The Evolution of Advanced Induction Motors to Advanced Linear Induction Motors

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Abstract—**Many Linear Induction Motor (LIM) systems have been supplied that use a fixed frequency AC Supply. Such systems must then use a variable winding LIM pitch to accelerate and control the speed of the moving load. This method tends to require LIMs with a high slip and this results in LIMs with a low power factor and high losses.**

The paper describes the development of a LIM system using a Variable Frequency Converter (VFC) as the source of power. This system can then use fixed pitch LIMs, and the acceleration and speed of the moving load is controlled by varying the frequency of the VFC.

The combination enables the LIM design to be optimised for low slip and this has many benefits. The benefits include improved speed control without any sensors, lower LIM losses and a high LIM power factor.

Test data on a prototype LIM are included together with typical applications.

Key words—**Control, Development, LIMs, LSMs.**

1. ROTARY INDUCTION MOTORS

Conventional rotary cage induction motors are used in many applications and are available in a very wide range of powers, voltages, pole numbers and speeds. These motors are normally designed to be started at full voltage and this requires that the impedance's of the motor windings have certain minimum values. This gives a significant difference between the no load speed and the full load speed. This is called the slip speed, which reduces the motor's speed control accuracy and produces extra losses and a reduced motor efficiency.

ALSTOM has led the way in using high power cage induction motors in conjunction with a range of power converters, to give drive systems with constant torque ability over a 0 to 100 % speed range. These motors are fully controlled, with the optimum voltage and current applied at all times, and do not have to be designed for starting at full voltage. This enabled the converter and motor designs to be optimised as a system and resulted in motors with a low slip speed, low losses and a high motor efficiency. ALSTOM calls these Advanced Induction Motors – AIMs.

The AIMs have a very good inherent speed control accuracy, high overload ability and field weakening operation when required. A typical example is shown in Fig. 1.

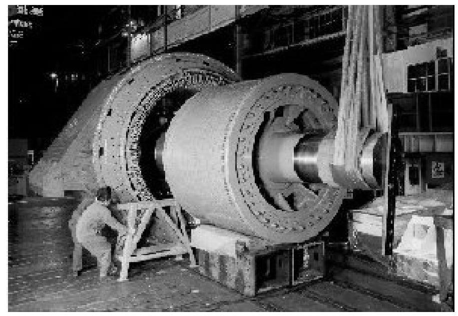

Figure 1. Steel rolling mill main drive of 5000 kW, 0/65/90 RPM and frequent peak torque to 250%.

The wide range of applications using ALSTOM's AIMs would not have been viable if conventional cage induction motors had been used. If conventional cage induction motors had been used the following features would result:

- The converters would need a 50% rating increase.
- The system efficiency would be significantly lower.
- The dynamic performance would be very limited.

2. TYPES OF LINEAR MOTORS.

Conventional linear motors have been used for many years on fixed frequency supplies, with reasonable success.

Following the success of the Advanced Induction Motors a development activity was undertaken by ALSTOM & Force Engineering to develop Advanced Linear Motors.

For the type of applications considered the length of the mechanical system meant that long stator linear motors are normally used. The main decision to be made was the type of linear motor to be used. There are two main types of linear motors in use with the basic circuit shown on Fig. 2.

Linear Induction Motors. These use a conductive plate on the moving load and work like a rotary induction motor, with a slip speed between the speed of the magnetic field and the moving load.

Linear synchronous motors. These use permanent magnets on the moving load and work like a rotary synchronous motor, with phase matching between the magnetic field and the moving load.

Fig. 2 shows that "the speed of rotation" of the 3 phase LIM voltage sets the linear speed of the magnetic field and the linear speed of the moving load.

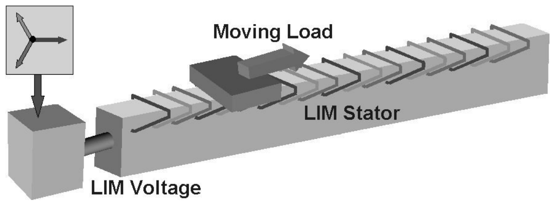

Figure 2. The circuit of a basic LIM.

3. CONVENTIONAL LINEAR INDUCTION MOTORS (LIMS)

Due to production reasons the linear motor is made up of a set of separate stator units. Fig. 3 shows the switches used to only energise the LIM stators, when required, to minimise the current in the fixed frequency AC supply.

