Comparison Between Plate and Wound Secondaries for Linear Induction Motors with Concentrated Winding Primaries

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***Abstract* – Concentrated windings that use planar non overlapping coils are simple in construction with comparatively narrow end regions. This leads to linear induction motor stators that can be butted together in sections to form long stator machines for urban transport and electromagnetic launch systems. The windings however produce two components of travelling field moving in opposite directions. The response of the plate rotor to the windings is therefore poor since opposing forces will be produced by the two fields. The use of a wound secondary rather than a plate dramatically improves the response. Here substantial emfs, currents and forces are produced only by the pole number for which the secondary is wound. The wound rotor therefore selects one of the fields produced by the concentrated winding for operation. The new principle is explored by the use of Finite Element Analysis and practical tests and it is shown that good force profiles and efficiencies are possible from concentrated stator wound rotor machines.**

***Index Terms* – Linear induction motors, Concentrated windings, Wound rotors**

I. INTRODUCTION

Concentrated windings are a simple form of machine stator winding commonly used with permanent magnet rotors in various applications such as disk drive motors and linear drives.

The use of concentrated windings in Linear Induction Machines would be extremely advantageous, particularly when the wound member is longer e.g. in short rotor machines.

This paper explores the use of concentrated winding linear induction machines, outlines the problem areas and presents a novel method to overcome these, validated by successful experimental results.

II. AC WINDINGS

A. Double Layer Windings

Double layer windings are commonly used for linear induction motors. They have overlapping coils and a phase sequence R -B Y –R B -Y This arrangement is shown in Fig. 1 and it will be seen that the coils are arranged with the leading side in the bottom half of one slot and the second side in the top half of a slot one coil pitch in front of the leading side. In conventional cylindrical machines the coils are positioned sequentially and when the leading side needs to occupy the bottom half of an already half filled slot it can be tucked under the excising coil side. The winding is therefore symmetrically disposed without an apparent start and finish. However in a linear motor the winding has a start and a finish so that at the ends of the machine there are either half-filled slots or coil sides around the stack ends. Fig. 1 shows these two possibilities. In addition to the difficulties at the machine ends the end windings at the sides of the machine tend to be bulky because the of the coil overlaps.

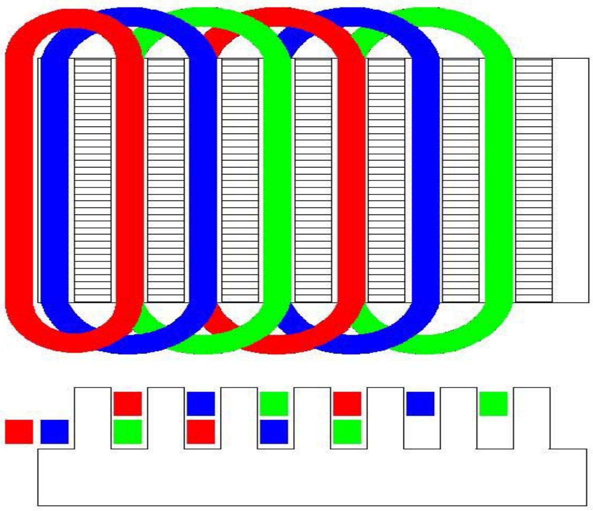

Fig. 1. Linear machine using a Double Layer Stator Winding
Top - Plan View
Bottom - Longitudinal cross section view

B. Concentrated windings

The simplest form of winding is the concentrated winding using planar non-overlapping coils each of which surrounds a single tooth. For the purposes of this paper, we will refer to this simply as a concentrated winding. The connection sequence is RYB which yields two poles pitches of excitation in a three coil span. The winding factor is relatively high at $\sqrt{3}/2$. Concentrated windings are commonly in use for permanent magnet machines [1] [2]. An example 6 coil 4 pole linear stator using a planar concentrated winding is shown in Fig. 2.

