Transient Analysis of Offset Stator Double Sided Short Rotor Linear Induction Motor Accelerator

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ABSTRACT: A new winding scheme using planar non-overlapping coils is described for use in linear induction motors for leisure rides, and proposed UAV and aircraft launch systems. The machine is double-sided and the stators stretch along the length of the launch track. The secondary is a short plate positioned between the stators and connected to the carriage. The use of planar coils is cost effective and produces modules which have short end turns and can be butted together. Time-stepped finite element analysis is used to calculate the transient performance of the new arrangement and to contrast its performance with conventional machines. A method to reduce the computational effort required for design of both conventional and planar wound machines is proposed.

1 INTRODUCTION

1.1 Linear Motor Topology

Linear induction motors can be made in many different topologies. The most common uses a linear stator which can conceptually be formed by cutting the stator of a conventional cylindrical induction machine in a radial plane and unrolling it. The secondary member uses a simplified version of an unrolled squirrel cage induction motor rotor that comprises a conducting plate backed by a solid iron core.

For continuous action either the linear stator or the linear secondary must be shorter than the other member. In the most common industrial applications the stator is short and the secondary is long as shown in Figure 1.

For use in leisure ride and proposed UAV and aircraft launch a double-sided topology is usually employed. Here the stator is long occupying the length of the launch track and the secondary is a simple short plate attached to the carriage. This arrangement has economy since no secondary iron is needed. The return path for the flux from one stator is provided by the second as shown in Figure 2.

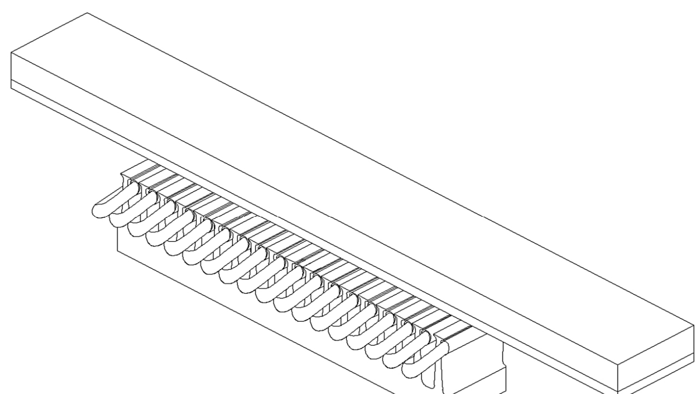

Figure 1. Linear motor configured as a short stator

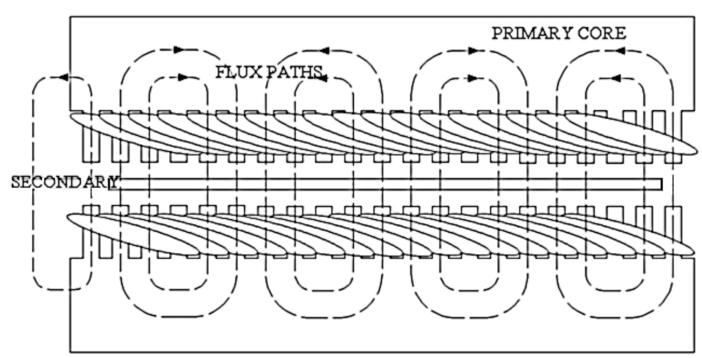

Figure 2. Flux paths in a double sided linear induction motor

An additional advantage is that there is virtually no force orthogonal to the plate in this arrangement. This is in contrast to the arrangement of Figure 1 where the normal force can be considerable. Figure 3 shows a double-sided stator launch assembly together with one of the component stators.

