5. LINEAR MOTORS

5.1 INTRODUCTION

Linear Electric Motors belong to the group of Special electrical machines that convert electrical energy into mechanical energy of translator motion. Linear Electric motors can be classified as follows

- Induction motors
- DC motors
- Synchronous motors including reluctance and stepper motors
- Oscillatory motors
- Hybrid motors

The Linear motors (LM) are very effective drive mechanisms for transportation and actuation systems. The high power linear motors are used in rapid transportation, baggage handling, conveyors, crane drives, theme park rides and flexible manufacturing systems. The low power ones are used in robotics, gate control, guided trajectories and stage and curtain movement. NASA envisions the use of such motors in launching spacecrafts in future.

5.2 APPLICATION OF LINEAR ELECTRIC MOTORS

Linear motors potentially have unlimited applications. Some of them are listed below

- Conveyor Systems
- Material handling and storage
- People movers (Elevators)
- Liquid metal pumping
- Machine tools operation
- Operation of sliding doors

Before the advent of linear motors, rotary motors with rotary to linear converters of some kind were used to produce linear motions. The most obvious advantage of ***a linear motor is that it has no gears and requires no mechanical rotary to linear converters***. Thus compared with rotary motors with mechanical gears, and similar devices, the linear motor is robust and more reliable.

5.2 LINEAR INDUCTION MOTORS

Linear Induction motor is a conventional development of conventional three phase induction machine. Instead of rotary motion in a three phase conventional induction motor rectilinear motion is obtained in a linear induction motor. *"Whenever a relative motion occurs between the field and short circuited conductors, currents are induced in them which results in electro-magnetic forces and under the influence of these forces, according to Lenz's law the conductors try to move in such a way as to eliminate the induced currents"* In this case the field movement is linear and so is the conductor movement.

Imaginary Process of Obtaining LIM

The imaginary process of "cutting" and "unrolling" rotary counterpart is illustrated in Figure 5.0.