The advantage of these windings is primarily mechanical. The end-winding is compact and far less bulky than the double layer winding due to the lack of overlapping coils. There are no half empty slots or overlapping coils at the stack ends. This later feature is particularly apt for long

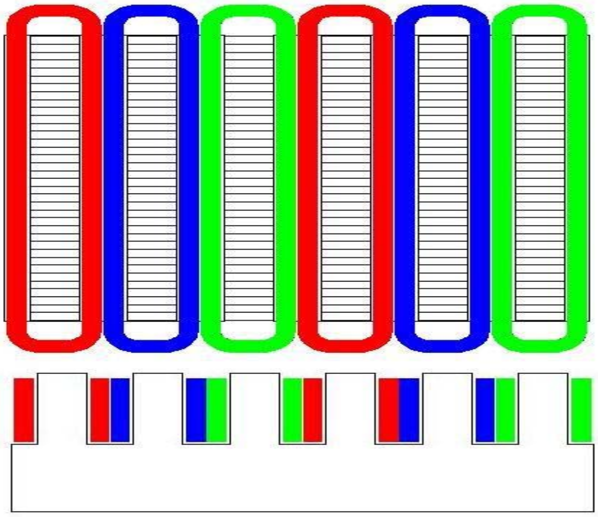

Fig. 2. Linear machine using a Concentrated Stator Winding
Top – Plan view
Bottom - Longitudinal cross sectional view

stator machines, for example those required for aircraft electro magnetic launchers since the modules can be butted together. This yields a system without magnetic discontinuities that would be caused by gaps between the stators. A further advantage of the winding is that if open slots are used then preformed coils can be manufactured and positioned directly in the slots. This leads to significantly reduced labour costs.

III. COMPARISON BETWEEN CONCENTRATED AND DOUBLE LAYER WINDINGS

The simplicity of construction of the planar concentrated winding is a great advantage, and would be even more so if it could be combined with a simple inexpensive rotor such as the plate rotor of a linear induction motor.

Double layer windings produce mmfs with only one large space harmonic component, of a pole number that is decided by the winding design. The rest of the harmonic components are small and do not effect the performance of a machine very much.

The concentrated winding however produces two principle harmonics. If the coil number is 3N, where N is a positive integer, the first harmonic wave is forward going and has a pole number of 2N. The second large harmonic is backward going and has a pole number of 4N. Thus the winding of Fig. 2 with N=2 gives a forward travelling wave of 4 poles and a backward travelling wave of 8 poles.

The windings are used mainly for permanent magnet machines where the production of two fields is not an issue. The magnet field can have either 2N or 4N poles. If for example a 2N pole magnet is chosen then torque will be generated by the 2N winding mmf but not the 4N (the two pole numbers must be the same to generate net torque around the periphery). The 4N mmf will simply drive flux in the air-gap to produce an extra component of leakage reactance.

IV. PLATE ROTOR USE WITH PLANAR CONCENTRATED STATORS

Commonly the rotor conductor of a linear induction motor is a simple aluminium plate. The machine can be either single-sided as shown in Fig. 3 or double-sided as shown in Fig. 4.

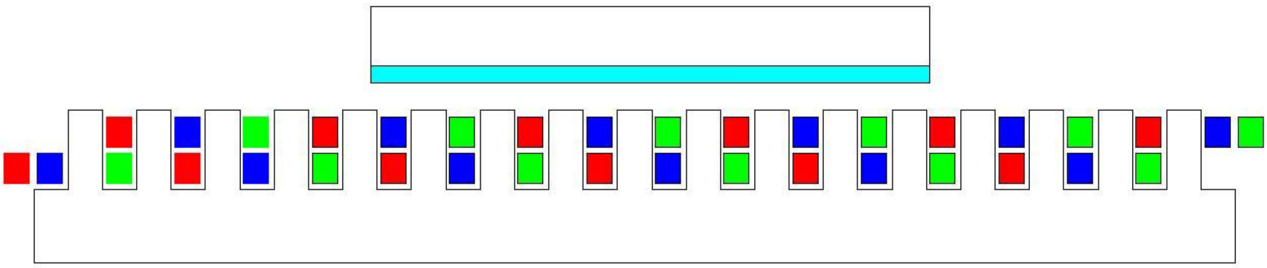

Fig. 3. A single-sided linear induction motor with a plate secondary and core iron

