CHAPTER 7

TRANSIENT PERFORMANCE OF LINEAR-INDUCTION MACHINES
FOLLOWING SUDDEN RECONNECTION OF SUPPLY

7.1 Introduction

The theoretical model for the simulation of electromagnetic transients in LIMs following sudden reconnection of supply is set forth in Chapter 6. In view of the assumption of constant rotor speed, the mechanical time constants of the machine do not enter into the analysis, and the machine is represented by a time-invariant system driven by a set of known signals. While the approach does not involve iterative calculations, it is still important to choose the various computational parameters of the program in order to obtain a valid numerical solution. The general considerations for the choice of these parameters along with their numerical values are discussed in Section 7.2.

The experimental set up for the determination of the transient characteristics of the LIM following reconnection of supply are discussed in Section 7.3. The oscillograms pertaining to the transient variation of the phase currents and developed thrust are presented
and correlated with the theoretical results in Section 7.4.

7.2 Computational Aspects

There are a few computational parameters to be selected for the implementation of the algorithm for the determination of the transient response functions. It is to be borne in mind that the range of the time domain solution \((0,t_1)\) in eqns. 6.9 to 6.11 is not entirely arbitrary, but is governed by the choice of the frequency domain sampling interval \(\Delta \omega\) by the frequency sampling theorem as specified in eqn. 6.17. In this problem the switching transients being of primary interest, a solution for a duration of 3 or 4 cycles of the 50 Hz supply is desired. It is advantageous to choose the largest value of \(t_1\), while keeping the computational requirements imposed by the frequency domain sampling rate within reasonable limits. For the constant speed solution considered above, a cut-off time \(t_1\) of 80 milliseconds, corresponding to 4 periods of the supply is found to be adequate, since the electromagnetic transients are completed within this time. This enables the frequency domain sampling interval to be fixed at 10 Hz, without introduction of any time domain aliasing error.

The other numerical aspect concerns the cut-off frequency in the computational procedure for the transient
modelling. It is recognised that a voltage-fed machine inherently has a low pass characteristic, as the higher frequency components give rise to lower values of useful flux density per unit applied voltage. In addition, for the above choice of $t_1$, the frequency components of the applied voltage above 250 Hz are less than 1 per cent of the amplitude of the fundamental and can be neglected. Accordingly, the cut-off frequency is chosen at 250 Hz and corresponds to $N = 50$ in eqn. 6.14 for the current and flux density waveforms. A subsequent check for the resulting time domain sampling interval for current waveforms indicates sufficient closeness of the final results with $\Delta t = 2$ milliseconds.

It is pointed out that following the discrete convolution of the current and flux density functions in eqn. 6.13, the number of data points for the thrust characteristic is increased to 100, with $\Delta \omega$ remaining as before. Hence the closeness of the transient thrust variations is enhanced with $\Delta t = 1$ millisecond.

As an additional check on the adequacy of the above parameters, a further run of the program with the cut-off frequency increased to 400 Hz was carried out. It is observed that the current and thrust transients remain essentially unaltered for $t > 4$ milliseconds, for all the values of slip considered. It is concluded that for the
machine considered here, the effects of the frequency
domain truncation are instrumental in affecting the
theoretical results only for a brief period following
the switching instant. A scheme for reducing this
error by means of a correction term is discussed in
Appendix II.

For the above choice of parameters, with the cut­
off frequency set at 250 Hz, the complete transient
simulation of the machine for a specific value of slip
and for three different values of the switching angle
requires about 145 secs. of CPU time in an IBM 360/44
System, with a memory requirements of about 118K bytes.

7.3 Experimental Work

The details of the double-sided, sheet-secondary type
LIM are given in Table 4.1. A switching unit consisting
of a pair of S.C.R's connected back to back on each phase
on the neutral side of the machine enables reconnection
of the LIM onto the supply. The gate currents for the
S.C.R's are derived from a zero-crossing detector unit
followed by pulse amplifying and shaping circuits, with
complete isolation between the three phases. The primary
sensing signal which is sinusoidal in time is derived
from a phase shifting transformer energised from the
terminals of the machine. This enables all the thyristors to be triggered simultaneously at any desired instant of the supply waveform. Three settings on the phase shifting transformer corresponds to switching angles of 0, 20 and 40 degrees with respect to the voltage wave \( v_{ab}(t) \). It may be noted that a switching angle of 60° merely implies repetition of the experiment with a different line voltage as reference. The phase currents are sensed by the voltage drops across three non-inductive low resistances in series with the stator windings and recorded in a 50 MHz storage oscilloscope. The oscillograms in fig. 7.11 cover the range of slip from 0.2 to 1.8 corresponding to both motor and braking modes. Since the mechanical transients involving changes in speed are outside the purview of the problem considered here, all the experiments were carried out with the machine run on no load.