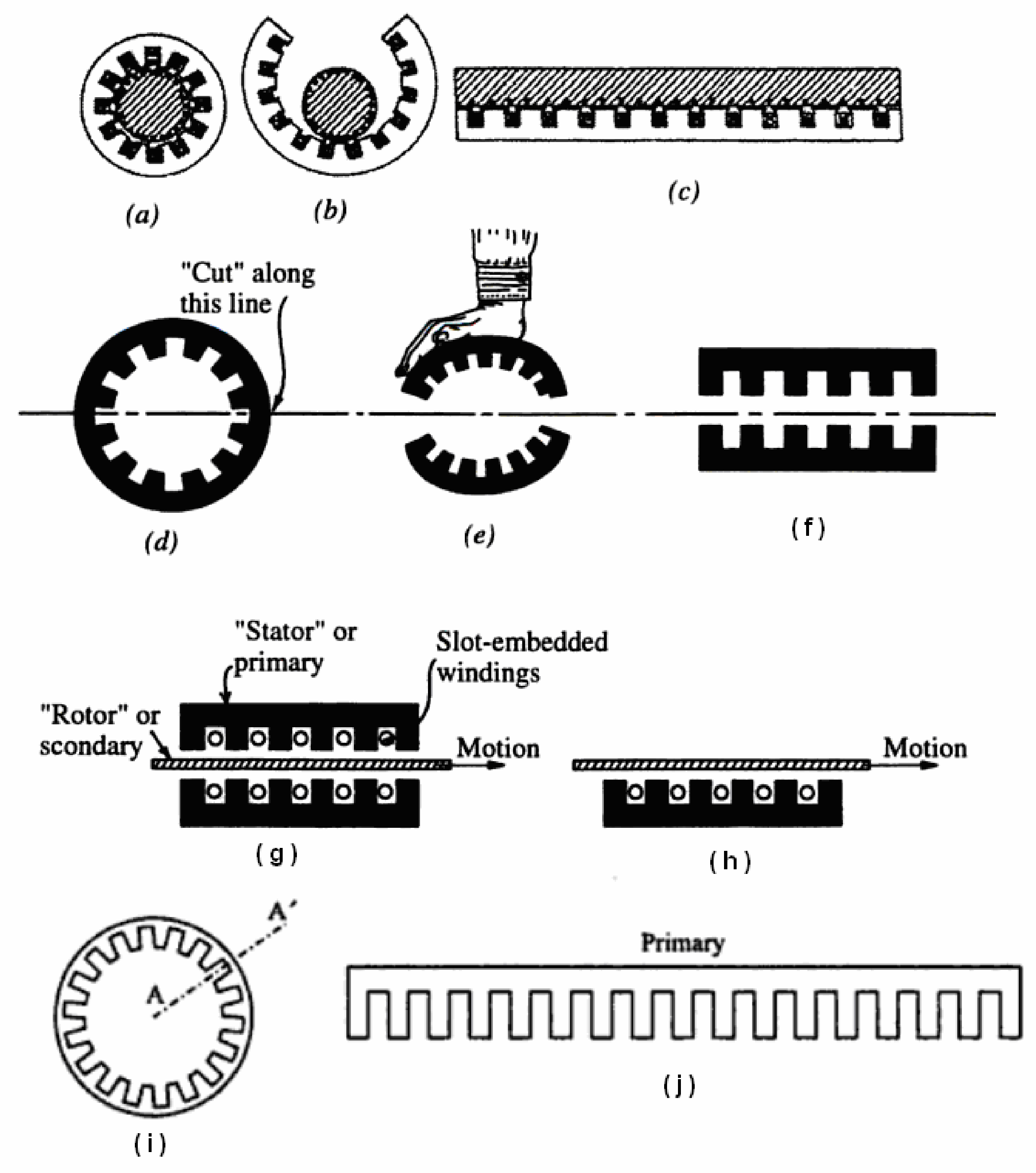

Fig 5.1 Imaginary process of obtaining LIM

5.2.1 Construction of LIM

The three phase winding can be obtained by cutting the stator winding along the plane AA' perpendicular to the paper as shown in the figure 5.1(a) and developing it as shown in the figure 5.1(b) The secondary or rotor of the linear induction motor consists of plate of copper or aluminum

A linear induction machine in its simplest form consists of a field system having a 3 phase distributed winding placed in slots as shown in the figure 5.2 (Short single primary)

The field system may be single or double primary system. The secondary of this type of induction machine is normally a *conducting plate made of either copper or aluminum in which interaction currents are induced.*

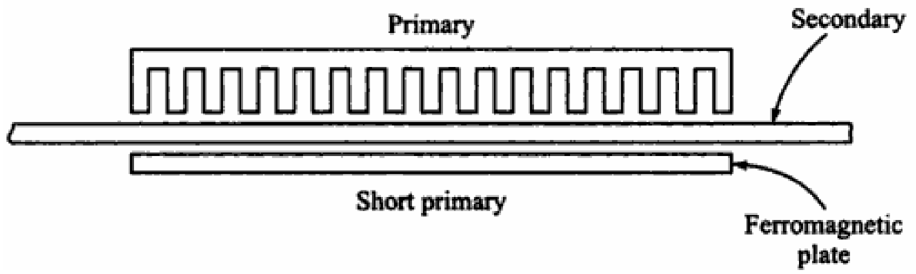

Fig 5.2 Linear Induction Motor

Depending upon the use, the linear induction machine can be one of the following three types

Short Primary

The primary is short and the secondary is long as shown in the figure 5.2. This type is useful when the total distance to be travelled is large. In this type over heating of rotor is eliminated because of the continuous movement of the primary over cold part of the rotor, leaving behind the heated part. In this case primary moves and the secondary are stationary.

Short Secondary

The secondary is short in comparison with primary as shown in the figure 5.3. This type is useful when the travel is limited. It must be light. The long primary and short secondary has the following drawbacks:

- Long primary is uneconomical as it requires a long three phase primary windings to be wound.
- Only that part of the primary windings which are adjacent the secondary are effective at any one time.

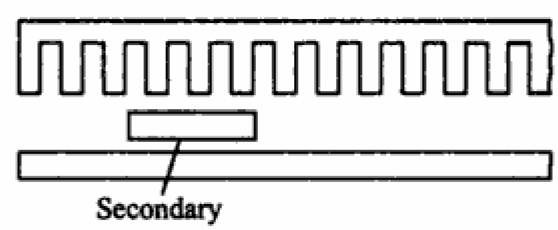

Fig 5.3 Short Secondary Type

Two Field Systems

There are two field (Primary) systems, one on either side of the secondary as shown in the figure 5.4. It is often used as it minimizes the leakage flux and avoids magnetic attraction between the moving parts and the reaction rail which exists in earlier two types.

