# Chapter 2

# Energy Machines

## 2.1 Introduction

The previous chapter dealt with literature survey and plan for work. This chapter explains comprehensively the problems encountered in designing **Energy Machines** operating under transient pulse three phase power.

## 2.2 Energy Machines

The use of linear induction motors for high speed propulsion is now a proven technology. Linear Motor has also revolutionized the Hyperloop technology in transport sector.Electromagnetic warfare-Thruster, Truck mounted launchers, Electromagnetic propulsion of an aircraft takes off on board of ship / occult takes off using an Electromagnetic Aircraft Launch System (EMALS) are major applications of linear motor in defence applications. The application of Linear Electrical Machines (LEM) in the space area for satellite launching is also a growing research area. Such application utilizes the Linear Induction motors as an **Energy Machines**, requiring high voltage high current three phase pulse power of desired frequency. Salient feature of linear motor based **Energy Machines** are:

- LIM secondary / primary exerts thrust to main mover in non-contact manner without any gear box.
- Static friction is not essential for movement, although wheel-rail (lesser diameter) system or slider type mechanism are required for maintaining the air clearance.
- Maximum Speed is not limited by dynamic friction.
- Levitation is also possible. However, wheel–rail system in levitated system acts as primary suspension.
- Wheel slip does not restrict movement, because wheels are only for movement support only and do not transfer mechanical power to the mover.
- Wheel slip does not overload the linear induction motor.

The Energy Machines operate under stringent conditions of:

- Extremely Large voltage of operation in pulse form for a fraction of second or a few half cycles of power frequency.
- Stress in Dielectric and insulating media
- Extremely high current density
- Extremely large thermal input in pulse form
- Large Magnetic saturation - high flux machine
- Extremely large thrust causing jerk in operation
- Presence of large conducted and radiated EMI

Energy machines are a class of machines which are used in special areas of defense application. The use of linear induction motors allows transfer of large force to mover in a non-contact way, which is not possible with rotary machine's contact based transfer of thrust and power.

The launchers designing hinges on mitigating:

- Negative thrust generation due to momentarily super synchronous operation (as will be seen in Fig. 4.10 of Chapter 4)
- Oscillations in thrust during initial period

The wheel-on-rail system in case of conventional rotary induction motor (RIM) based transport or thruster machines requires gearing arrangement through which power or thrust is transferred. In case of Linear Induction Motor (LIM) and levitated machines, wheel-rail system merely assists in maintaining a nominal air clearance required for electromagnetic propulsion. Even if, in remote cases, wheel slip happens, it does not restrict movement and does not over load the linear induction motor. Wheel rail system or slider system may be required for maintaining only the air clearance in LIM based systems. They do not assist in transfer of power and thrust to mover. The energy machine used in thruster or launching applications utilizes a large initial force of LIM and never runs continuously under steady state condition. These machines are ON for only a few cycles of power frequency.

In most of the cases the thrust produced by machines are so high that its natural speed of operation crosses the synchronous speed and if power is not switched off before natural synchronous speed, then the speed swings back to even less that synchronous speed and settles at less than synchronous speed after several oscillations. Such actions halt the operation of energy machines. The energy machines are designed to utilize the initial large thrust of electrical machines and are to be switched off much before the linear synchronous speed in order to avoid the problems mentioned above. When rotary machines are employed for such systems, the essential demand of wheel-rail based energy transfer to moving mass require heavy machines as per traction principles. Although linear induction motors were in beginning regarded as poor machines having larger air clearance and end effects, these LIM based energy machines transfer the thrust to moving body in a non-contact manner. As such large thrust can be imparted to comparatively lesser mass. This unique quality of linear induction motor to transfer thrust/power to low mass projectile in a non-contact manner has widespread applications ranging from wheel on rail transport, levitated transport, space launch, launchers and EMALS system.