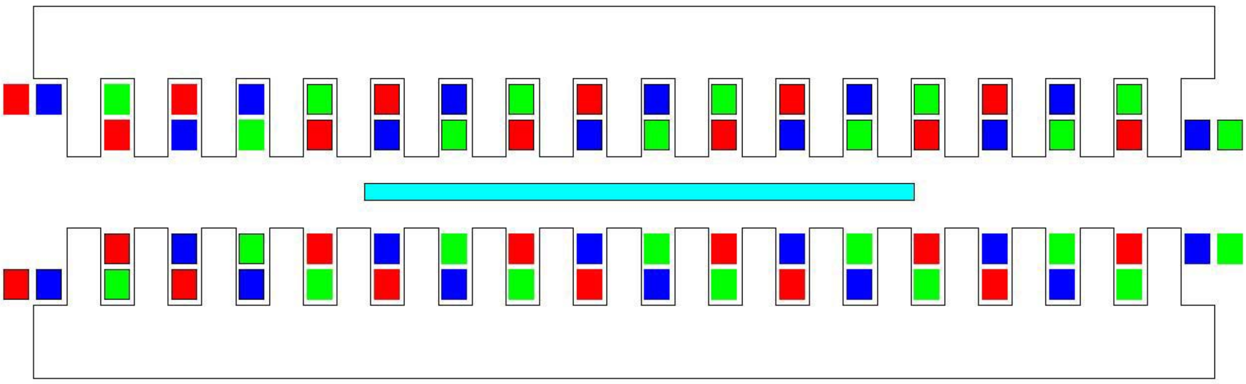

Fig. 4. A double-sided linear induction motor with a plate secondary

The single–sided machine needs rotor core iron as shown but in the double-sided case the need for rotor iron is eliminated since each stator completes the other's magnetic circuit.

A critical disadvantage is observed when simple plate rotors are used with planar concentrated windings. Unlike a permanent magnet rotor, a simple plate rotor is able to couple with any harmonic mmf wave, regardless of direction or pole number.

Therefore, it can be shown that for the machine shown in Fig. 2, both the 4 pole forwards going field component and the 8 pole backwards going field component will couple with the plate rotor, reducing the net force from the machine and its performance. This is demonstrated in Fig. 8 using time-stepping finite element modelling [3].

It shows the thrust speed curves of both a conventional 2 layer wound LIM and an equivalent planar concentrated LIM with equal winding factors, using plate rotors. It is obvious that the concentrated planar machine has severely reduced performance.

V. IMPROVING PLANAR CONCENTRATED STATOR PERFORMANCE

A method was sought to reduce or eliminate the effects of the negative stator harmonics.

A typical 2 layer AC winding is designed to suppress any harmonics other than its principle operating harmonic. If this type of winding is used as a wound rotor, the rotor winding will couple only with the required harmonic from the stator and ignore other negative harmonics, just as a permanent magnet rotor does. Therefore a four pole wound rotor will couple only with the four pole field from a concentrated winding stator, not the 8 pole.

Wound secondary linear machines are known [4] [5] [6]. Yamamura suggested a 'wound plate' for use with a double-sided machine and with the objective of reducing the entry and exit effects in a short stator machine. Wound rotors are also possible for short stator machines and single and double-sided versions are shown in Fig. 5 and Fig. 6 respectively. In the secondary shown in Fig. 6 the flux travels through the secondary so that the links between each of the rotor teeth are sized solely from mechanical considerations.