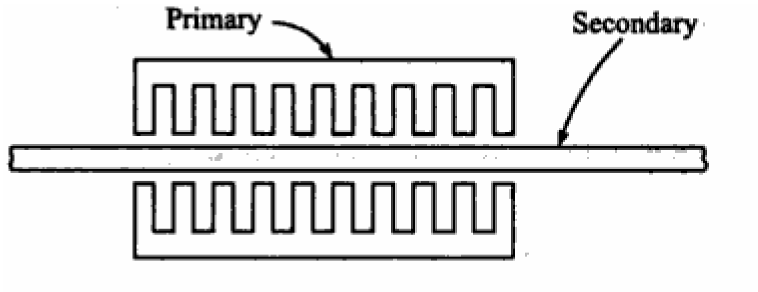

Fig 5.4 Two Field System

Depending upon the particular requirements either member can be the stator, the other being the rotor

- The ferromagnetic plate, in a single primary system, is usually placed on the other side of the conducting plate to provide a path of low reluctance to the main flux. The ferromagnetic plate however gets attracted towards the primary when the field is energized. Consequently unequal gap length results on the two sides of the plate. Double primary system can be used to overcome this problem.
- The use of the motor decides which of the two primary and secondary will be shorter in length compared to the other. The primary is made shorter than secondary when the operating distance is large (Since winding a very long 3 phase primary is costly proposition) and the short secondary is used when the operating distance is limited.

5.2.2 Working Principle

When a three phase primary winding of the motor is energized from a balanced three phase source, a magnetic field moving in a straight line from one end to other at a linear synchronous speed V_s is produced. The linear synchronous speed V_s is given as

$$V_s = 2f\zeta \text{ meter per second} ------------- 5.1$$

Where f is the supply frequency and τ is the pole pitch in metes. The interaction of magnetic fields with the current induced in the secondary exerts a thrust on the secondary to move in the same direction if the primary is held stationary. Alternatively if the secondary is stationary and the primary is free to move, the primary moves in the direction opposite to that of the magnetic field. The relative speed of the stator and rotor is

$$V_r = (1 - s)V_s --------------------- 5.2$$

Where s is the slip and the relative speed between the moving field and the secondary is sV_s. The slip is therefore given by

$$s = \frac{(V_S - V_r)}{V_s} ----------------------- 5.3$$

On the line of conventional three phase induction motor, the power and thrust in a linear induction motor can be expressed. The air gap power P_g is given by

$$P_g = 3I_2^2\left(\frac{r_2}{s}\right) \text{--------------------} 5.4$$

And developed power P_r is given by

$$P_r = (1-s)P_g \text{--------------------} 5.5$$

The developed thrust F_m is therefore given by

$$F_m = \frac{P_r}{V_r} = \frac{P_g}{V_s} = 3I_2^2\frac{r_2}{sV_s} \text{------------------} 5.6$$

The speed thrust characteristics of a linear induction motor is shown in the figure 5.5. It is similar to the speed torque characteristics of a three phase conventional induction motor. The speed of the linear induction motor decreases rapidly with the increasing thrust. For this reason the linear induction motor often operate at low slip, resulting a relatively low efficiency.

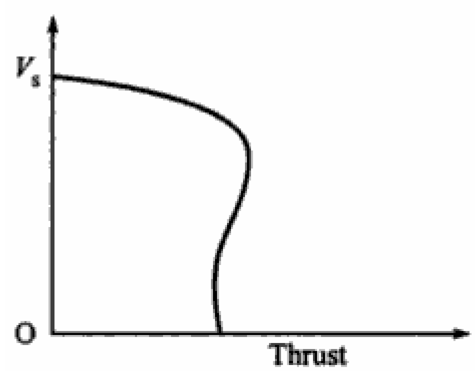

Fig 5.5 Speed-Thrust Characteristics

Because of open ended construction of linear induction motor, it displays a peculiar effect known as end effect. This effect can be grouped into static end effect and dynamic end effect. In static end effect the mutual inductance of the phase windings are not equal to one another. This leads to asymmetric flux distribution in the air gap and gives rise to unequal induced voltages in the phase winding. The dynamic end effect occurs due to the relative motion between primary and secondary. As the primary moves over the secondary at every instant, a new secondary conductor is coming under the leading edge of the primary, while one old secondary conductor is leaving the trailing edge of the primary. The conductor coming under the leading edge opposes the magnetic flux in the air gap, while the conductor leaving the trailing edge tries to maintain the flux. Therefore the flux distribution in the air gap is distorted. The flux is weaker in the leading edge region as compared to the trailing edge. It also leads to braking action especially at lower values of slip.