The linear synchronous speed is given as

$$v_s = 2 \times f \times \frac{L}{p} \tag{2.1}$$

for an LIM of length ‘L ‘ and poles ‘p’. The linear slip in LIM is fairly large as compared to rotary induction motor due to presence of entry-end and exit–end effects. The linear slip may be taken in the range of 0.1 to 0.2 for designing purpose. Depending on the actual speed required the linear synchronous speed as well as length of machine, number of poles and frequency may be decided. When number of poles increases beyond 24 poles, the entry and exit end effects are minimized. Table 2.1 shows typical frequency and poles in 3 m length of machines for 50 m/s linear synchronous speed.

Table 2.1 Typical frequency and poles in 3m length of machines for 50 m/s linear synchronous speed

| Frequency (Hz) | 50 | 100 | 150 | 200 |
|---|---|---|---|---|
| Poles | 6 | 12 | 18 | 24 |
| Pole pitch | 0.5 | 0.25 | 0.167 | 0.125 |
| Synchronous Velocity | 50 | 50 | 50 | 50 |

### 2.2.1 Operating Conditions of Energy Machines

An extremely large voltage is suddenly applied causing large winding currents of transient nature to flow in the linear motor stator. Heavy currents of the order of few kA flow in these machines momentarily for a fraction of second. The current density in such machines may exceed even beyond 45 A per sq mm against nominal current density of 4 A per sq mm in induction motors design and 2.2 A per sq mm in transformers for normal duty of operation. Thin strip conductors insulated with Kapton tape and short circuited at both the ends of coil sides of the windings are used in higher current density machines to allay the skin effect problems in AC machines. In such machines number of turns per slot is also kept small from the view point of design optimization.

The current transients in three phase system at the instant of switching ON may lead to unpredictable forces. As such the phases should be switched ON successively at their voltage peak [51]. Separate single phase rising frequency generators with phase shift for supplying three phase power to energy machines is advantageous. The presence of large current and flux density makes the core to operate in saturation region. The electrical machines operate in its extreme limits of magnetic saturation causing drop in thrust per ampere of current as compared to normal LIM based system. This demands better magnetic material for core. Currently, Cobalt steel is being used instead of Silicon sheet steel in Energy Machines. Typical B-H curves of Steel 1010 and Cobalt sheet steel are shown in Fig. 2.1. Since machines operate under essentially high level of magnetic saturation, the conventional theories of electrical machine design are no longer valid. This requires Class H or better class of insulation in the slot lining, winding conductors and cables supplying large power though momentarily for few cycles. The electrostatic stress in dielectric medium should be mitigated otherwise it will shorten the life of whole system.

Energy machines may even be subjected to quick successive operations. The intense thermal loading should be checked to avoid rise in temperature beyond safe zone so that insulations and winding materials are not degraded due to thermal stresses. These machines (such as coil guns and rail guns) require pulse DC power, whereas the launchers are based on the principles of Linear Induction Motor, Linear Synchronous motor, Linear Permanent Magnet Brushless Motor (LPMBM) and Linear Reluctance motors (LRM). The LIM