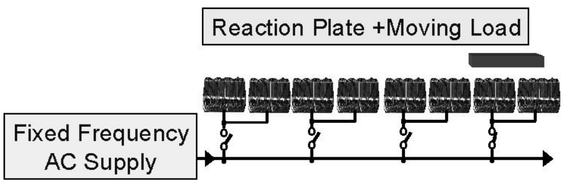

Figure 3 . Conventional LIM system

The slip speed difference between the reaction plate and the moving magnetic field induces a voltage and current in the reaction plate, this produces the thrust. As the AC supply frequency is fixed, the winding pitch of the LIMs is increased to speed up the moving load. Fig. 4 shows four sets of LIMs.

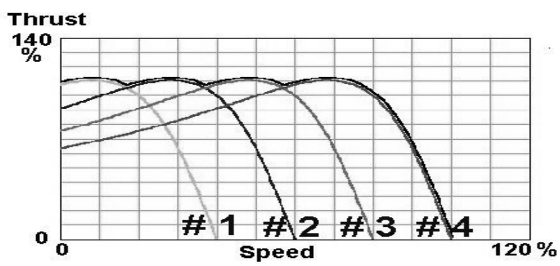

Figure 4. LIM thrust / speed curves.

A typical use of LIMs is shown in Fig. 5. This is for the MAD Cobra roller coaster at Suzuka Japan. The top speed is 26.8 m/s. (60 mph) with an acceleration time of 3 seconds.

Figure 5. The Mad Cobra LIM roller coaster

The experienced gained in applying the conventional Linear Induction Motors clarified the types of possible improvement if a variable frequency power converter was used to power the LIMs.

These improvements are:

- Could use the same winding pitch for all the LIMs.
- Could accelerate the load at a constant slip and force.
- Could develop low slip LIMs with a high power factor and efficiency.
- Could reduce the losses in the reaction plate and reduce its temperature rise.
- Could minimise the thrust variations as the reaction plate moves between LIMs. For conventional LIMs the changes in the winding pitch give thrust transients.
- Could switch on the LIM groups to avoid current surges.
- Could significantly reduce the demands / voltage dips in the AC supply.

4. ADVANCED LINEAR SYNCHRONOUS MOTORS (ALSMS)

Again due to production reasons the linear motor is made up of a set of separate stator units. Fig. 6 shows the switches used to only energise the ALSM stators, when required, to minimise the voltage of the variable frequency supply.

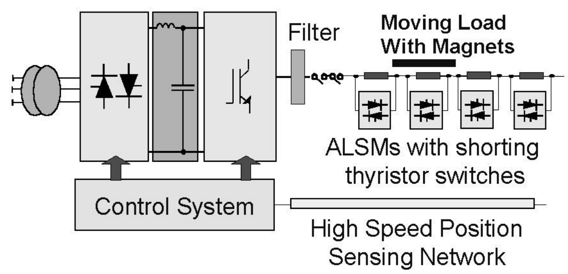

Figure 6. Advanced LSM system

The moving load travels at the same speed as the moving magnetic field. The magnetic field between the magnets and the moving magnetic field produces the thrust. The winding pitch is fixed and the variable frequency is used to speed up the moving load at constant thrust as shown in Fig. 7.

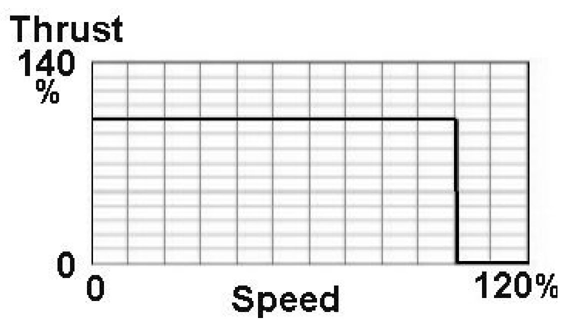

Figure 7. Advanced LSM Thrust / speed curve

The drive system has a fully reversing power flow as shown in Fig. 6. The high speed position sensing network is essential to keep the phase of the inverter's output current exactly in phase with the moving load. A position error of 1 millisecond at 200 Hz will change the thrust from 100% to 0%. The sensor network is a very significant technical challenge. A project using ALSMs is shown in Fig. 8.