5.3 The concept of Current Sheet

The analysis of Linear Induction motor is carried out in terms of electromagnetic equations. Clearly, the slotted primary structure with its windings is by no means an ideal boundary, or even a sufficient simple one, where the solutions to be governing field equations can be obtained. To overcome this difficulty the actual slotted structure is replaced by the smooth surface and the current carrying winding are replaced by fictitious, infinitely thin current elements called current sheets, having linear current densities (A/m). The current density distribution of the current sheet is equivalent to that of the slot embedded conductor configurations, such that the field in the air gap remains unchanged. The actual airgap of the machine is replaced by the effective airgap (which is about 1.02 to 1.2 time greater than the actual airgap). The leakage flux in the airgap also increases apparently the effective airgap. The effective airgap variation for a large linear induction motor as influenced by airgap leakage is presented in figure 5.6

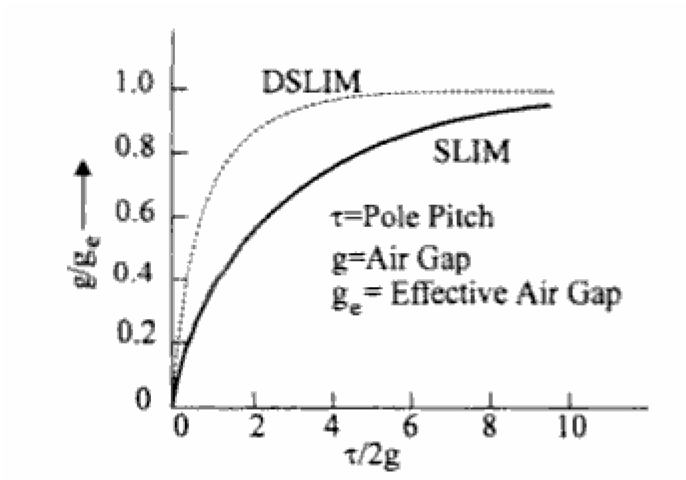

Fig 5.6 Effective airgap ratio versus pole pitch/ Double airgap ratio.

It is well know that sinusoidal space distribution of the windings (resulting in a sinusoidal varying airgap field) is ideal and most desirable. However, in reality, (Especially in LIM), such as sinusoidal distribution of the windings cannot be accomplished. In such a case, the resulting magneto motive force (mmf) of the winding is resolved into harmonics by fourier series analysis. Generally, the fundamental component of the distribution is only considered as the source of the airgap field. For instance, in figure 5.7 a stepped mmf is resolved into its harmonics and the fundamental component is then the equivalent current sheet. The amplitude of the current sheet J_m is found from the relationship,

$$J_m = \frac{\textit{Maximum}\text{ total current along machine periphery}}{\text{Length of machine periphery x total winding factor A/m}} \text{ -------------- (5.7)}$$

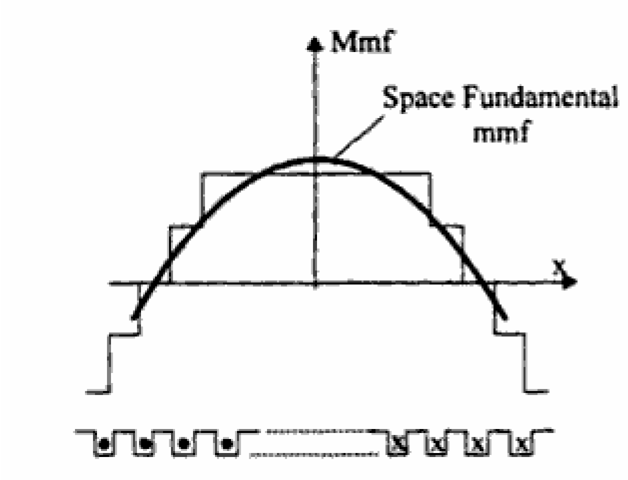

Fig 5.7 The primary mmf

In this expression, the total winding factor takes into account the derivation from a sinusoidal distribution because of chording, slots and so on. We can also rewrite (5.7) as

$$J_m = \frac{m\left(2W\sqrt{2}\right)I}{2p\tau}k_w = \frac{\sqrt{2}mWIk_w}{p\tau} \quad \text{--------------------------------------- (5.8)}$$

Where m is the number of phases, $2p\tau$ is the length of the machine (p being the number of pole pairs and τ the pole pitch, W is the number of turns per phase, $\sqrt{2}I$ is the maximum phase current and K_w is the total winding factor

5.4 Linear Synchronous Motors

A *linear synchronous motor* (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 travelling magnetic field. The thrust (propulsion force) can be generated as an action of

- ✓ travelling 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 a.c. armature windings)
- ✓ Magnetic field produced by electronically switched D.C. windings and an array of magnetic Poles N, S...N, S or variable reluctance ferromagnetic rail (linear stepping or switched reluctance motors).