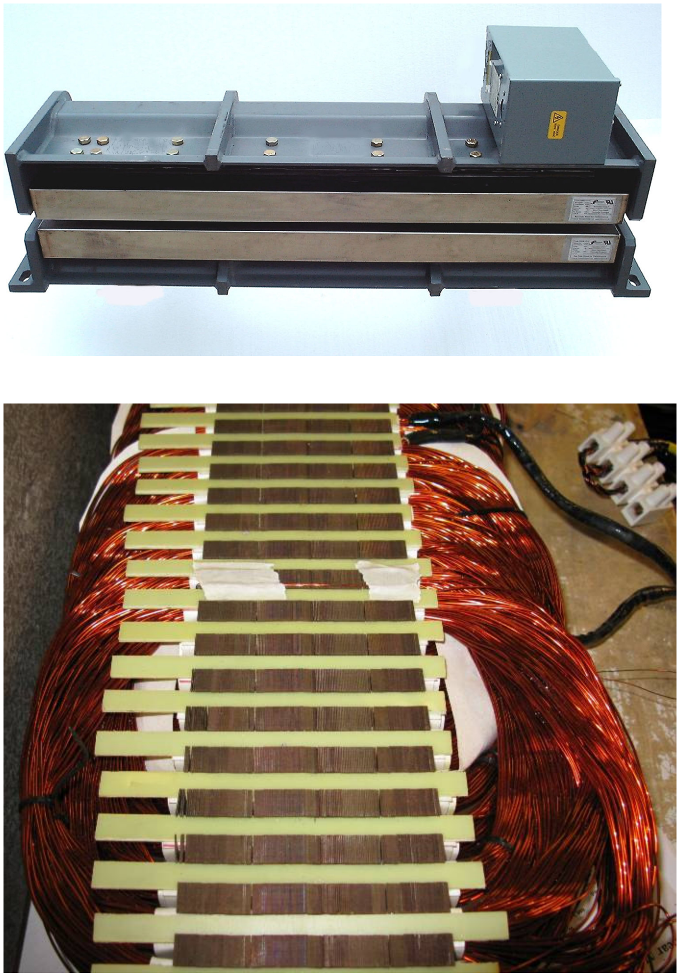

Figure 3. Double sided stator launch assembly

2 STATOR WINDINGS

2.1 Double Layer

Double layer windings are generally used for linear stators and it can be seen from the example in Figure 3 that the end turns at the sides of the machine are bulky, mainly because the construction leads to overlapping coil sides. This is a disadvantage since the width of the stator is increased and so is the size of the housing required. A second disadvantage is that either half filled slots or coil sides around the ends of the core must be used so that butting stator modules together is more difficult.

2.2 Planar Non-Overlapping Windings

Polyphase ac windings can be formed using coils that are planar and which do not overlap adjacent coils. These windings are very cost effective when open slotted stators are used since the coils can be completely pre-formed before insertion.

The construction of planar windings is shown in Figure 4. The winding connection sequences are given in Table 1 for the three most apt configurations. Planar windings of this type are excellent mechanically. However, they all have a high harmonic content and in particular produce two large fields, one forward going and the other backward. For example the designation 12 coil 10/14 pole indicates that this is a 12 coil module that produces a high 10 pole forward going field and a high 14 pole backward going field.

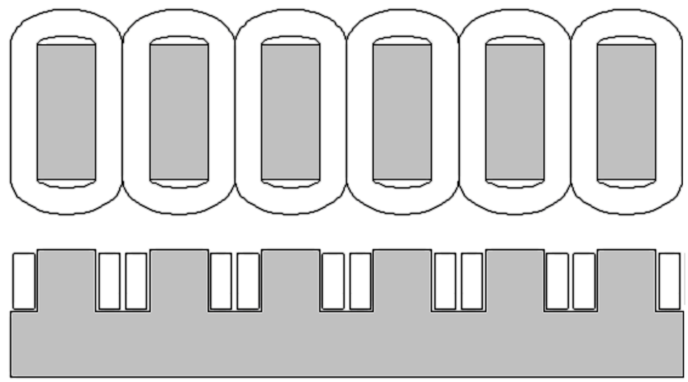

Figure 4. Planar winding construction

Table 1. Configurations for planar non-overlapping windings

Winding type	Coil configuration
3 coil 2/4 pole	U V W
9 coil 8/10 pole	U -U U V -V V W -W W
12 coil 10/14 pole	U -U -V V W -W -U U V -V -W W

The planar windings are in common use only in machines with permanent magnet excitation. In these machines a time average torque is produced only when the permanent magnet field and the stator field have the same pole number. Therefore, either of the two large stator fields can be employed by using an appropriate permanent magnet array. The other stator field produces air-gap leakage flux but plays no other part. Essentially the permanent magnet array acts as a selector for one or other of the fields.

