the polyphase armature winding and salient poles of the reaction rail produce the thrust. Such a homopolar LSM has been proposed for the propulsion of maglev trains of *Swissmetro* [17].

Further simplification of the double-sided configuration can be made to obtain a single-sided PM LSM shown in Figure 34.16.

34.1.3 Flux-Switching PM Linear Motors

Large gantry systems and machining centers require powerful linear motors, preferably with PM-free reaction rail. Siemens 1FN6 PM LSMs with a magnet-free reaction rail belong to the group of the so

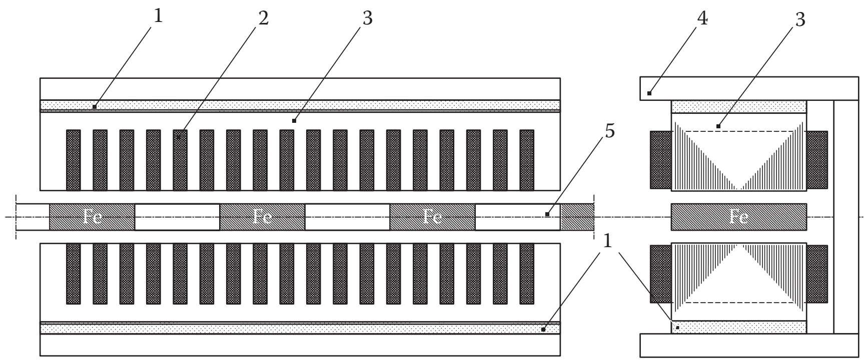


FIGURE 34.15 Double-sided homopolar PM LSM with passive reaction rail. 1, PM; 2, armature winding; 3, armature stack; 4, yoke; 5, reaction rail.

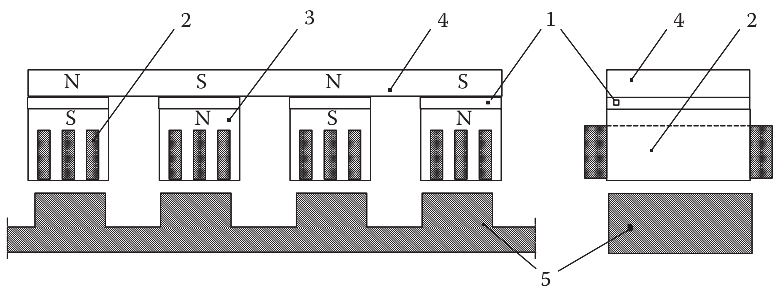


FIGURE 34.16 Single-sided PM LSM with a passive reaction rail. 1, PM; 2, armature winding; 3, armature stack; 4, yoke; 5, ferromagnetic reaction rail.

TABLE 34.6 Specifications of 1FN6 PM LSMs Manufactured by Siemens, Erlangen, Germany

Armature Unit	Rated Thrust N	Max. Thrust N	Max. Speed at Rated Thrust m/min	Max. Speed at Max. Thrust m/min	Rated Current A	Max. Current A
1FN6008-1LC17	235–350	900	263	103	1.7–2.6	9.0
1FN6008-1LC37	235–350	900	541	224	3.5–5.3	18.0
1FN6016-1LC30	470–710	1800	419	176	5.4–8.0	28.0
1FN6016-1LC17	935–1400	3590	263	101	7.0–10.5	36.0
1FN6024-1LC12	705–1060	2690	176	69	3.5–5.3	18.0
1FN6024-1LC20	705–1060	2690	277	114	5.4–8.0	28.0
1FN6024-1LG10	2110–3170	8080	172	62	10.5–16.0	54.0
1FN6024-1LG17	2110–3170	8080	270	102	16.2–24.3	84.0

Source: Synchronous Linear Motor 1FN6, *The Electrical Gear Rack*, Siemens AG Industry Sector, Drive Technologies, Motion Control, Erlangen, Germany, 2008.

called *flux-switching PM machines* [10,16]. The armature system is air cooled, degree of protection IP23, class of insulation F, line voltage from 400 to 480 V, rated thrust from 235 to 2110 N, maximum velocity at rated thrust from 170 to 540 m/min (Table 34.6), overload capacity 3.8 of rated thrust, modular type construction [20]. These LSMs operate with Siemens *Sinamics* or *Simodrive* solid-state converters and external encoders. According to Siemens [20], these new LSMs produce thrust forces and velocities equivalent to competitive classical models for light-duty machine tool, machine accessory, and material handling applications.

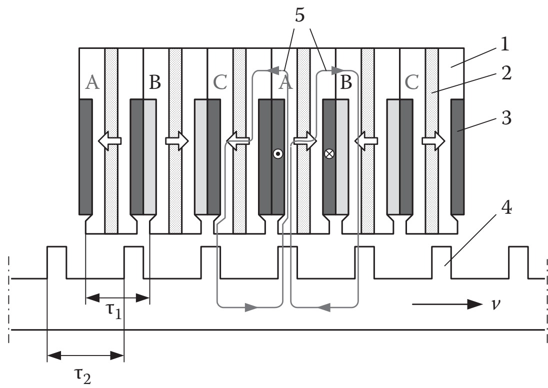


FIGURE 34.17 Construction of flux-switching LSM with PM-free reaction rail. 1, laminated armature core; 2, PM; 3, armature coil (phase C); 4, toothed passive steel reaction rail; 5, linkage magnetic flux (phase A is on).

The magnet-free reaction rail is easy to install and does not require the safety considerations of standard PM reaction rails. Without PMs, there is no problem with ferrous chips and other debris being attracted to these sections. Maintenance becomes a simple matter of installing a wiper or brush on the moving part of the slide.