The part producing the travelling magnetic field is called the *armature* or *forcer.* The part which provides the D.C. 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 linear induction motors or transformers. The operation of a LSM does not depend which part is movable and which one is stationary.

Traditionally, a.c. polyphase synchronous motors are motors with d.c. electromagnetic excitation, the propulsion force of which has two components:

1. Due to the travelling magnetic field and D.C. current magnetic flux (synchronous component) and
2. Due to the travelling magnetic field and variable reluctance in *d* and *q* axis (reluctance component).

Replacement of D.C. electromagnets by permanent magnets (PMs) is common, except for LSMs for magnetically levitated vehicles.

5.4.1 Classifications

LSMs can be classified according to whether they are

1. flat (planar) or tubular (cylindrical);
2. single sided or double sided;
3. slotted or slotless;
4. iron-cored or air-cored;
5. Transverse flux or longitudinal flux.

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

1. PMs in the reaction rail;
2. PMs in the armature (passive reaction rail);
3. electromagnetic excitation system (with winding);

5.5 Permanent Magnet Motors with Active Reaction Rail-Construction

Fig 5.8 a shows a single-sided flat LSM with the armature winding located in slots and surface PMs. Fig. 5.8 b 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 travelling magnetic field and the yoke is non- ferromagnetic, e.g. made of aluminum.

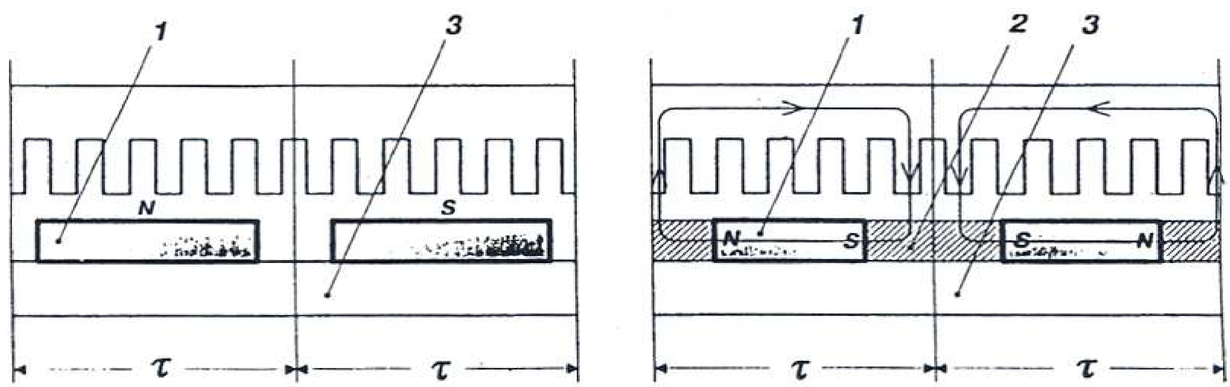

Figure 5.8 Single sided flat PM LSMs with slotted armature core and: (a) surface PMs, (b) buried PMs. 1 -PM, 2 – mild steel pole, 3 - yoke.

It is recommended to furnish a PM LSM with a *damper*. A rotary synchronous motor has a cage damper winding embedded in pole shoe slots. When the speed is different than 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 travelling magnetic field.

Double sided, flat PM LSMs consist of two external armature systems and one internal excitation system (Fig. 5.9 a) or one internal armature system and two external excitation systems (Fig. 5.9 b). 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

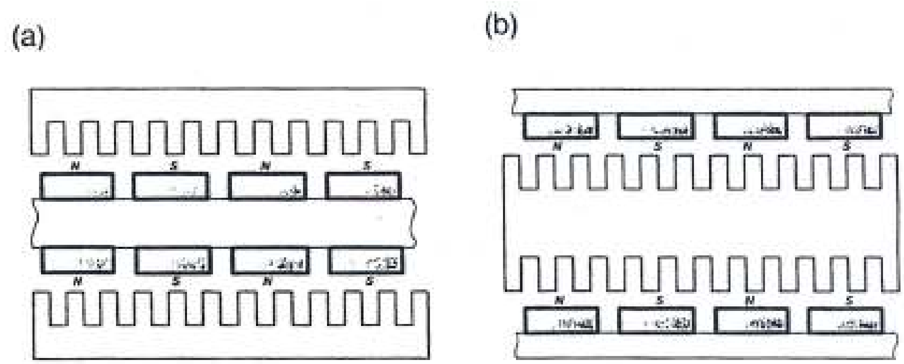

Figure 5.9 Double sided flat PM LSMs with: (a) two external armature systems (b) one internal armature system.