The experimental determination of the transient thrust developed presented some problems. As described in Chapter 4, this is given by means of the reaction force on the stator frame and is measured by means of the strain imposed on a short cantilever, the free end of which arrests the motion of the stator. Direct recording of the developed thrust through the strain gauge output signal requires a wide bandwidth for the mechanical system
that is difficult to obtain in view of the large mass of the stator. The largest undamped natural frequency of oscillation of the mechanical system that was possible to attain consistent with signal strength and repeatability in the presence of some noise was 86.1 Hz, which is of the same order of magnitude as the cut-off frequency of the thrust transients predicted by the theory. Consequently some form of processing the strain gauge output signal by modelling of the measurement system was necessary. This is presented in Appendix III. A least square curve-fitting of the measured signal in terms of exponential and trignometric functions is carried out. The actuating signal, that is the developed thrust is identified from the above filtered output by treating the same as the response of the second order system modelling the thrust transducer.

7.4 Discussion of Results

The results of the investigation on the transient performance of the LIM following reconnection of supply are presented in figs. 7.1 to 7.10. In this chapter the continuous curves represent the experimental results obtained from recorded oscillograms, while the theoretical results are available only in discrete form. The analytical and experimental transient current waveforms
shown in figs. 7.1 to 7.5 correspond to $\delta = 0$ and five different values of slip from 0.2 to 1.8. It is observed that the current waveforms are generally devoid of any severe overshoots and their departure from a sinusoidal variation is practically confined to the first one or two cycles of the applied voltage. This can be partly traced to the larger effective air-gap associated with the double-sided, sheet-secondary type LIM, which effectively forestalls any transient saturation of the stator iron. In addition, the relatively larger stator overhang leakage reactance of the longitudinal flux $LIM_1$ results in attenuation of higher frequency components of currents. This feature also lends validity to the choice of cut-off frequency in Section 7.2.

The presence of subharmonic (lower than fundamental frequency) components in figs. 7.2 and 7.3 is of interest, and point to the generation of transient travelling waves of lower velocity than that of the rotor. It is convenient to portray the spectral distribution in the frequency domain. The spectra of currents for different values of slip are shown in fig. 7.6. The subharmonic peaks in the current spectrum for slips less than 0.5 indicate introduction of transient negative thrusts during reconnection.

The variation of $i_a$ and $i_b$ at slip 0.2 for $\delta = 20^\circ$ and $40^\circ$ are given in figs. 7.7 and 7.8.
The instantaneous thrust variations following switching-in of the machine at different speeds is given in fig. 7.9. Since the thrust trajectories are only slightly affected by the switching angle, this figure shows only the case corresponding to $\delta = 0$. The actual theoretical curves of variation of thrust at $s = 0.2$ for the three values of $\delta$ are presented separately in fig. 7.10.

It is observed from fig. 7.9 that the transient peaks and the periodicity of oscillations are essentially functions of the rotor speed at the instant of reconnection. The largest positive peak is nearly three times the full load thrust, and corresponds to the standstill case with the oscillations nearly at supply frequency. It is interesting to note the monotonic increase of the frequency of thrust pulsations with slip.

The transient negative thrust developed by the machine when reconnected with residual speed on the rotor is noteworthy. A similar result for rotory induction motors had been reported by Flynn et al. in an earlier paper. The largest negative peak thrust for slip 0.2 is again about three times the full load thrust, while that corresponding to slip 0.1 is about 4.2 times. The plugging of the machine at normal voltage gives rise to severe braking thrusts with a peak of nearly six times the full load thrust, corresponding to $s = 1.8$. 
Finally it may be noted that there exists some ripple in the thrust characteristics at the end of the transient period. This is also predicted by the steady state voltage-fed model in Chapter 5 and can be attributed to the inherent unbalance in the machine imposed by the entry-exit effects, discernable especially at higher rotor speeds.

7.5 Summary

The analytical results of the transient problem following reconnection of supply, formulated in terms of the frequency domain model of the LIM are presented in this chapter. These are interpreted and compared with corresponding experimental oscillograms. The variations of the instantaneous current and thrust predicted by the theory are in agreement with the experimental results for different operating conditions. This suggests that the harmonic response technique is a feasible and acceptable method for the study of a class of transient problems associated with LIMs. Certain important conclusions derived from the study are presented and discussed in Section 7.4.
Fig. 7.1

Variation of phase currents

\( s = 1.0, \delta = 0 \)

\( \times, \circ - \) theoretical results
Fig. 7.2

Variation of phase currents

$s = 0.5, \beta = 0$

$x, -$ theoretical results
Fig. 7.3

Variation of phase currents

$s = 0.2, \ \delta = 0$

$x, \circ$ - theoretical results
Fig. 7.4

Variation of phase currents

$s = 1.5, \ b = 0$

$x, \bullet -$ theoretical results
Fig. 7.5

Variation of phase currents

$s = 1.8, \delta = 0$

$x, o -$ theoretical results
Fig. 7.6

Spectrum of \( i_a, \delta = 0 \)
Fig. 7.7

Variation of phase currents

$i_a, i_b$ per side, A

$t, \text{msec.}$

$s = 0.2, \delta = 20^\circ$

$x, \bullet$ - theoretical results
Fig. 7.8

Variation of phase currents

s = 0.2, β = 40°
x, • - theoretical results
Fig. 7.9

Variation of developed thrust
full-load thrust = 1
x, o, A, v - theoretical results
Fig. 7.11 Variation of the phase currents, $i_a$ and $i_b$
Fig. 7.11 Variation of the phase currents, $i_a$ and $i_b$

Fig. 7.12 Thrust transducer output signal