If the planar windings are used with a plate secondary in linear machines then eddy current and force are produced by both the forward and backward fields and since the fields travel in opposite direction the forces are in opposition. There is little resultant force. Figure 5 illustrates the effect by comparing the response of a plate to a double layer winding with little harmonic content to the response with a winding using the 3 coil 2/4 pole module. It is clear that planar windings cannot be used with plate rotors unless the harmonics produced by the winding are modified.

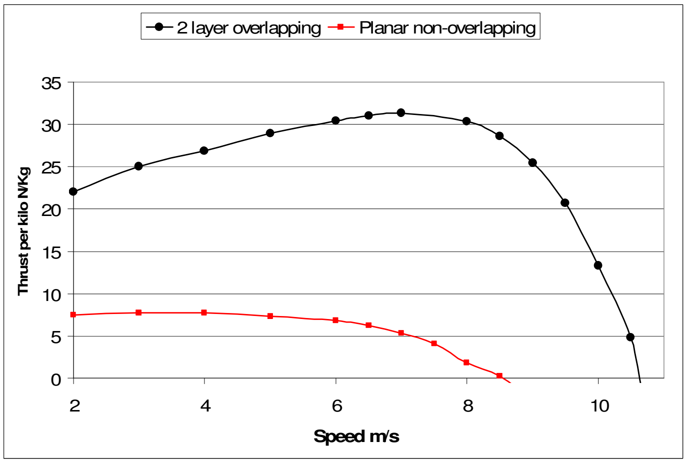

Figure 5. Comparison of stator performance using a plate rotor

2.3 *Offset Stator Machines*

Either of the two fields from a planar winding can be cancelled in a double-sided machine by offsetting the space position of the stator on one side of the plate with respect to the other [1] [2]. For example Figure 6 illustrates the effect using a 3 coil 2/4 pole winding. Here the second stator winding is reversed and offset a wave length. It can be seen from Figure 6 that the 4-pole field is cancelled whilst the 2-pole field from the stators adds.

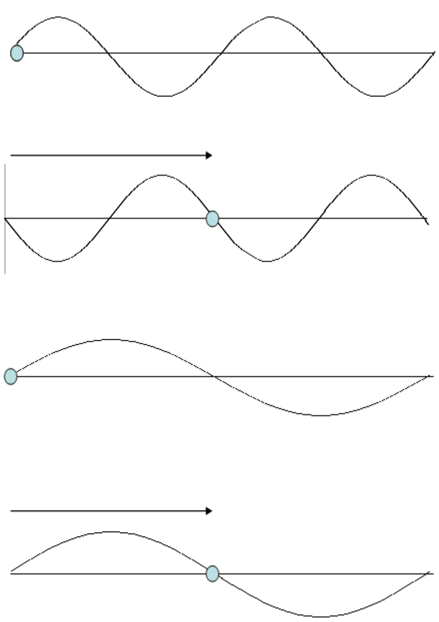

Figure 6. Harmonic cancellation of the 4 pole field and reinforcement of the 2 pole field

Similar results can be obtained using the 9 coil 8/10 pole and 12coil 10/14 pole windings. Figure 7 shows a machine in which 9 coil 8/10 pole stators are used with a 4 pole offset on the 8 pole field. This will eliminate the 10 pole fields and completely add the 8 pole fields from the stators.