The flux-switching LSM comprises an armature section that is equipped with coils and PMs as well as a nonmagnetic, toothed reaction rail section (Figure 34.17). The key design innovation is an LSM in which PMs are integrated directly into the lamination of the armature core along with the individual windings for each phase. Both magnitudes and polarities of the linkage flux in the armature winding vary periodically along with the reaction rail movement. The magnetic flux between the armature core and steel reaction rail is controlled by switching the three-phase armature currents according to a designated algorithm. The passive reaction rail consists of milled steel with poles (teeth) and is much simpler to manufacture.

34.1.4 Motors with Electromagnetic Excitation

The electromagnetic excitation system of an LSM is similar to the salient-pole rotor of a rotary synchronous motor. Figure 34.18 shows a flat single-sided LSM with salient ferromagnetic poles and *DC field excitation winding*. The poles and pole shoes can be made of solid steel, laminated steel, or sintered powder. If the electromagnetic excitation system is integrated with the moving part, the DC current can be delivered with the aid of brushes and contact bars, inductive power transfer (IPT) systems, linear transformers, or linear brushless exciters.

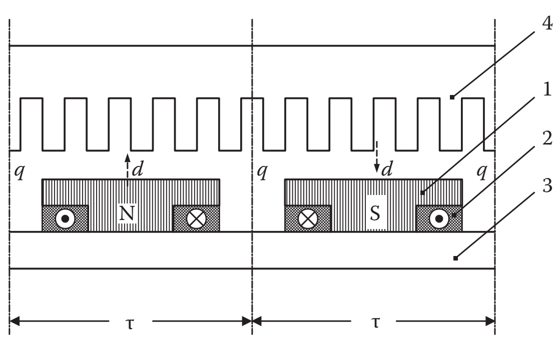


FIGURE 34.18 Electromagnetic excitation system of a flat single-sided iron-cored LSM. 1, salient pole; 2, DC excitation winding; 3, ferromagnetic rail (yoke); 4, armature system.

FIGURE 34.19 Transrapid 09 maglev train driven by LSMs with electromagnetic excitation. (Photo courtesy of Thyssen Transrapid System GmbH, Munich, Germany.)

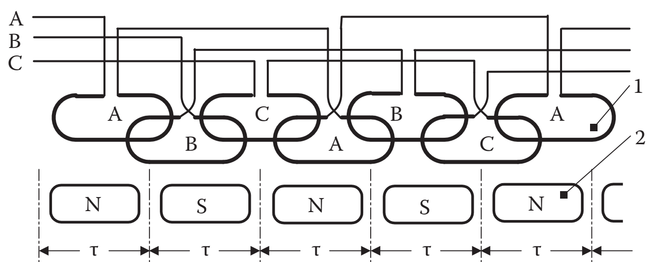


FIGURE 34.20 Three-phase air-cored LSM with SC excitation system. 1, armature coils; 2, SC excitation coils.

LSMs with electromagnetic excitation (wound-field reaction rail) are used in German *Transrapid* maglev train (Figure 34.19).

34.1.5 Motors with Superconducting Excitation System

In large-power LSMs, the electromagnets with ferromagnetic core that produce the excitation flux can be replaced by coreless SC electromagnets. Since the magnetic flux density produced by the SC electromagnet is greater than the saturation magnetic flux density of the best laminated alloys ($B_{sat} \approx 2.4$ T for cobalt alloy), there is no need to use the armature ferromagnetic core. An LSM with SC field excitation system is a totally air-cored machine (Figure 34.20).

Experimental maglev trains on the Yamanashi Maglev Test Line (YMTL) in Yamanashi Prefecture (west from Tokyo), Japan, are driven by air-cored LSMs with SC excitation systems (Figure 34.21).

34.2 Linear Induction Motors

LIMs have found the widest prospects for applications in *transportation systems*, beginning with electrical traction on small passenger or material supply cars (used at airports, exhibitions, electrohighways, elevators) and ending with pallet transportation, wafer transportation, belt conveyors, transportation systems of bulk materials, etc. The second important place for LIM applications is in industry, i.e., *manufacturing processes* (machine tools, hammers, presses, mills, separators, automated manufacturing systems, strip tensioners, textile shuttles, index tables, turntables, disk saws for wood, sliding doors, robots, etc.).

FIGURE 34.21 YMTL in Yamanashi Prefecture (near Tokyo), Japan. YMTL maglev trains use air-cored LSMs with SC excitation system. (Photo courtesy of Central Japan Railway Company and Railway Technical Research Institute, Tokyo, Japan.)

LIMs can also play an important part in *industrial investigations and tests*, for example, high acceleration of model aircraft in aerodynamic tunnels; high acceleration of vessels in laboratory pools; propulsion of mixers, shakers, and vibrators; and adjusting x–y tables and instruments. There is also a possibility of using LIMs in *consumer electronics* (sound and vision equipment, knitting machines, curtains) and in offices (transportation of documents, letters, and cash). The *Handbook of Linear Motor Applications* [21] printed in Japan in 1986 contains about 50 examples of applications of LIMs in operation or in the process of implementation.

34.2.1 Basic Geometries and Constructions

A LIM can be obtained by cutting in the same way either a cage rotor induction motor or a wound rotor induction motor. The stator becomes the *primary*, and the rotor becomes the *secondary* [12]. The secondary of a LIM can be simplified by using a solid steel core and replacing the cage (ladder) or slip-ring winding with a high-conductivity nonferromagnetic plate (Al or Cu). The nonferromagnetic plate is a secondary electric circuit with distributed parameters, and the ferromagnetic core is a conductor both for the magnetic flux and the electric current. It does not matter from the principle of operation point of view which part (primary or secondary) is in motion. Thus, the *flat, single-sided LIM* can be obtained from a solid rotor induction motor (Figure 34.1a) and the *flat, double-sided LIM* can be obtained from a hollow-rotor induction motor with wound external and internal stator (Figure 34.1b). In a double-sided LIM, the secondary ferromagnetic core is not necessary, since the magnetic flux excited by one of the primary windings after passing through the air gaps and nonferromagnetic secondary is then closed up by the core of the second primary unit.