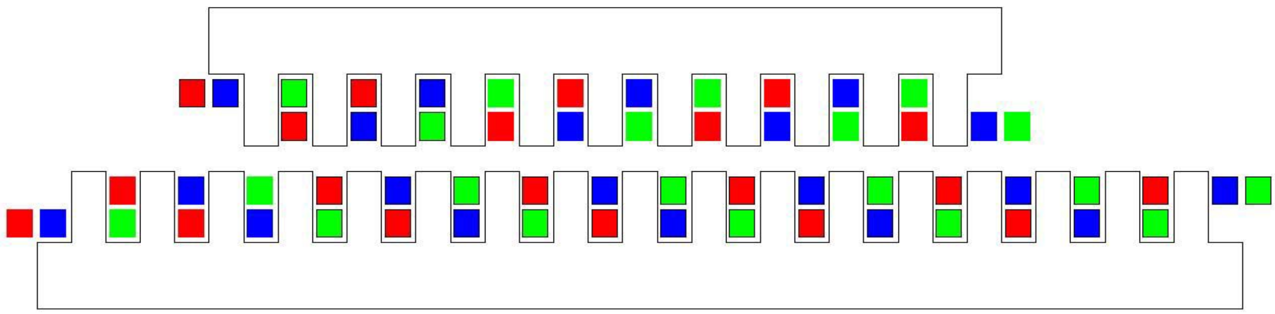

Fig. 5. A single-sided short rotor wound secondary machine

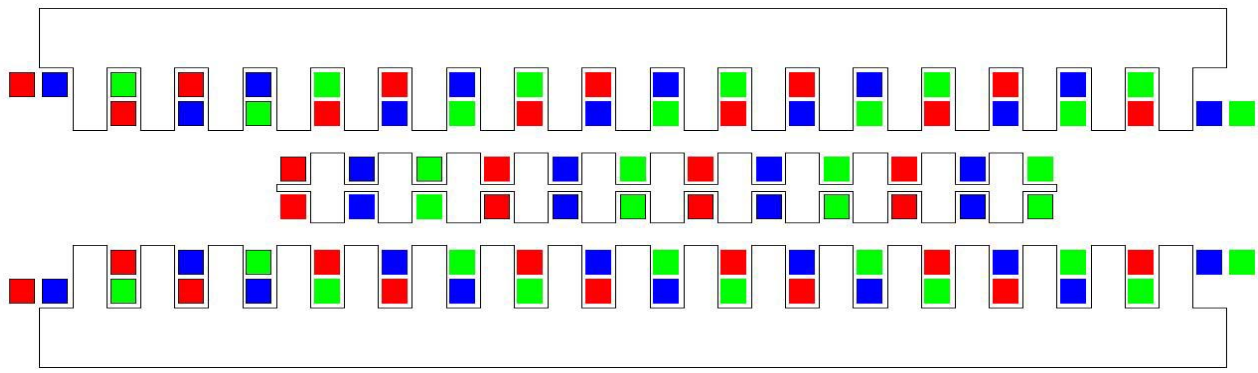

Fig. 6. A double-sided short rotor wound secondary machine

VI. FINITE ELEMENT MODELLING

Modeling of the various motor configurations was carried out using 2D Finite Elements Analysis (FEA) [3]. Electromagnetic fields can be modeled in 2D, using the magnetic vector potential, **A**, the governing equation is:

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

where:

μ is the permeability in henries/meter

A is the magnetic vector potential in webers/metre

σ is the conductivity in siemens/metre

The governing equation can be transformed into a system of equations by using the finite element method together with the Galerkin weighted residual procedure.

A time-stepping scheme, which takes into account the transient nature of the supply to the motor and the dynamic motion of the rotor, was used to simulate the dynamic action. A special sliding surface FE scheme was used to handle the motion of the rotor. In this scheme, the stator and rotor of the motor are represented by separate FE meshes, which touch each other at a common interface. This common interface was located at the middle of the air-gap for the modeling work presented here. The stator and rotor mesh slide freely relative to each other along the interface and in so doing enable the dynamic motion of the rotor to be analysed without the need of any re-meshing. Fig. 7 shows the meshing scheme with the stator and rotor mesh touching each other at the middle of the air gap.

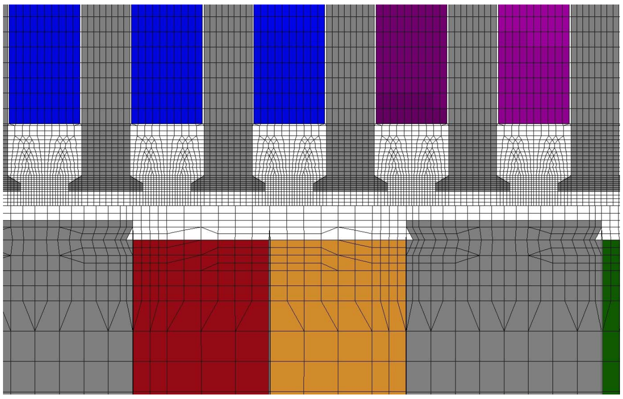

Fig. 7. FE modeling mesh

The Lagrange Multipliers technique was used to couple the meshes electromagnetically, the method essentially enforces the constraint of Equation 2 at the interface of the stator and rotor mesh.

$$A_s - A_r = 0 \tag{2}$$

where A_s and A_r are the vector potential unknowns at the stator and rotor interface nodes respectively.