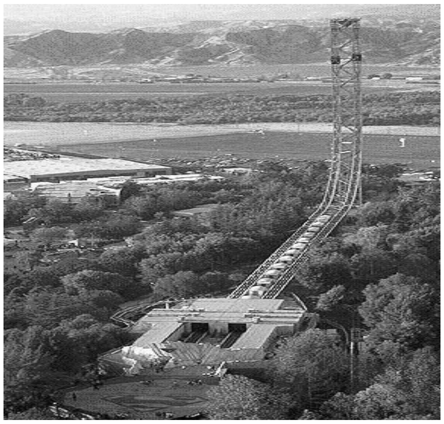

Figure 8. Super Man The Escape

The Key ride data is:

- The ride is Super Man The Escape.
- The ride opened in 1997 at Magic Mountain LA.
- Initial acceleration is 2.0 G linear on a level track.
- The top speed is 45 metres / second = 100 mph.
- The rotational force to go vertical is 4.5 G.
- The vertical height is 121 metres = 415 feet.

  This is the same as a 41 story building like the Blackpool tower or the London Eye.
- The vertical section gives 6.5 seconds at zero G.
- The ride car holds 15 persons and weighs 6 tons.
- The total ride time is 25 seconds.
- The total project cost was $ 20 M.

The experienced gained in applying the Advanced Linear Synchronous Motors clarified the types of possible improvement if a variable frequency power converter was used to power the LIMs. These improvements are:

- By using a low slip LIM could achieve the required speed holding accuracy on open loop control.
- Could eliminate any form of feedback sensors. These are essential for a high performance ALSM, and as they are distributed along all the stators can reduce the systems availability and reliability.

The ALSMs do have some advantages over LIMs:

- They have a safe stopping mode by using fixed reaction rails in the emergency stopping zone.
- There is less heating of the moving load.
- The required inverter is a little smaller, however the ALSMs do not operate at unity power factor due to the added inductance of the non-active LSM stators.
- The ALSMs and ALIMs have a very similar demand in the AC supply network which is much lower than the demand made by conventional LIMs.

  This is due to a property of voltage source inverters, which is that they only transfer the load's power component into the AC supply system.

5. ADVANCED LINEAR INDUCTION MOTORS (ALIMS)

Again due to production reasons the linear motor is made up of a set of separate stator units. Fig. 9 shows the thyristor switches used to only energise the ALIM stators, when required, to minimise both the operating currents and the inrush currents in the variable frequency supply.

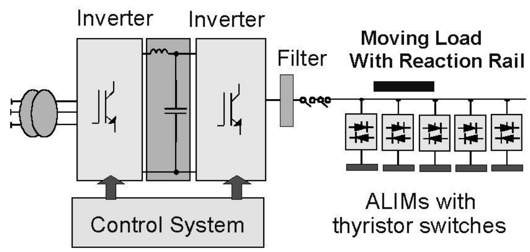

Figure 9. Advanced LIM system.

The slip speed difference between the reaction plate and the moving magnetic field induces a voltage and current in the reaction plate, this produces the thrust. With ALIMs the slip speed is low giving accurate open loop speed control. The winding pitch is fixed and the variable frequency is used to speed up the load at constant thrust, as shown in Fig. 7.

The drive system has a fully reversing power flow, unity supply power factor and very low harmonics. The thyristor switches are essential to minimise the inverter's rating.

The ALIMs have a very low slip and the system has a high speed control accuracy on open loop control, without needing any feedback sensors. The system also adapt to unexpected changes of the mass of the load with a very small speed error.

A possible use for ALIMs is shown on Fig 10.

Figure 10. Existing aircraft steam catapults.

The present USA super carriers use steam catapults. The USN has embarked on an EMALS (Electromagnetic Aircraft Launching System) program to replace these with a Linear Motor launching system. A smaller program called EMCAT (Electromagnetic Catapult) for the UK MoD has also looked at Linear Motors for aircraft launching.

The key to developing ALIMS is to use a low slip design to give low losses, as shown in Fig. 11. By using the knowledge gained in developing advanced rotary induction motors and conventional linear induction motors a development program to produce an advanced linear induction motor has been completed by ALSTOM and Force Engineering Ltd. under funding from the UK MoD. This ALIM has now been successfully tested.

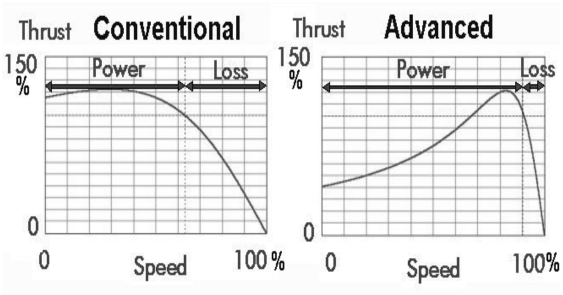

Figure 11. Advantages of low slip LIMs.