Theoretically, a *double-sided LIM* with primary windings located on two cores, in comparison with a single-sided LIM exciting the same MMF, has twice the air gap magnetic flux density. Therefore, the *thrust* of such a motor is four times greater, assuming the same dimensions. If only one primary core is wound, the output parameters of a double-sided LIM are the same as those for a single-sided LIM with laminated secondary back iron. The fundamental advantage of double-sided LIMs is the elimination of the normal attractive force between the primary and the secondary because the secondary is usually nonferromagnetic.

Flat LIMs can have primary cores consisting of an array of cores arranged in parallel at appropriate distances and connected magnetically by additional yokes perpendicular to the direction of the

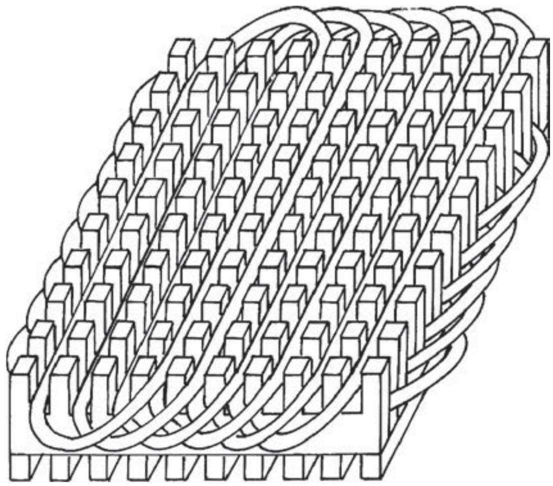


FIGURE 34.22 The primary of a flat LIM with two DOFs.

traveling field. A magnetic circuit designed in such a way makes it possible to apply two windings, in general multiphase windings, with perpendicular conductors, as shown in Figure 34.22. Adjusting the current in each winding, the secondary can be moved in two perpendicular directions and can be positioned at any point of the x–y plane. A *flat LIM with two degrees of freedom* (DOFs) can be designed both as single-sided and double-sided machines.

By rolling a flat, single-sided or double-sided LIM around the axis parallel to the direction of the traveling magnetic field, i.e., parallel to the direction of the thrust, a tubular motor can be obtained (Figure 34.23).

A *tubular (cylindrical) LIM*, similar to a flat LIM, can be designed both as single-sided and double-sided machines and can have a square or rectangular cross section, as in Figure 34.24. There are possible

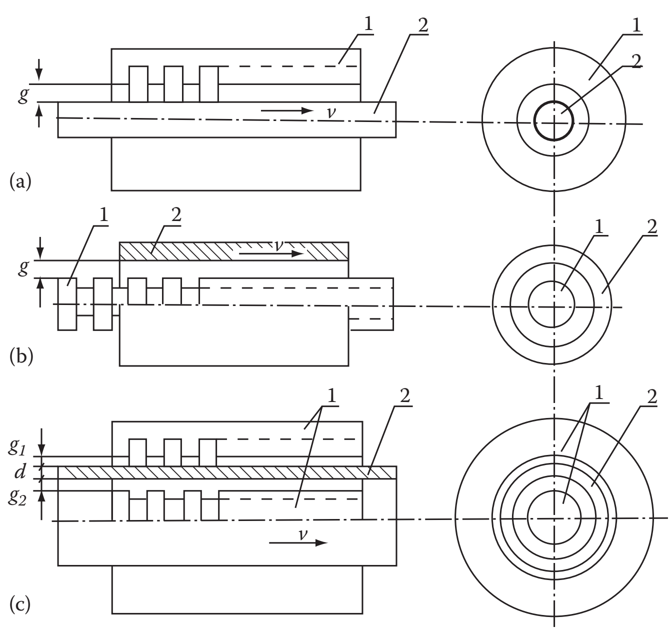


FIGURE 34.23 Tubular LIMs: (a) single-sided with an external short primary, (b) single-sided with an external short secondary, and (c) double-sided with short primary. 1, primary; 2, secondary.

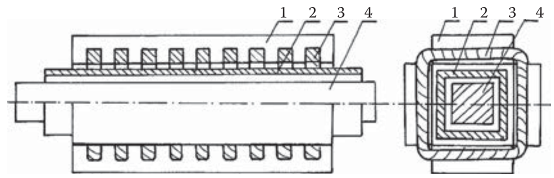


FIGURE 34.24 Tubular, double-sided LIM with a square cross section: 1, primary; 2, secondary; 3, primary coil; 4, internal core.

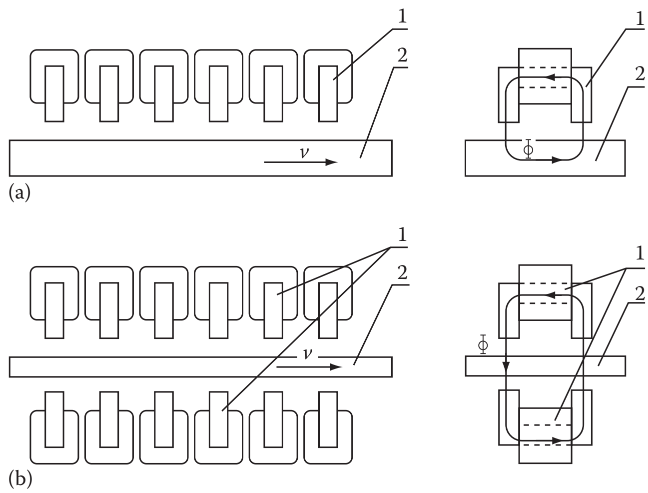


FIGURE 34.25 Flat LIM with transverse magnetic flux and salient poles: (a) single-sided and (b) double-sided. 1, primary; 2, secondary.

configurations other than that in Figure 34.23, regarding the length of the secondary with respect to the length of the primary.