The stator windings were modeled as current forced coil regions. Winding resistance and end winding inductance components were incorporated into the simulation as components in an external circuit coupled to the FE model.

Fig. 8 shows the results of the Finite Element Analysis of force using a single-sided long stator machine carrying a planar concentrated LIM primary winding as described in relation to Fig. 2. This is modeled with two different secondary members, a plate-conductor rotor 4 pole–pitches in length backed with an iron core and a slotted secondary carrying a multi-layer winding.

Also shown are the results for a conventional stator with a plate rotor.

VII. Test Results from an Experimental Rig

To verify the results of the finite element work, a practical wound rotor model has been made. A planar concentrated winding stator was constructed to use as the primary together with a wound secondary of identical pole pitch. This used a special winding in order to minimise locking forces. The secondary phases were connected in star at both ends to give the required rotor current paths.

The stator was mounted to a test bed, and the wound rotor was mounted above the stator, on a rig instrumented to record static thrust. The stator was fed through an inverter and the feed was instrumented to display the relevant inputs to the stator.

In order to gain results for various velocity points, variable frequency testing was used [7]. This test allows the prediction of dynamic performance from static test conditions.

The results of the tests are shown in Fig. 8, together with the results of finite element modelling. It will be observed that the agreement between the calculated results and the experimental results is good.

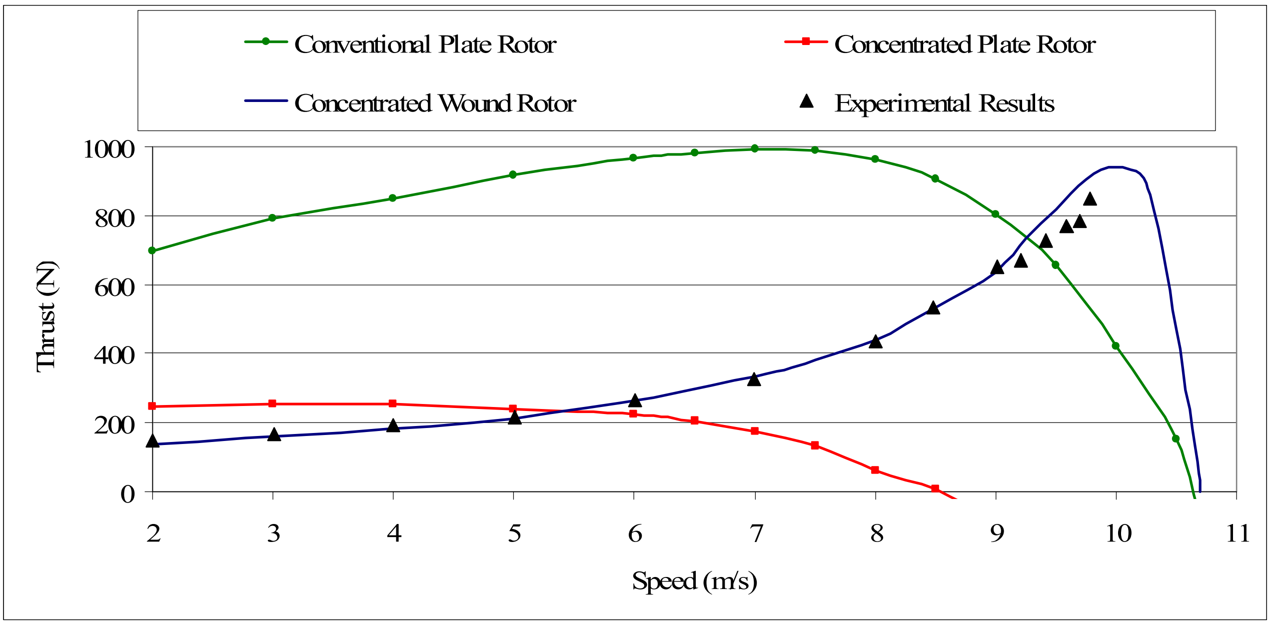

Fig. 8. Comparison between Plate and wound rotors used with concentrated windings

VIII. Planar Concentrated winding Results

It can be seen from Fig. 8 that as anticipated the force when using a plate rotor is very disappointing. This is due to the large backwards travelling mmf that is produced in addition to the wanted forward going mmf, which produces negative forces that reduce the wanted force. It can be seen that the force is low and that the running light speed is only 80% or so of the synchronous speed. The maximum efficiency is 52%.