Fig. 5.10 a shows a single sided flat slotless motor with armature core and Fig. 5.10 b shows a double sided slotless motor with inner air-cored armature winding (moving coil motor).

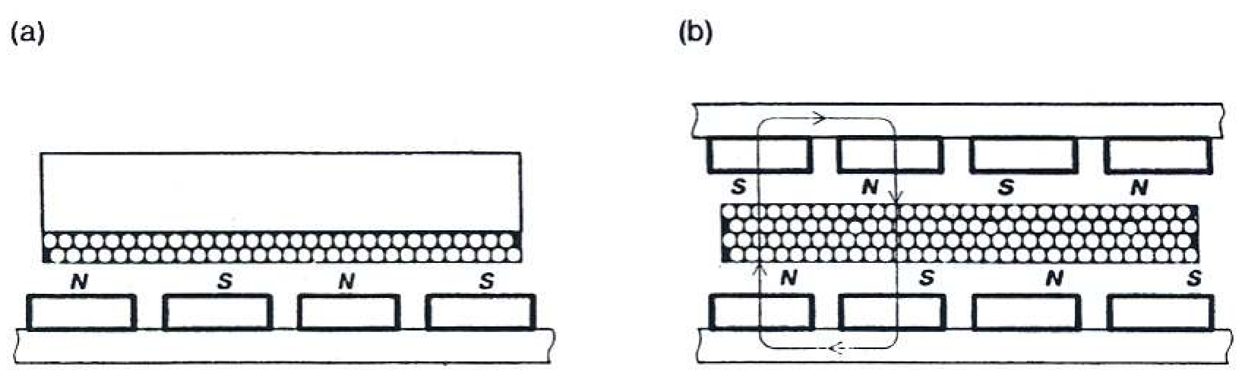

Figure 5.10 Flat slotless PM LSMs: (a) single sided with armature core (b) Double sided with inner air-cored armature winding.

5.6 <u>PM Motors with Passive Reaction Rail-Construction</u>

The drawback of PM LSMs is the large amount of PM material which must be used to design the excitation system. Normally, expensive rare earths PMs are requested.

A cheaper solution is to apply the PM excitation system to the short armature which 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 [32, 115] is a double sided a.c. linear motor which consists of two polyphase armature systems connected mechanically and magnetically by a ferromagnetic U-type yoke (Fig. 5.11). 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 1SM. The PMs can also be replaced by electromagnets. The variable reluctance reaction rail is passive. The saliency is created by using ferromagnetic (solid or laminated) cubes separated by a non ferromagnetic material. The reaction rail poles are magnetized by the armature PMs through the airgap. The travelling magnetic field of the polyphase armature winding and salient poles of the reaction rail produce the thrust. Further simplification of the double sided configuration can be made obtain a single sided PM LSM shown in Fig. 5.12

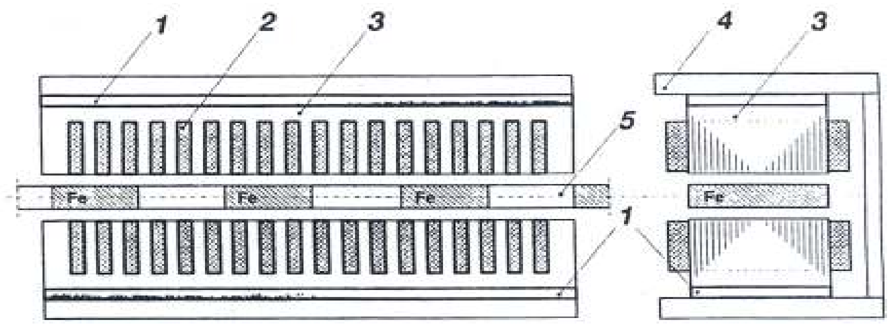

Figure 5.11 Double sided homopolar PM LSM with passive reaction rail.1 - PM, 2 - armature winding, 3 – armature stack, 4 - yoke, 5.Reaction rail.