All the aforementioned LIMs are motors with *longitudinal magnetic flux*, i.e., the lines of magnetic flux lie in the plane parallel to the direction of the traveling magnetic field. A LIM can also be designed in such a way as to obtain magnetic flux lines perpendicular to the direction of the traveling field. Such motors are said to have *transverse magnetic flux* (Figure 34.25).

The fundamental advantage of a LIM with transverse magnetic flux in comparison with a LIM with longitudinal magnetic flux is the lower magnetizing current necessary due to the shorter magnetic flux paths. The significant disadvantage is lower thrust. A flat LIM with transverse magnetic flux usually has a primary winding of concentrated coils located on salient poles.

A flat, single-sided LIM with transverse flux can produce not only thrust but also *electrodynamic suspension*. In the design shown in Figure 34.26, the secondary is suspended electrodynamically and propelled and stabilized laterally by the primary magnetic field [8]. The primary magnetic circuit consists of E-shaped laminations assembled in two rows. The short secondary is made of light Al alloy in the form of a boat. The lateral sides of the boat are inclined by 60° with respect to the active surface. Such a shape provides maximum normal repulsive force and maximum lateral stabilization.

According to their geometry, the LIMs can be divided into the following groups:

- With movable primary or movable secondary
- Single sided and double sided
- Flat and tubular
- With short primary and short secondary
- With longitudinal and transverse magnetic flux

FIGURE 34.26 Flat LIM with transverse magnetic flux, salient poles, and nonferromagnetic secondary propelled, suspended, and stabilized electrodynamically. (From Gieras, J.F. et al., Analytical calculation of electrodynamic levitation forces in a special-purpose linear induction motor, *International Electric Machines and Drives Conference (IEMDC'11)*, Niagara Falls, Ontario, Canada, 2011 [on CD-ROM].)

The linear speed of a LIM is

$$v = (1 - s)v_s \tag{34.6}$$

where
s is the slip
v_s is the synchronous speed according to Equation 34.1

Neglecting the *longitudinal end effect* [6], the electromagnetic thrust developed by a LIM can be expressed in a similar way as for a rotary induction motor, i.e.,

$$F_{dx} = \frac{m_1}{v_s}\left(I_2'\right)^2 \frac{R_2'}{s} \tag{34.7}$$

where
m_1 is the number of phases of the primary winding
v_s is the synchronous speed according to Equation 34.1
I_2' is the secondary current referred to the primary system
R_2' is the secondary resistance referred to the primary system
s is the slip

The secondary resistance R_2' must include the so-called *edge effect* [6].

34.2.2 Propulsion of Wheel-on-Rail Vehicles

Modern railway systems and electrical traction should meet the following requirements:

- High level of automatization and computerization
- Propulsion and braking independent of adhesion which in turn is affected, first of all, by climate and weather
- Low level of noise, sometimes below 70 dB (A)

- Ability to cope with high slopes, at least 6%, and sharp bends with radius of curvature less than 20 m
- No pollution to natural environment and landscape
- High reliability

The congestion problems of big cities should be solved by creating collective transport forms that can be implemented without affecting a highly populated city. For example, there are many cities in Italy where the historical center has remained the same since the Renaissance. A heavy railway might be a completely wrong solution and have a notable impact on the city planning. An adequate solution might be a light railway, a *people mover*, with transport capacity of 10,000–20,000 passengers per hour, to replace the traditional transport nets and to integrate the existing railway nets.

All the requirements mentioned earlier can be met by using LIMs as propulsion machines. Replacing electrical rotary motors with linear motors in traction drives (electrical locomotives) generally does not require new tracks but only their adjustment to linear drives. Single-sided LIMs (Figure 34.27a and b) are best, since the normal attractive force of these can strengthen the adhesion of wheels and rails. The air gap is from 10 to 15 mm. Most frequently, the motor car has two LIMs with short primaries (Figure 34.27a) assembled in series. The double-layer secondary consists of a solid back iron and an Al cap and is located between the rails. Cables for computer communication with the vehicle and, quite often, collectors for electrical energy delivery to the vehicle are located along the track. Three-phase LIMs are fed from variable-voltage, variable-frequency (VVVF) voltage-source inverters. A linear propulsion system of wheel-on-rail vehicles allows more flexibility (Figure 34.28), reducing noise on bends and wear of the wheels and rails.

Double-sided LIMs (Figure 34.27c and d) have found very limited application due to the technical difficulty of eliminating faults caused by bends in the secondary with primary cores on either side. It is more difficult to keep a small and uniform air gap in double-sided LIMs than that in single-sided LIMs.

The LIM-*driven wheel-on-rail vehicles* are built for low velocities, i.e., less than 100 km/h, and for short routes, i.e., less than 50 km (urban transit systems and short-distance trains). At present, LIM-driven trains operate in Toronto and Vancouver, BC, Canada; in Detroit, MI (Figure 34.29); Tokyo (Figure 34.30) and Osaka, Japan; and Kuala Lumpur, Malaysia.