To be able to test the ALIM a test system was installed with a high power inverter and a thyristor switch. A mechanical test frame was developed to measure all the forces produced, as shown in Fig. 12.

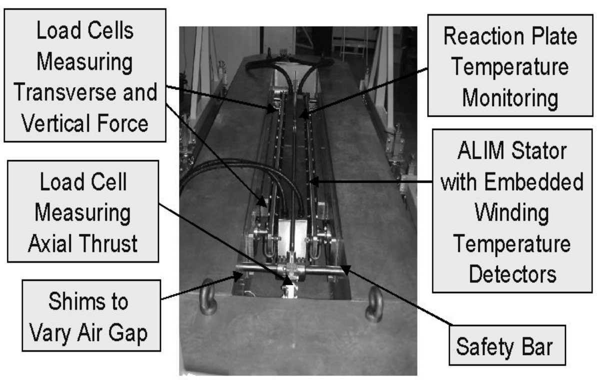

Figure 12. The Stall Test Frame

The ALIM was designed for a thrust of 4 kNewtons at up to 80 m/s. (180 mph) at 200 Hz. The ALIM was stall tested at the rated current of 1000 amps, and at 500 amps, with a frequency varying from 0 to 200 Hz.

The test results have been compared with the data from the model developed during the design phase. The data verifies the design of the ALIM and the accuracy of the model. This is shown on Figure 13.

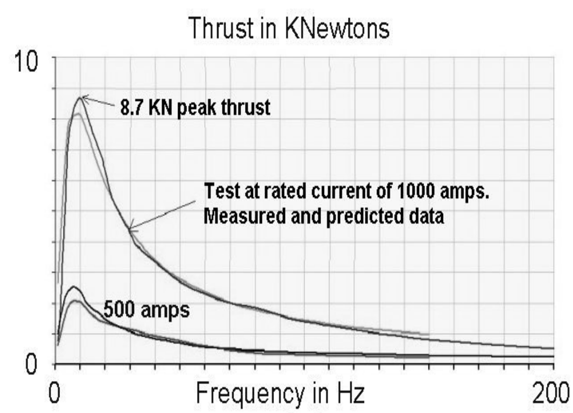

Figure 13. The test results

A constant current tests is significantly easier to implement than plotting the conventional torque / slip curve. The temperature rise of the reaction rail was less than 10 degrees C after 2 seconds at rated thrust.

6. Application Of Advanced Linear Induction Motors

The development of the ALIM has already given many application benefits including:

- A reduction in the converter size to 50% compared to using conventional LIMs.
- A reduction in the AC supply current to 20% compared to using conventional LIMs.
- A reduction in the AC supply voltage dip to 10 % compared to using conventional LIMs.
- An open loop speed control accuracy of better than 1% for a 10 % load variation.

These and the other benefits will enable many more successful projects to be completed including:

- Theme park rides with increased speeds and acceleration.
- Baggage handling.
- Ship test tanks.
- Lifting systems.
- Launching aircraft including UAVs or UCAVs (Unmanned Aerial Vehicles) or (Unmanned Combat Aerial Vehicles).

7. Conclusion

The developments reported in this paper have produced advanced linear motors that have the following properties :

- Optimised to work with the latest generation of power converters
- Optimised to work with a variable frequency and variable voltage power supply.
- Have a high open loop speed accuracy, without feedback sensors.
- Are able to adapt to the mass of the moving load.
- Designed for high speeds of 200 Hz at 80 m/second.
- Designed with a practical air gap of 8 mm.
- Designed with a constant thrust versus time ability.
- Have a high overload ability (>150% rated thrust)
- Have a low slip giving low losses.
- Have a high on load efficiency (> 78% versus 45% originally).
- Have a high on load power factor (> 0.6 pu versus 0.4 pu originally)
- Have a low off load current consumption (< 30%).
- Designed to minimise the end effects.
- Proven to minimise the ALIM switching transients.
- Proven to minimise the EMI / EMC effects.

These objectives result in a system with lower capital and running costs.

Acknowledgment

The authors wish to thank their companies and the UK MoD for permission to publish this paper.