CHAPTER 1
INTRODUCTION

1.1 Topological Aspects

Ever since the invention of the polyphase induction motor by Tesla in the latter half of the 19th century, there has been rapid development of the induction machine prompted by a wide variety of industrial requirements. These machines known for their ruggedness and reliability have been built in sizes ranging from fractional horsepower to more than 10,000 h.p. for various applications. Throughout this long period of intense research and development of the induction machine, the initial cylindrical configuration of the stator and rotor has remained unaltered. This peripheral symmetry has also been utilised with advantage in developing both the circuit and field models of the machine.

Developments in the past three decades have brought in their wake new members of the induction machine family such as the tubular motor, and the arch, spherical or log motors that are related to the conventional motor topologically. Probably the most important outcome of this topological innovation is the development of the linear induction motor (LIM). The pioneering work of Laithwaite and his associates has revealed the potential advantages a
LIM drive can offer in a number of applications, especially in high-speed ground transportation systems. A number of research projects with full scale LIM prototypes as thrust machines aimed at establishing appropriate vehicle and track technologies for rapid transit systems are under way in many countries\textsuperscript{5-7}.

Reference 1 gives a detailed account of the sequence of topological variations one might encounter in arriving at the linear induction motor from its rotary counterpart, along with a classification of LIMs. Accordingly there are configurations known as short-stator or short-rotor, single- or double-sided, longitudinal - or transverse-flux, and isotropic - or composite-rail types of LIMs.

Fig. 1.1 shows a three-dimensional view of a short-stator, double-sided, sheet-secondary type LIM along with the chosen cartesian co-ordinate system. The present investigation is concerned with the theoretical and experimental studies of certain aspects of the steady state and transient behaviour of this type of linear induction motors.

Though the basic principle of operation of the LIM is similar to that of the conventional induction motor, there are a number of points of departure in the analysis and performance of the LIM. Usage has, at the same time, carried over most of the terminology of the conventional machine into the LIM literature. Accordingly the reaction
Fig. 1.1

3-dimensional model of LIM
rail is often termed the rotor or secondary. All the basic phenomena associated with LIMs can be explained with reference to fig. 1.1. The x-axis which is the direction of relative motion between the stator and rotor is known as the longitudinal axis. The second direction y is the depth of the machine, in line with the length of the airgap. The active primary currents flow across the width of the stator; this is called the transverse or z direction.

1.2 Basic Phenomena in Linear Induction Machines

Geometrically, for a machine of finite dimensions, there is a topological discontinuity in each of the three directions. The magnetic discontinuity in the x-direction gives rise to entry-exit transients, commonly known as end effects. This is unique for the LIM and is responsible for the deterioration in performance of the machine at high speeds, as reported by a number of authors. Theoretically, the open magnetic structure makes the analysis of the LIM considerably more difficult. The discontinuity in the z-direction due to the finite width of the stator and rotor gives rise to the transverse edge effects, as the closure of the secondary currents causes a redistribution of airgap flux density across the width of the machine. This effect is similar to the end effects in solid rotor and sleeve rotor rotary induction motors.
The other basic phenomenon resulting from the finite thickness and isotropy of the rotor is the diffusion of the field in the secondary. This is known as the skin effect and is dependent on the properties of the reaction rail and the rotor frequency.

An exact 3-dimensional analysis of the LIM taking into account all the above factors is rather difficult. However, from an engineering point of view, it is possible to simplify the problem by resorting to either one-dimensional or two-dimensional approaches for investigating certain specific aspects, as revealed by a number of recent publications, discussed below.

(a) Rotor skin effects

The problem of diffusion of magnetic field in thick rotor plates was first examined by West and Hesmondhalgh, while its importance in the analysis of LIMs was studied by Wang. Both these papers ignored the transverse edge effects and assumed idealised sinusoidal variation of flux in the longitudinal direction. Nasar and Kliman and Elliott have recently made use of a skin-effect correction factor for dimensional simplification of the problem.
(b) Transverse edge effects