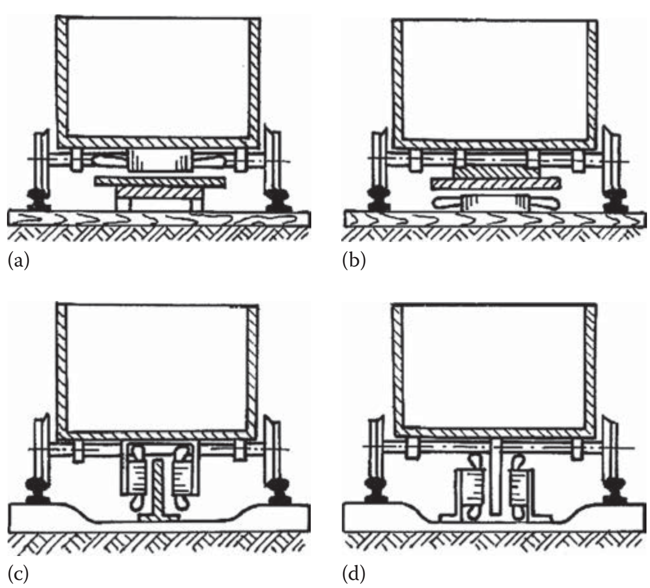
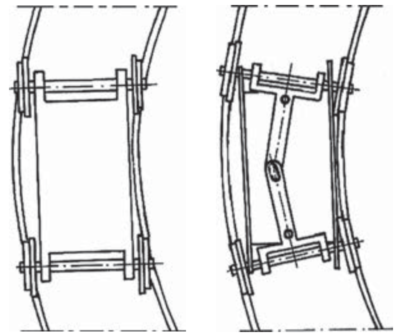


FIGURE 34.27 LIM-driven wheel-on-rail cars: (a) single-sided LIM with short primary mounted on the undercarriage, (b) single-sided LIM with short secondary mounted on the undercarriage, (c) double-sided LIM with short primary mounted on the undercarriage, and (d) double-sided LIM with short secondary mounted on the undercarriage.



(a) (b)

FIGURE 34.28 The undercarriage of a wheel-on-rail vehicle: (a) rotary motor propulsion and (b) LIM propulsion.

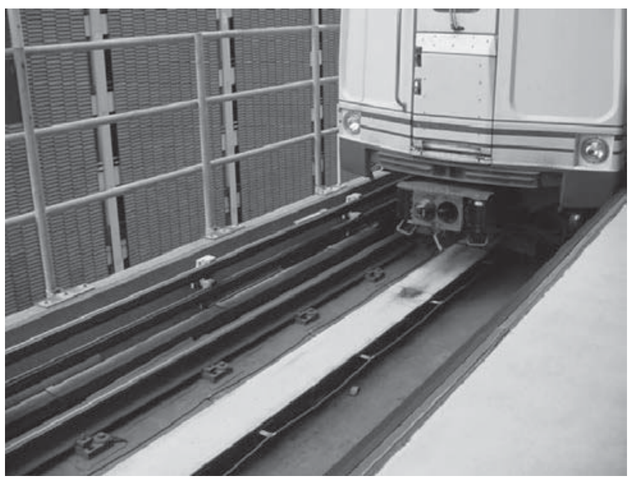


FIGURE 34.29 Detroit people mover driven by single-sided LIMs.

FIGURE 34.30 Toei Oedo subway line in Tokyo driven by single-sided LIMs.

TABLE 34.7 Design Data of Single-Sided, Three-Phase LIMs for Propulsion of Vehicles

	LIM					
Quantity	JLMDR	ICTS	KU	CIGGT	GEC	Unit
Pullout thrust at frequency given in the following, F_x	12.5	9.0	3.5	1.7	0.7	kN
Input frequency, f	20.0	40.0	25.0	40.0	60.0	Hz
Rated phase current, V_1	275.0	465.0	130.0	200.0	200.0	A
Number of poles, $2p$	8	6	4	6	4	—
Number of turns per phase, N_1	128	96	128	108	48	—
Equivalent diameter of conductor, d_1	—	8.93	5.28	1.115	8.1	mm
Number of parallel conductors	—	1	—	19	1	—
Effective width of primary core, L_i	0.23	0.216	0.29	0.101	0.1715	m
Pole pitch, τ	0.27	0.2868	0.30	0.25	0.20	m
Length of single end connection, l_e	—	0.3483	—	0.2955	0.3685	m
Coil pitch, w_c	0.225	0.1673	0.25	0.1944	0.1555	m
Air gap, g	15.0	12.6	12.0	15.0	18.2	mm
Number of slots, $z_1(z_1')$	96(106)	72(79)	48(58)	54(61)	36(43)	—
Width of slot, b_{11}	—	15.6	17.0	15.0	13.08	mm
Width of slot opening, b_{14}	—	15.6	—	10.44	13.08	mm
Depth of slot, h_{11}	—	53.0	38.0	34.21	61.47	mm
Height of yoke, h_{1y}	—	43.6	39.3	71.63	50.0	mm
Conductivity of back iron at 20°C, σ_{Fe}	—	4.46	9.52	4.46	5.12	$\times 10^6$ S/m
Conductivity of Al cap at 20°C, σ_{Al}	—	30.0	30.3	32.3	21.5	$\times 10^6$ S/m
Width of back iron, w	0.3	0.24	0.3	0.111	0.1715	m
Thickness of back iron, h_{sec}	19.0	12.5	25.0	25.4	47.4	mm
Thickness of Al cap, d	5.0	4.5	5.0	4.5(2.5)	3.2	mm
Thickness of Al cap behind Fe core, t_{ov}	5.0	17.0	5.0	12.7	3.2	mm
Width of Al cap	0.30	0.32	0.40	0.201	0.2985	m

JLMDR, Japanese Linear Motor Driven Railcar, Japan; ICTS, Intermediate Capacity Transit System, Canada; KU, Kyushu University LIM, Japan; CIGGT, Canadian Inst. of Guided Ground Transport, Canada; GEC, General Electric Company, United States; (z_1') is the number of half filled slots.

The design data of some single-sided traction LIMs are presented in Table 34.7 and double-sided traction LIMs in Table 34.8.

34.3 Variable Reluctance Motors

The simplest construction of a *variable reluctance LSM or linear reluctance motor* (LRM) is that shown in Figure 34.18 with DC excitation winding being removed. However, the thrust of such a motor would be low as the ratio of d-axis permeance to q-axis permeance is low. Better performance can be obtained when using *flux barriers* [18] or steel laminations [15]. To make flux barriers, any nonferromagnetic materials can be used. To obtain high permeance (low reluctance) in the d-axis and low permeance in the q-axis, steel laminations should be oriented in such a way as to create high permeance for the d-axis magnetic flux.