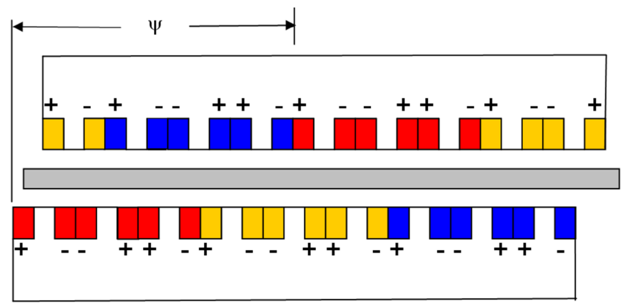

Figure 7. Machine using 9 coil 8/10 pole stators

3 FINITE ELEMENT ANALYSIS

The motor configurations were modeled using the Bath University MEGA 2D finite element (FEA) package [3]. The analysis uses magnetic vector potential A with the governing Equation 1.

$$\nabla \times \frac{1}{\mu} \nabla \times \mathbf{A} + \sigma \frac{\partial \mathbf{A}}{\partial t} = \mathbf{J} \qquad (1)$$

This was transformed into an equation system using the finite element method and the Galerkin weighted residual procedure.

A time-stepping scheme was used to simulate the dynamic behavior of the moving plate secondary. A special sliding surface interface FEA technique was employed in which the moving plate and the stators are represented by separate meshes. These are joined together by two interfaces. Since the meshes are separate they can slide relative to each other which enables the dynamic motion of the plate to be modeled without re-meshing. The modeling is 2D and so in order to allow for the effect of 'end-ring' longitudinally directed plate currents that are present in the practical case the rotor resistivity was modified by a factor derived from [4]. The modeling was checked against preliminary experimental results from a rotating test rig, which gave the satisfactory comparison shown in Table 2.

Table 2. Experimental and FEA force comparison

	Experimental	FEA
Force at 1m/s (N)	960	971

4 SHORT ROTOR OPERATION

In a conventional non-offset machine with infinitely long stators and secondary plate the instantaneous current in the plate has a sinusoidal distribution in space. However in the short rotor case transients at the plate edges disturb this pattern [5]. These transients are due to the flux in the plate region being different to the flux elsewhere. This causes transients as the edge of the plate traverses from one flux to the other. Examples comparing the short rotor plate current with the current in the conventional case when a double layer conventional winding is used are shown in Figure 8.

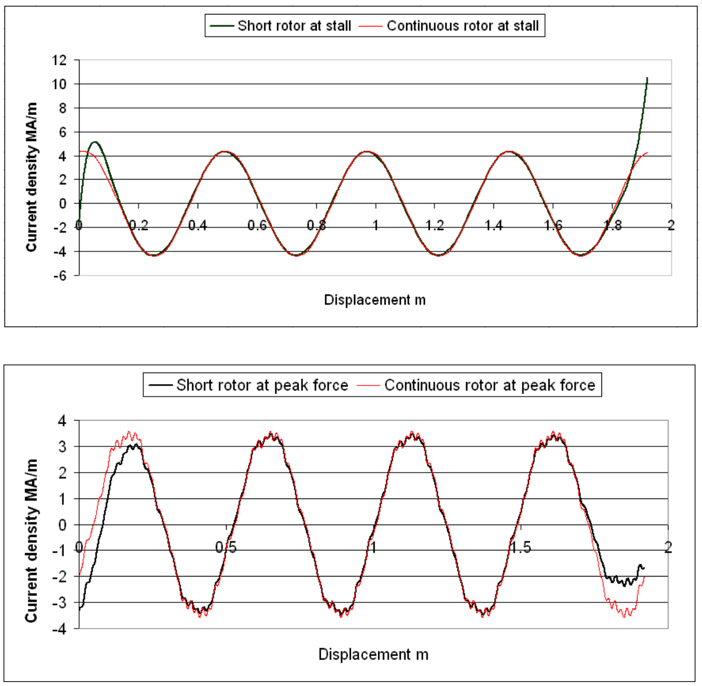

Figure 8. Short rotor plate currents

It will be seen that the effect takes place over only a small region. The thrust force is therefore compromised by only a few percent by the short rotor effect with double layer windings. This is illustrated in Figure 9 and it can be seen that the reduction in peak thrust is of the order of 10%.