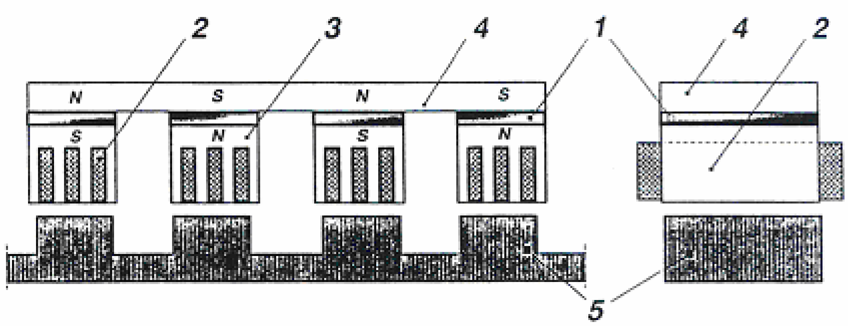

Figure 5.12 Single sided PM LSM with a passive reaction rail. 1 - PM, 2 - armature winding, 3 - armature stack, 4 -yoke, 5.ferromagnetic reaction rail.

5.7 Motors with Electromagnetic Excitation

The electromagnetic excitation system of a LSM is similar to the salient pole rotor of a rotary synchronous motor. Fig. 5.13 shows a fiat single sided LSM with salient ferromagnetic poles and d. c. *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 D.C. current can be delivered with the aid of brushes and contact bars, inductive power transfer (IPT) systems, linear transformers or linear brushless exciters.

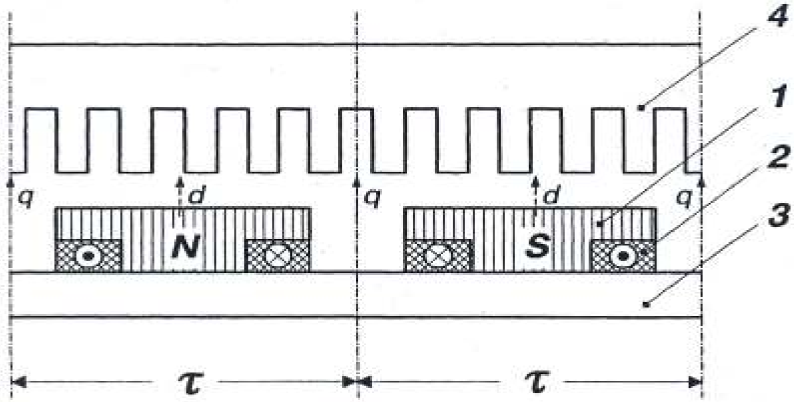

Figure 5.13 Electromagnetic excitation system of a flat single sided iron-cored LSM. 1 - Salient pole, 2 - D.C. excitation winding, 3 .Ferromagnetic rail (yoke), 4 - armature system.

5.8 PRINCIPLE OF OPERATION

The operation of a synchronous motor is simple to imagine. The armature winding, when excited by a poly-phase (usually 3-phase) Supply, creates a linear magnetic field inside the air gap. The field winding, which acts as a permanent magnet, simply locks in with the rotating magnetic field and rotates along with it. During operation, as the field locks in with the rotating magnetic field, the motor is said to be in synchronization.

Once the motor is in operation, the speed of the motor is dependent only on the supply frequency. When the motor load is increased beyond the break down load, the motor falls out of synchronization i.e., the applied load is large enough to pull out the field winding from following the rotating magnetic field. The motor immediately stalls after it falls out of synchronization.

5.9 PERFORMANCE EQUATION OF LINEAR SYNCHRONOUS MOTORS

The *time-space distribution of the MMF* of a symmetrical poly phase winding with distributed parameters fed with a balanced system of currents can be expressed as

$$
\begin{aligned}
F(x,t) &= \frac{N_1\sqrt{2}I_a}{\pi p}\sin\omega t\sum_{v=1}^{\infty}\frac{1}{v}k_{\omega 1v}\cos\left(v\frac{\pi}{\tau}x\right) \\
&+\frac{N_1\sqrt{2}I_a}{\pi p}\sin\left(\omega t-\frac{1}{m_1}2\pi\right)\sum_{v=1}^{\infty}\frac{1}{v}k_{\omega 1v}\cos v\left(\frac{\pi}{\tau}x-\frac{1}{m_1}2\pi\right)+\dots \\
&+\frac{N_1\sqrt{2}I_a}{\pi p}\sin\left(\omega t-\frac{m_1-1}{m_1}2\pi\right)\sum_{v=1}^{\infty}\frac{1}{v}k_{w1v}\cos v\left(\frac{\pi}{\tau}x-\frac{m_1-1}{m_1}2\pi\right) \\
&=\frac{1}{2}\sum_{v=1}^{\infty}F_{mv}\{\sin\left[\left(\omega t-v\frac{\pi}{\tau}x\right)+(v-1)\frac{2\pi}{m_1}\right] \\
&+\sin\left[\left(\omega t+v\frac{\pi}{\tau}x\right)-(v-1)\frac{2\pi}{m_1}\right]\}
\end{aligned}
$$

where I_a is the armature phase current, m_1 is the number of phases, P is the number of pole pairs, N_1 is the number of series turns per phase, $K_{\omega 1}$ is the winding factor, $\omega = 2\pi f$ is the angular frequency τ is the pole pitch and