Figure 34.31a shows a variable reluctance platen with flux barriers, and Figure 34.31b shows how to arrange steel laminations to obtain different reluctances in the d- and q-axes. The platen can be composed of segments, the length of which is equal to the pole pitch τ. Each segment consists of semicircular *lamellas* cut out from electrotechnical sheet. A filling, for example, epoxy resin, is used to make the segment rigid and robust. By putting the segments together, a platen of any desired length can be obtained.

TABLE 34.8 Design Data of Double-Sided, Three-Phase LIMs for Propulsion of Vehicles

	LIM		
Quantity	GEC	LIMVR	Unit
Maximum thrust at input frequency, F_x, given in the following	0.85	16.68	kN
Input frequency, f	60.0	173.0	Hz
Input phase current, I_1	200.0	2000.0	A
Number of poles, $2p$	4	10	—
Number of turns per phase, N_1	144	100	—
Diameter of conductor, d_1	0.75	1.10	mm
Effective width of primary core, L_i	0.0869	0.254	m
Pole pitch, τ	0.1795	0.3556	m
Coil pitch, w_c	0.05	0.05	m
Number of slots, $z_1(z_1')$	36(45)	150(160)	—
Width of slot, b_{11}	13.7	16.0	mm
Width of slot opening, b_{14}	13.7	—	mm
Depth of slot, h_1	63.0	—	mm
Height of yoke, h_{1y}	23.9	—	mm
Width of tooth, c_1	20.0	7.7	mm
Resultant air gap, $2g + d$	38.1	38.075	mm
Air gap, g	2×12.7	2×11.1	mm
Thickness of secondary, d	12.7	15.875(hollow)	mm
Effective thickness of Al secondary	12.7	7.2	mm
Width of secondary, w	$\geq$0.3046	—	m
Conductivity of Al cap at 20°C, σ_{Al}	$\approx$24.34	$\approx$24.0	$\times 10^6$ S/m

GEC, General Electric Company, United States; LIMVR, LIM Research Vehicle, Pueblo, CO, United States; (z_1') is the number of half filled slots.

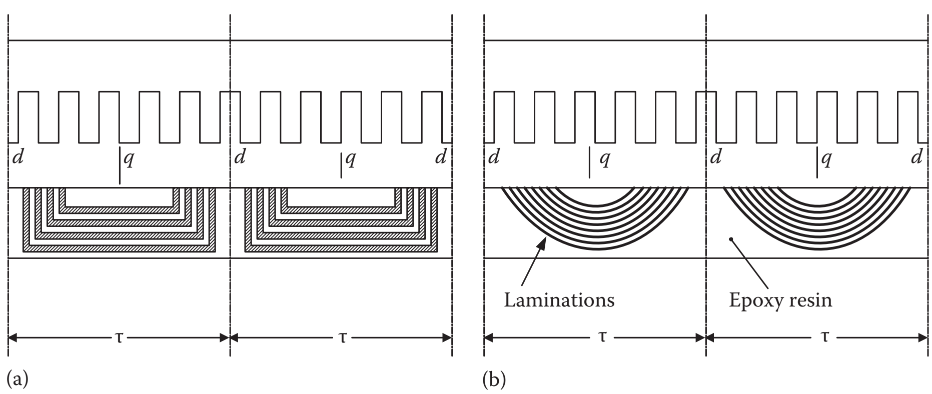


FIGURE 34.31 Variable reluctance LSMs with (a) flux barriers and (b) steel laminations.

34.4 Stepping Motors

A *linear stepping motor* has a concentrated armature winding wound on salient poles and PM excitation rail or variable reluctance platen. The thrust is generated as an action of the armature magnetic flux and PM flux (active platen), or the armature magnetic flux and salient ferromagnetic poles (variable reluctance platen). Stepping motors have no position feedback.

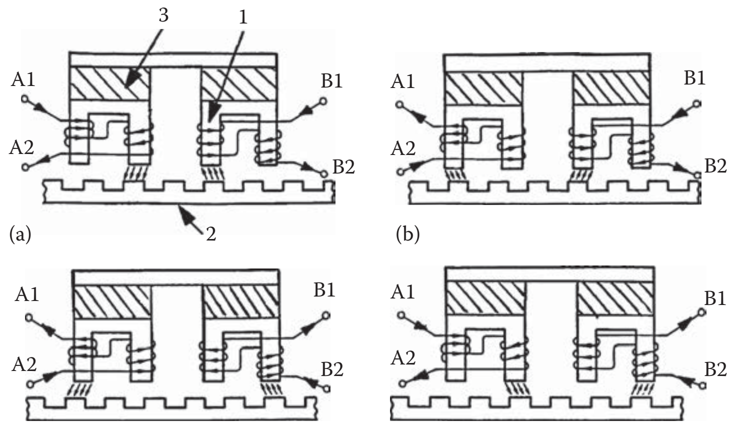


FIGURE 34.32 Principle of operation of an HLSM: (a) initial position, (b) 1/4 tooth pitch displacement of the forcer, (c) 2/4 tooth pitch displacement, and (d) 3/4 tooth pitch displacement. 1, forcer; 2, platen; 3, PM.

So far, only stepping linear motors of hybrid construction (PM, winding and variable reluctance air gap) have found practical applications.

The *hybrid linear stepping motor* (HLSM), as shown in Figure 34.32, consists of two parts: the *forcer* (also called the *slider*) and the variable reluctance platen [4]. Both of them are evenly toothed and made of high-permeability steel. This is an early design of the HLSM, the so-called Sawyer linear motor. The forcer is the moving part with two rare-earth magnets and two concentrated-parameter windings. The tooth pitch of the forcer matches the tooth pitch on the platen. However, the tooth pitches on the forcer poles are spaced 1/4 or 1/2 pitch from one pole to the next. This arrangement allows for the PM flux to be controlled at any level between minimum and maximum by the winding so that the forcer and the platen line up at a maximum permeance position. The HLSM is fed with two-phase currents (90° out of phase), similarly as a rotary stepping motor. The forcer moves 1/4 tooth pitch per each full step.