However the force speed characteristic of the case using a wound rotor is excellent with a good peak force and a high efficiency of 92%. The good performance of the machine is due to the action of the secondary winding which has a high winding factor only on the pole number for which it is designed and therefore has induced emf, current and force only corresponding to that wanted pole number. The wound rotor machine therefore has an action that is analogous to that of a permanent magnet rotor and selects the forward going field.

Fig. 8 can be used to draw further comparisons between the responses of plate short rotor and wound rotor machines. It will be seen that the force speed curve for the wound rotor has a high force low slip characteristic indicating that the rotor resistance is low and the magnetising reactance is high. Conversely, the plate rotor shows a drooping characteristic indicating that the rotor resistance is higher and the magnetising reactance is lower. It is not possible to reduce the resistance in the plate rotor case without reducing magnetising reactance because the quantities are linked. For example, increasing the plate thickness to reduce the resistance results in an increased magnetic gap and hence a reduced magnetising reactance. This means that the shape of the force speed curve cannot be significantly altered without a change in plate materials.

However in the wound rotor case the two quantities are independent, the magnetising reactance depends on the clearance only and the resistance is an independent variable depending on factors such as the slot depth.

The force speed curve shape change results in the rotor efficiency being considerably larger in the wound case compared with the plate rotor case. The peak force available is also greater in the wound rotor case compared to a plate rotor using the same stator.

IX. Conclusions

The wound rotor used with a planar concentrated stator winding provides an excellent novel arrangement, [8] for example it enables an inexpensive track arrangement for use with an urban transport system. The use of wound rotors also enables design freedom. This means that higher forces and efficiencies become available, with the ability to generate high thrusts at lower slips and a reduced size and cost of the overall system, including a reduction in the size and cost of power conditioning equipment.

Single-sided machines of both plate and wound rotor types suffer from normal forces between the primary and the secondary and problems of secondary weight. There is evidence that the normal force in the wound type will be generally larger than in the plate type. Therefore, the single–sided wound machine is more apt for urban transport systems (where a horizontal gap is of advantage) rather than EM catapult launch systems. Double-sided machines are usually favoured for EM launch and double-sided iron-cored arrangements are possible. These largely deal with the normal force problem but the weight penalty remains. For some applications an air-gap type wound rotor construction as in [4] could be advantageous.

References

[1] Magnussen, C Sadarangani, "Winding factors and Joule losses of permanent magnet machines with concentrated windings" IEMDC 2003, Volume: 1, pp 333- 339

[2] J Wang, Z P Xia, D Howe, S A Long, "Comparative Study of 3-Phase Permanent Magnet Brushless Machines with Concentrated, Distributed and Modular Windings" IET Power Electronics, Machines and Drives, Mar. 2006 Page(s):489 - 493

[3] MEGA Finite Element Modelling Package Bath University

[4] S Yamamura, H Ito "End Effect of a Linear Induction Motor of the Wound Secondary Type" Report 434 of the General Meeting, IEEJ Japan, 1971

[5] S Yamamura, H Ito, Y Ishikawa "Theories of the Linear Induction Motor and compensated linear induction motor" IEE Trans. On Power Apparatus and Systems 1972 p1700

[6] Onuki T and Kamiya Y, "Improvement of short primary member linear induction motor performance by partial adoption of the wound secondary" IAS 33: 1998 IEE, pp 179 - 186 volume 1

[7] J F Eastham, P C Coles, M Benarous, J Proverbs, A Foster "Linear Induction Motor Variable Frequency Standstill Tests to Predict Operational Velocity Performance" LDIA 2003 Birmingham, UK pp 81-84

[8] J F Eastham, Force Engineering Patent "Improvements in and relating to Electromotive Machines" International Patent Application No PCT/GB2007/003849