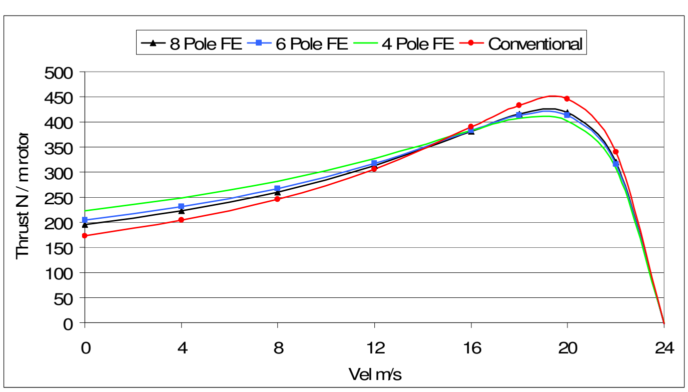

Figure 9. Short rotor thrust speed curves

In performing initial system design work it is therefore sufficient to ignore the short rotor effect and use much smaller models since only one module length has to be included if the plate is effectively infinite in length.

5 OFFSET MACHINE FORCE RESULTS

It is important to check if the new offset machines with short plate secondary members behave in a similar manner to the double layer machines. Time stepped results were therefore calculated first for a conventional infinitely long plate and secondly with a plate length of 8 poles. The calculations were performed with the plate accelerating against an inertia and Figures 10 & 11 show the comparative force-time and speed-time graphs. It will be observed from the graphs that initial system design can again be done using the much simpler conventional rotor calculations.

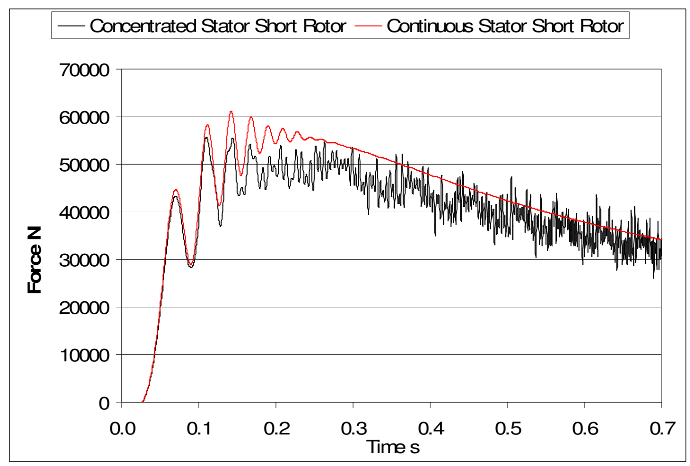

Figure 10. Force-time curve for offset launcher

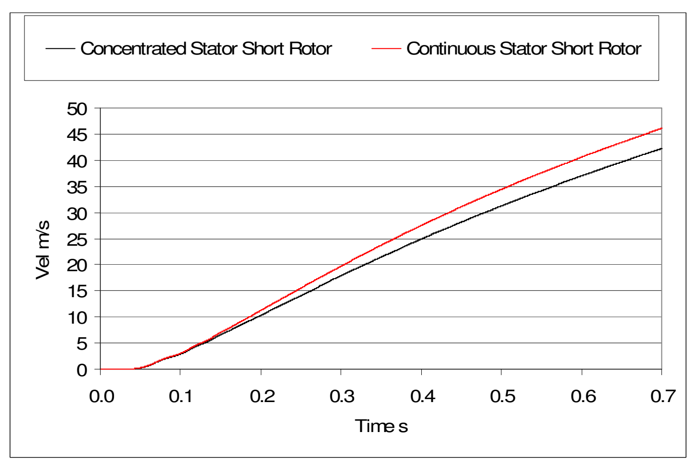

Figure 11. Speed-time curve for offset launcher

6 DESIGN COMPARISON

The use of the new offset machines has been compared with the use of conventional machines for a notional UAV launcher. The results of FEA time-stepped calculations for Force against time and VA per Newton against time are shown in Figures 12 & 13.