There is a very small air gap between the two parts that is maintained by strong air flow produced by an air compressor. The average air pressure is about 300–400 kPa and depends on how many phases are excited.

Table 34.9 shows specification data of HLSMs (Figure 34.33) manufactured by Tokyo Aircraft Instrument Co., Ltd., Tokyo, Japan [13]. The *holding force* is the amount of external force required to break the forcer away from its rest position at rated current applied to the motor. The *step-to-step accuracy* is a measure of the maximum deviation from the true position in the length of each step.

TABLE 34.9 Data of HLSMs Manufactured by Tokyo Aircraft Instrument Co., Ltd., Tokyo, Japan

Parameter	LP02-20A	LP04-20A	LP04-30A	LP60-20A
Driver	Bipolar chopper			
Voltage, V	24 DC			
Resolution, mm	0.2	0.4	0.4	0.423
Holding force, N	20	20	29.5	20
Step-to-step accuracy, mm	±0.03			
Cumulative accuracy, mm	±0.2			
Maximum start–stop speed, mm/s	60	120	120	127
Maximum speed, mm/s	400	600	500	600
Maximum load mass, kg	3.0	3.0	5.0	3.0
Effective stroke, mm	330	300	360	310
Mass, kg	1.4	1.2	2.8	1.4

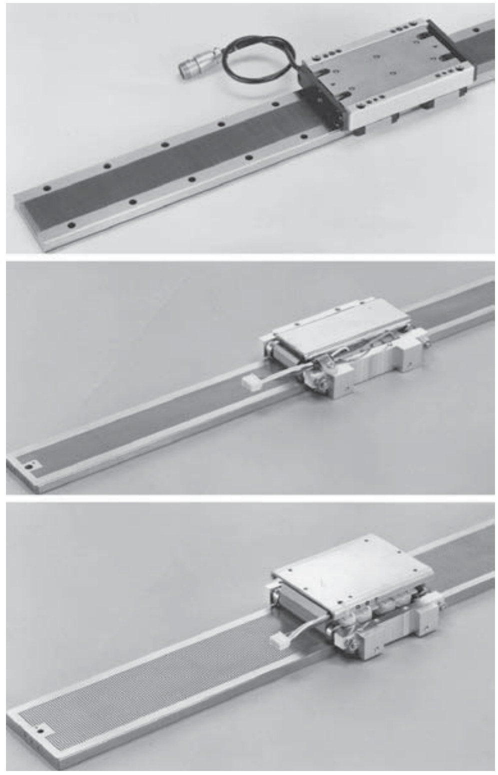


FIGURE 34.33 PM linear stepping motors. (Photo courtesy of Tokyo Aircraft Instrument, Co., Ltd., Tokyo, Japan.)

This value is different for full-step and microstepping drives. The *maximum start–stop speed* is the maximum speed that can be used when starting or stopping the motor without ramping that does not cause the motor to fall out of synchronism or lose steps. The *maximum speed* is the maximum linear speed that can be achieved without the motor stalling or falling out of synchronism. The *maximum load mass* is the maximum allowable mass applied to the forcer against the scale that does not result in mechanical damage. The *full-step resolution* is the position increment obtained when the currents are switched from one winding to the next winding. This is the typical resolution obtained with full-step drives, and it is strictly a function of the motor construction. The *microstepping resolution* is the position increment obtained when the full-step resolution is divided electronically by proportioning the currents in the two windings. This resolution is typically 10–250 times smaller than the full-step resolution [13].

HLSMs are regarded as an excellent solution to positioning systems that require a high accuracy and rapid acceleration. With a microprocessor controlled *microstepping mode*, a smooth operation with standard resolution of a few hundred steps/mm can be obtained. The advantages such as high efficiency, high throughput, mechanical simplicity, high reliability, precise open-loop operation, and low inertia of the system have made these kind of motors more and more attractive in such applications as factory automation, high speed positioning, computer peripherals, facsimile machines, numerically controlled machine tools, automated medical equipment, automated laboratory equipment, and welding robots. This motor is especially suitable for machine tools, printers, plotters, and computer-controlled material handling in which a high positioning accuracy and repeatability are the key problems.

When two or four forcers mounted at 90° and a special grooved platen ("waffle plate") are used, the x–y motion (two DOFs) in a single plane is obtained (Figure 34.34).

Specification data of the x–y HLSMs manufactured by Normag Northern Magnetics, Inc., Santa Clarita, CA, are given in Table 34.10.

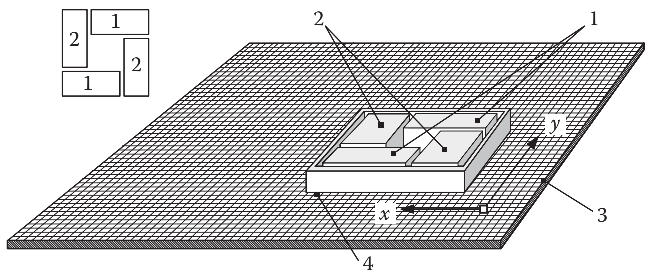


FIGURE 34.34 HLSM with a four-unit forcer to obtain the x–y motion: 1, forcers for the x-direction; 2, forcers for the y-direction; 3, platen; 4, air pressure.