There have appeared a series of papers emphasising the transverse edge effects, the earliest being authored by Russel and Norsworthy\textsuperscript{14}. In treating the eddy currents and wall losses in screened rotor induction machines, they introduced a resistivity correction factor for the secondary, which found acceptance in many of the subsequent publications\textsuperscript{4,10,15}. The problem was later reformulated by Bolton\textsuperscript{16} resulting in the derivation of elaborate correction factors for the transverse distribution of the flux density, equivalent power factor and rotor conductivity. These expressions are functions of the Goodness factor\textsuperscript{1} and rotor speed, and are helpful at the design stage\textsuperscript{9}. In another important paper, Preston and Reece\textsuperscript{17} considered the same problem, taking into account the airgap leakage, rotor skin effect and the flux in the overhang region. This two-dimensional approach leads to series solutions for the field quantities, that are generally quite complicated. A transfer-matrix formulation to the problem of simultaneous consideration of the skin effect and transverse edge effects has been presented by Alden and Nolan\textsuperscript{18}. This paper, which is based on the general results of field propagation in multiple laminar regions, put forward earlier by Cullen and Barton\textsuperscript{19} and by Grieg and Freeman\textsuperscript{20,21} also ends up with series solutions whose convergence has
been accelerated using appropriate data smoothing techniques. An observation that applies to all the above investigations is the assumption of sinusoidal distribution of field quantities in the longitudinal direction, which implies that the entry-exit effects are ignored.

(c) Longitudinal end effects

The longitudinal end effects in LIMs has been the subject of extensive analysis by a number of authors\(^9,10,22\). Yamamura\(^8,22\) has shown that analytical solutions taking into account the end effects can be obtained by considering the finite length of the primary excitation without serious error. On the other hand, introduction of the physical iron boundaries corresponding to the ends of the stator to model the finite iron length leads to some major problems in the solution of the field equations. Such an exercise would entail solution of coupled partial differential equations in three independent variables for the airgap, rotor and stator regions, satisfying appropriate boundary conditions. Analytical solutions for this type of problems are not known presently, making it necessary to go in for numerical solutions. Nasar and del Cid\(^{23}\) have put forward a two-dimensional finite-element method for treating the end effects, neglecting the transverse variations. On the other hand, in the mesh-matrix method of Kliman and Elliott\(^{13}\), the rotor is modelled by a train of coupled circuits.
Here the rotor skin effect is accounted by a correction factor, and the mesh currents obtained by solving a large number of simultaneous algebraic equations. Both these papers represent significant advances in the state of the art, but generally require large computer time and memory. Another noteworthy contribution towards the analysis of current-fed LIMs has been made by Dukowicz\textsuperscript{10}, which removes many of the restrictions mentioned earlier. This 2-dimensional model is amenable for the treatment of arbitrary primary currents and the finite length of the stator iron by the artifice of a fictitious current sheet at either ends of the core. The conductivity and distribution of these current sheets are determined by a lengthy analysis involving a pair of integral equations and comparison of the end results with a static fringing flux distribution.

1.3 Scope of the Present Work

The objectives of the present investigation, along with the original aspects characterising the work vis-a-vis the state of the art in the area of LIMs, are as follows.

1. Development of a general purpose steady state model of the current-fed LIM, which will be adequate for the investigation of the LIM performance under general conditions of source unbalance, with the single phase and plugging operations of the machine as special cases of interest.
2. Analysis of the stator overhang leakage fields which differ from that of a conventional rotary machine on account of the geometry of the LIM so as to predict the stator leakage reactances from design data.

3. Examination of the voltage-fed operation and performance of the LIM covering both the motoring and braking modes in the presence of supply unbalance.

4. Formulation of a general purpose transient model of the LIM suitable for the study of switching transients.

5. Determination of the transient response of the LIM following sudden switching-in of supply both in the motoring and plugging modes analytically and experimentally.

The development of the thesis is along the following lines.

Chapter 2 discusses the theoretical development of the basic steady state current-fed field model for arbitrary slot current distribution using the Fourier transform method. This forms the nucleus for the subsequent work in Chapters 4, 5 and 6.

The field theoretic model for the calculation of the stator overhang leakage reactance is developed in Chapter 3. Calculation of the slot leakage reactances is also discussed here.
The contents of Chapter 4 include the constructional details of the LIM disc drive and the experimental work pertaining to the current-fed operation of the machine. The theoretical characteristics of the LIM are presented and correlated with experimental work.

The extension of the results of Chapters 2 and 4 for the analysis of the voltage-fed operation is discussed in Chapter 5. Both the analytical and experimental characteristics of the voltage-fed operation are presented and compared.

An approach for the study of electromagnetic transients in LIMs following a switching operation is evolved in Chapter 6. Here the transient model of the machine is obtained in terms of the frequency response functions by extension of the field equations discussed in the earlier chapters.

The transient performance of the machine following sudden reconnection of supply is examined both theoretically and experimentally in Chapter 7.

A summary of the work done is given in Chapter 8 along with general observations and concluding remarks.