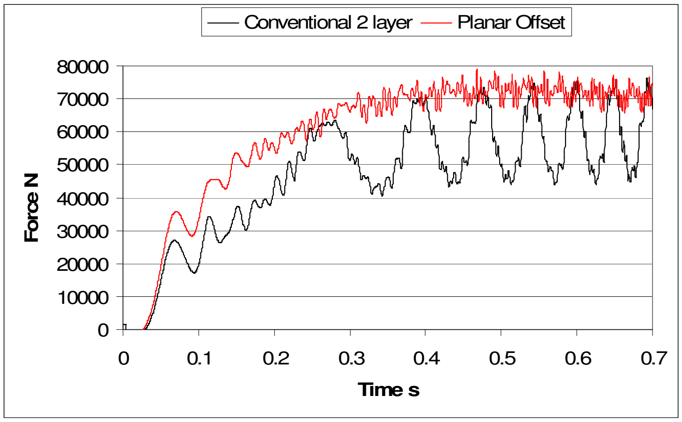

Figure 12. Launcher comparison force-time

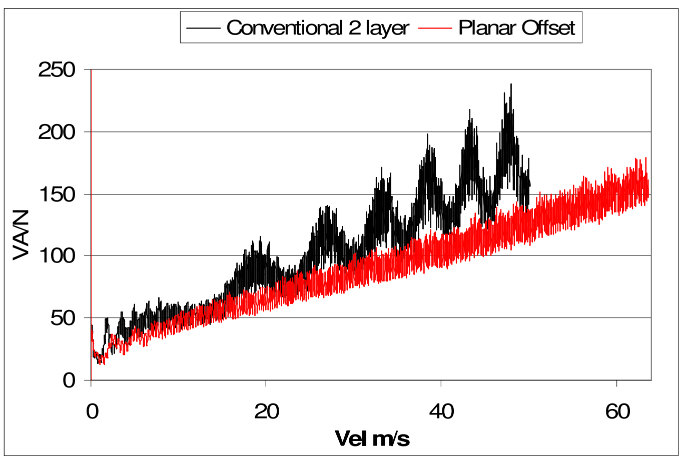

Figure 13. Launcher comparison VA/N-time

The superior performance of the new offset machine can be seen. This is partly due to the perturbations on the graphs caused by the transitions between the stator units in the conventional machine case due to the difficulties of butting the stators together.

7 CONCLUSIONS

A new form of double-side linear induction motor has been presented. This is less costly to build with an estimated 30% saving and gives a superior performance. It has been confirmed that simpler FEA models can be used for the design of the new machine.

References

J. F. Eastham, T. Cox, H. C. Lai, J. Proverbs, “The use of concentrated windings for offset double stator linear induction motors,” LDIA, Lille, pp. 106-107, Sep. 2007 and published in Electromotion, Vol. 15, No. 2, pp. 51-56, Apr. 2008

J F Eastham, Force Engineering Patent “Improvements in and relating to Electromotive Machines” International Patent Application No PCT/GB2007/003849

P.J. Leonard, D. Rodger, H.C. Lai, M. Norton, R.J. Hill-Cottingham, “Coupling FE with power electronics and rotor dynamics of motors” IEE Seminar on Current Trends in the Use of Finite Elements (FE) in Electromechanical Design and Analysis, Ref. 2000/013, pp. 6/1-6/6, 14 Jan. 2000.

R.L. Russell, K.H. Norsworthy, “Eddy current and wall losses in screened rotor induction motors,” Proc. IEE, Vol. 105A, pp. 163, Apr. 1958.

T Cox, Prof. J F Eastham, Dr H C Lai, J Proverbs, “Investigation of short-rotor linear induction motors using finite element modelling”, Linear Drives for Industrial Applications, Lille, Sep. 2007