TABLE 34.10 Data of x–y HLSMs Manufactured by Normag Northern Magnetics, Inc., Santa Clarita, CA

Parameter	4XY0602-2-0	4XY2002-2-0	4XY2004-2-0	4XY2504-2-0
Number of forcer units per axis	1	1	2	2
Number of phases	2	2	2(4)	2(4)
Static thrust, N	13.3	40.0	98.0	133.0
Thrust at 1 m/s, N	11.1	31.1	71.2	98.0
Normal attractive force, N	160.0	400.0	1440.0	1800.0
Resistance per phase, Ω	2.9	3.3	1.6	1.9
Inductance per phase, mH	1.5	4.0	2.0	2.3
Input phase current, A	2.0	2.0	4.0	4.0
Air gap, mm	0.02			
Maximum temperature, °C	110			
Mass, kg	3.2	0.72	2.0	1.5
Repeatability, mm	0.00254			
Resolution, mm	0.00254			
Bearing type	Air			

34.5 Switched Reluctance Motors

The topology of a linear switched reluctance motor is similar to that of a stepping motor with variable reluctance platen. In addition, it is equipped with position sensors. The *turn-on* and *turn-off* instant of the input current is synchronized with the position of the moving part. The thrust is very sensitive to the turn-on and turn-off instant.

In the case of a linear stepping or linear switched reluctance motor, the speed v of the moving part is

$$v = v_s = f_{sw}\tau \qquad (34.8)$$

where
f_{sw} is the fundamental switching frequency in one armature phase winding
τ is the pole pitch of the reaction rail

For a rotary stepping or switched reluctance motor, $f_{sw} = 2p_r n$, where $2p_r$ is the number of rotor poles and n is rotational speed in rev/s.

A *linear switched reluctance motor* has a doubly salient magnetic circuit with a polyphase winding on the armature. Longitudinal and transverse flux designs are shown in Figure 34.35. A linear switched reluctance motor allows precise speed and position-controlled linear motion at low speeds and is not subject to design constraints (minimum speed limited by minimum feasible pole pitch) of linear AC motors.

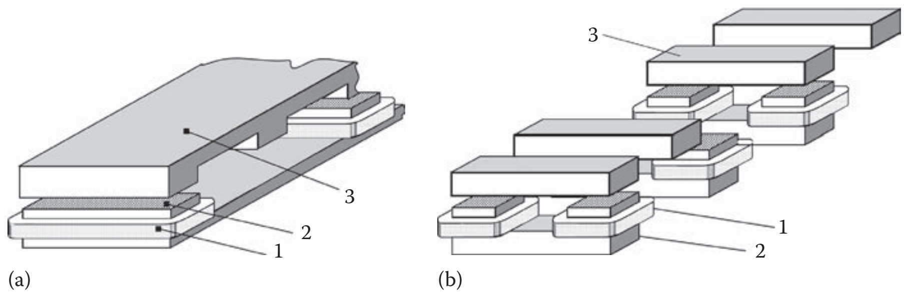


FIGURE 34.35 Linear switched reluctance motor configurations: (a) longitudinal flux design and (b) transverse flux design. 1, armature winding; 2, armature stack; 3, platen.

34.6 Linear Positioning Stages

Linear motors are now playing a key role in *advanced precision linear positioning. Linear precision positioning systems* can be classified into open-loop systems with HLSMs and closed-loop servo systems with LSMs, LBMs, or LIMs.

A PM LSM–driven *positioning stage* is shown in Figure 34.36. A stationary base is made of Al, steel, ceramic, or granite plate. It provides a stable, precise, and flat platform to which all stationary positioning components are attached. The base of the stage is attached to the host system with the aid of mounting screws.

The *moving table* accommodates all moving positioning components. To achieve maximum acceleration, the mass of the moving table should be as small as possible, and usually, Al is used as a lightweight material. A number of mounting holes on the moving table is necessary to fix the payload to the mounting table.

Linear bearing rails provide a precise guidance to the moving table. A minimum of one bearing rail is required. Linear ball bearing or air bearings are attached to each rail.

The armature of a linear motor is fastened to the moving table, and reaction rail (PM excitation system) is built in the base between the rails (Figure 34.36).

A linear encoder is needed to obtain precise control of position of the table, velocity, and acceleration. The read head of the encoder is attached to the moving table.

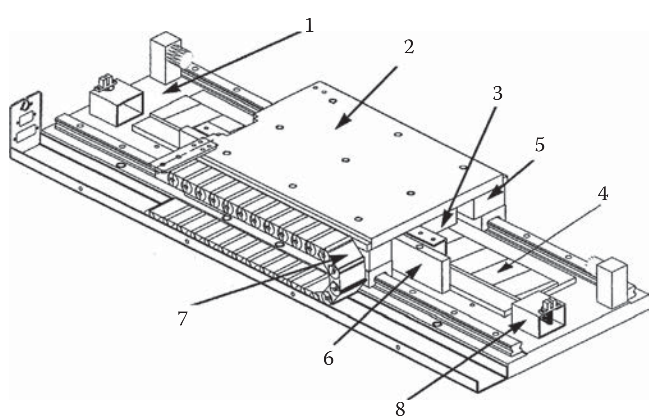


FIGURE 34.36 Linear positioning stage driven by PM LBM. 1, base; 2, moving table; 3, armature of LBM; 4, PMs; 5, linear bearing; 6, encoder; 7, cable carrier; 8, limit switch. (Courtesy of Normag, Santa Clarita, CA.)

Noncontact limit switches fixed to the base provide an overtravel protection and initial homing. A cable carrier accommodates and routes electrical cables between the moving table and stationary connector box fixed to the base.

An HLSM-driven linear precision stage is of similar construction. Instead of PMs between bearing rails, it has a variable reluctance platen. HLSMs usually need air bearings, and, in addition to the electrical cables, an air hose between air bearings and the compressor is required.

Linear positioning stages are used in semiconductor technology, electronic assembly, quality assurance, laser cutting, optical scanning, water jet cutting, gantry systems (*x*, *y*, *z* stages), color printers, plotters, and Cartesian coordinate robotics.

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