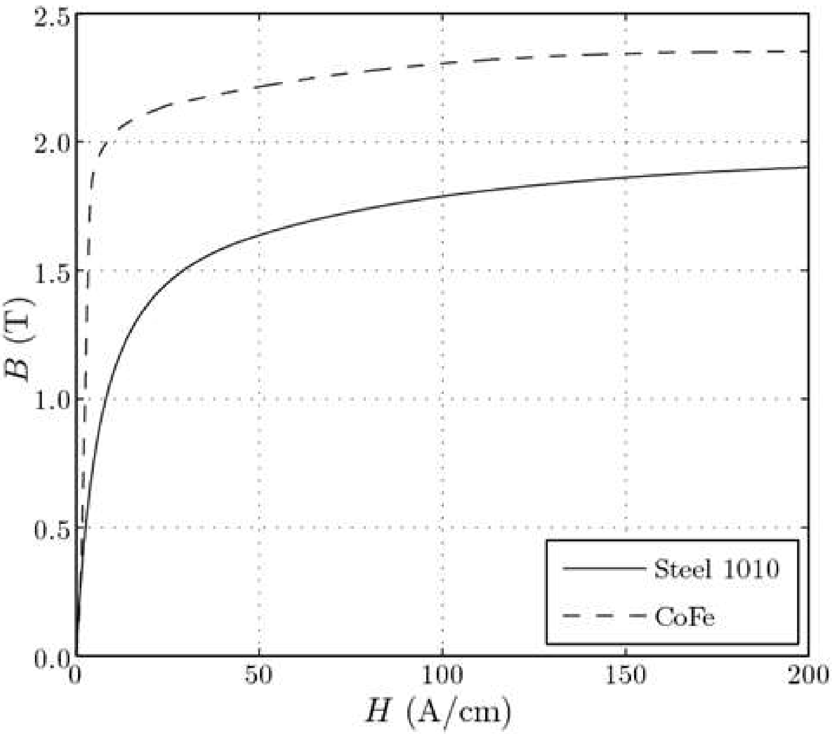


Fig. 2.1 Typical BH curve of Co-iron And Silicon iron sheet steel

and LSM require a Variable Voltage Variable Frequency VVFD for their operations. In LPMBL motor and LRM, power supply is position based switching ON/OFF of different poles. Rail Gun and Coil gun demand pulse DC power which is met using discharging of super capacitors. The requirement of power in energy machines is extremely large of the order of few MW to hundreds of MW for few cycles of power frequency. The AC power requirement is met by extracting energy stored in large flywheel attached to axial flux generator or rotary compulsators. The latter is a form of synchronous generator driven by some prime mover. In the event of demand of large power, the limit of prime mover output as well as field currents can be breached as per requirement.

The high current results in extremely large heat generation due to ohmic losses even though the current flow is transitory. This along with the core losses cause intense rise in the temperature. Since the operation of energy machine is for a fraction of a second, the temperature rise would be much below than the prescribed limit. In such machines cooling arrangement based on hydrogen or ammonia may be used. These machine may also have hollow conductors for forced water cooling, but since machines are used in remotest areas, additional cooling infrastructure is normally avoided. However, in EMALS on ship, such schemes may be successfully installed. From the view point of EMI / EMC compatibility, for avoiding radiation field due to portion of cable or winding overhang, suitable measures are required to properly shield the source of radiation. The cables need to be enclosed in copper or aluminum pipes. For safe operation of any electrical devices all the aspects of magnetic circuit, electrical circuit, dielectric circuit, thermal circuit, mechanical circuit and EMI/EMC compatibility are to be taken care of.

### 2.2.2 Joules Limit Criterion

A very thin conducting sheet may give better thrust in energy machine by reducing the entrefer (iron to iron distance) but the secondary loss in energy machine used in launcher application may cause melting of conducting sheet metal (aluminium) or losing the strength of secondary material when temperature goes beyond 200°C. Sheet of conducting metal or alloys loses its mechanical strength much before the melting point. Launchers works by applying momentarily a very high voltage for few cycles, resulting in extremely large current and extremely large power loss resulting in rise is temperature. These launchers may operate successively several time after a period. Joules limit criterion need to be adopted for deciding the thickness of aluminium sheet and design of secondary, which relies of thermal computation. The use of conducting material having higher melting point such as German Silver and Tungsten is inevitable.

### 2.2.3 Thrust speed characteristics

It is essential that the launchers based on LIM should quickly start. When hard characteristics are used, there are severe oscillations in starting current and thrust oscillates severely during unstable portion of the characteristics. When launchers are made using soft characteristics with maximum thrust at the time of starting, the initial transient in current and thrust are mitigated and launcher responds is least time, although in such cases the speed decreases when launcher is in loaded conditions. But since launcher is using only the large initial thrust in sub synchronous zone and switches off prior to synchronous speed,a the drop in speed or the transient oscillation in speed close to synchronous speed are not observed by the mover. The mechanical time constant of such system are comparable to electrical time constant.