- ✓ for the forward-travelling field

$$v = 2m_1k + 1 \qquad k = 0,1,2,3,4,5,...$$

- ✓ for the backward travelling fie1d

$$v = 2m_1k - 1 \qquad k = 0,1,2,3,4,5,...$$

The magnitude of the v harmonics of the primary MMF is

$$F_{mv} = \frac{2m_1\sqrt{2}}{\pi p} N_1 I_a \frac{1}{v} k_{w1v} = m_1 \left[F_{mv}\right] m_1 = 1$$

The winding factor for the v space harmonic is the product of the distribution factor, K_{d1v}, and pitch factor, K_{p1v}, i.e.,

$$k_{w1v} = k_{d1v} k_{p1v}$$

$$k_{d1v} = \frac{\sin\left[v\pi / (2m_1)\right]}{q_1 \sin\left[v\pi / (2m_1 q_1)\right]}$$

$$k_{p1v} = \sin\left(v\frac{\pi}{\tau}\frac{\omega_c}{2}\right)$$

Assuming that $\omega t \mp \frac{v\pi x}{\tau} = 0$ the *linear synchronous speed* of the v th harmonic wave of the MMF is

$$v_{sv} = \mp 2 f \tau \frac{1}{v}$$

For a three-phase winding the time space distribution of the MMF is

$$F(x,t) = \frac{1}{2}\sum_{v=1}^{\infty} F_{mv} \{\sin\left[\left(\omega t - v\frac{\pi}{\tau}x\right) + (v-1)\frac{2\pi}{3}\right]$$

$$+ \sin\left[\left(\omega t + v\frac{\pi}{\tau}x\right) - (v+1)\frac{2\pi}{3}\right]\}$$

For a three-phase winding and the fundamental harmonic v =1

$$F(x,t) = \frac{1}{2} F_m \sin\left(\omega t - \frac{\pi}{\tau}x\right)$$

$$F_m = \frac{2m_1\sqrt{2}}{\pi p} N_1 I_a k_{\omega 1} \approx 0.9 \frac{m_1 N_1 k_{\omega 1}}{p} I_a$$

The peak value of the armature line current density or *specific electric loading* is defined as the number of conductors in all phases $2m_1N_1$ times the peak armature current $\sqrt{2}I_a$ divided by the armature stack length 2 $p\tau$

$$A_m = \frac{m_1\sqrt{2}N_1I_a}{p\tau}$$

PROBLEMS

1. An overhead crane in a factory is driven horizontally by means of two similar linear induction motors whose rotors are the two steel I beam on which the crane rolls. The three phase two pole linear stators which are mounted on opposite sides of the crane have a pole pitch of 5 cm and are energized by variable frequency source. The tests on one of the motors gave the following results.

Stator frequency	=	50 Hz
Stator copper and iron loss	=	1 KW
Power to stator	=	5 KW
Crane Speed	=	2.5 m/sec

Calculate

i. Synchronous speed and slip
ii. Power input to rotor
iii. Copper loss in the rotor
iv. Gross mechanical power developed
v. Thrust.

Solution

$$\text{Synchronous speed}, V_S = 2Wf = 2 \text{ x } 5 \text{ x } 10^{-2} \text{ x } 50 = 5 \text{ m/sec}$$

$$\text{Slip, S} = \frac{V_s - V}{V_s} = \frac{5-2.5}{5} = 0.5 \text{ or } 50\%$$

$$P_2 = \text{Power to stator - Stator cu and Iron loss}$$

$$= 5 - 1 = 4 \text{ KW}$$

$$P_{cu} = sP_2 = 0.5 \text{ x } 4 = 2\text{KW}$$

$$P_m = P_2 - P_{cu} = 4 - 2 = 2KW$$

$$\text{Thrust} = F = \frac{P_2}{V_s} = \frac{4 \text{ x } 10^3}{5} = 800N$$