When high voltage is applied to launcher, the initial starting force developed by the machine may be extremely large. If such as large thrust is applied by some other means, its natural operation will result in extremely large speed in super synchronous region. Because of induction machine principle, if the supply is still ON due to any reason, theinduction action will allow the launcher to operate in super synchronous speed and results in dip in thrust and speed. As such these machines requires essential compensation if the supply remains ON for longer duration of time. When the length of travel is large like in case of EMALS, where several blocks are switched ON /OFF successively to support movement of short secondary, each blocks are ON /OFF with fixed line voltage and frequency which are known in advance. such system give EMI/EMC compatibility issues.

### 2.2.4 Sheet secondary in LIM

The SLIM of DSLIM have sheet secondary in which width of secondary is more than the core width / back iron. The aluminum plate in transverse directions which is beyond the core serves the path for return eddy current to flow. It is designed according to Russel's and

Norsworthy factor.A lesser overhang will offer larger eddy current losses which are flowing in overhang portion and are not productive.A larger secondary overhang will increase cost of conducing reaction rail when laid in longer distance. Wider secondary overhang causes movement difficulties with short secondary mover. As such modified secondary structure is preferable to be used. This has been shown in Fig. 2.2. The width of primary core and width of back iron are kept identical. At high speed the normal force of attraction between primary iron core and secondary back iron increases. This results in increase of virtual weight of mover and results in better movement of secondary which is not get dynamically perturbed by transverse forces of any type.

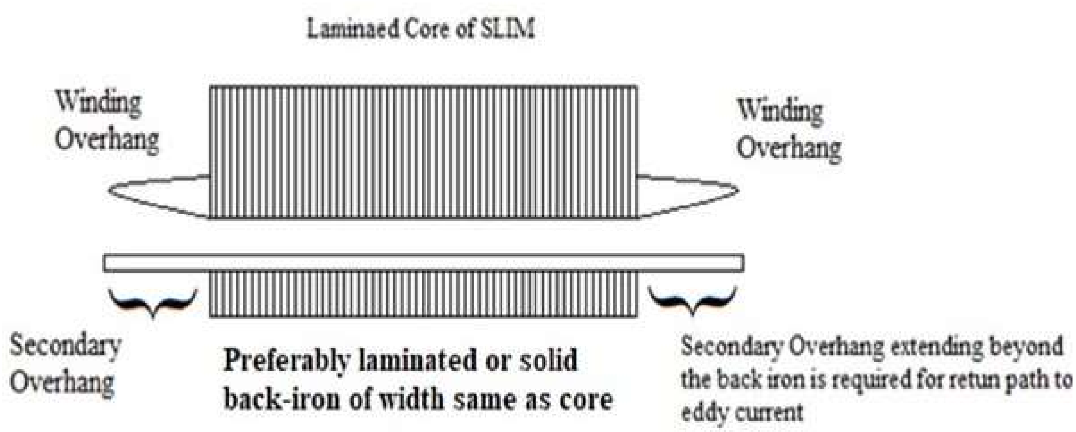


Fig. 2.2 (a) Actual Secondary overhang – transverse direction

In **Energy Machine** it is required to keep the minimum volume of equipment which can fit into a smaller space in a secured manner. Depending on application and design the mover which is analogous to rotor of rotary induction motor, can be of:

- Plane sheet of conducting material such as aluminum, copper, brass, bronze, tungsten, German Silver and Beryllium copper etc. – However plane conducting sheet secondary gives inferior thrust as that of composite secondary

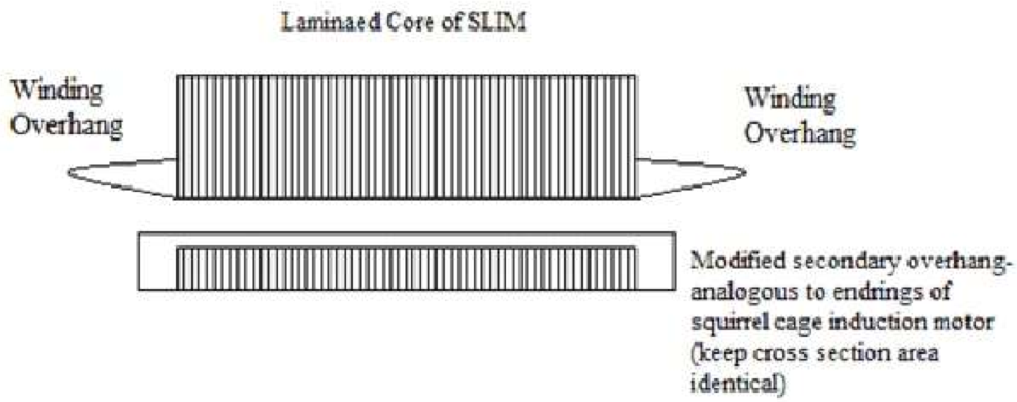


Fig. 2.3 (b) Modified secondary overhang

- Composite secondary- conducting sheet secondary backed by iron plate –solid / laminated
- Ladder secondary
- Squirrel cage secondary

Conducting (say Aluminium) plate and back iron may be fixed to form a composite secondary using pressure ( in lab development ); Adhesive such as araldite (small versions) ; Explosion arc welding – preferred for launcher application. In most of the cases of SLIM Composite secondary is preferred. In case of Blade launcher, the loss of secondary material when plane and composite secondary are in use can be managed. Recovery of the secondary using parachutes or some other means can also be used. When same secondary is to be used several times, plugging is required which release projectile at high speed and the movers come back. When secondary has performed the job, it releases the object to be launched from the secondary mover once brake (electrical plugging) are applied. The counter current thrust brings the secondary back to original start point. The release point at which plugging is applies is judged using proximity sensor. Continuous cycles of launch may be completed; however thermal conditions of the launcher should be ensured. It may require a centralized controller and data logger along with necessary instrumentations to check current, loss, rise in temperature etc. The design of controller is beyond the scope of present work.

## 2.3 Typical construction of Energy Machines

The normal forces in SLIM are large which can destabilize the operation, Use of multiple SLIM such that normal force is perpendicular to gravitational field is preferred. In case of DSLIM or multiple SLIM the normal forces gets cancelled. The use of conducting material with ferromagnetic is expected to give better performance or squirrel cage secondary may be preferred for small stroke operation.

## 2.4 Windings

The windings in SLIM or DSLIM may be of following types

- Fully filled end slot double layer three phase distributed winding
- Half-filled end slots double layer three phase distributed winding
- Single layer winding three phase distributed winding
- Double layer Slot by slot winding
- Single layer slot by slot.

The short pitching is possible only with distribution double layer winding. Gramme Ring type of windings are not preferred. In conventional linear induction motor Fullyfilled orhalf-filled end slot double layer distributed windings are used. The conventional three phase windings can be either single layer or double layer. Single layer windings is less complicated and offers easy repair and replacement of faulty coils. Single layer windings exhibitsDC spatial flux density resulting in slightly larger normal force, which can be well tolerated [5]. Slot by slot windings are not so common in Linear Induction machine and were regarding as a half slot per pole per phase machine [52]. But these windings have lowest overhang portion, lower copper losses. These slot-by-slot windings have been evaluating to have lowest transient thrust swings in launcher applications by the author as has been reported in Chapter 4. The present work is aimed at finding the best type of winding arrangement for launcher application which results in lowest thrust swing during launching period.

## 2.5 Conclusion

This Chapter has dealt with the salient features of the energy Machines, oscillations in thrust during launch when large voltage is suddenly applied of a few cycles, Joules Limit criterion, role of secondary material and different types of three phase windings. The next Chapter deals with the constant current studies of SLIM.

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