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Linear Induction Motors with Modular Winding Primaries and Wound Rotor Secondaries

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Linear induction motors commonly use double layer windings, which produce good sinusoidal travelling fields, but have relatively bulky end windings and use either half-filled slots or overhanging coil sides at the ends of the machine. Long stator systems are difficult since it is not possible to butt stator modules against each other. Arguably the simplest and most cost effective winding uses modular construction where the coils are planar and do not overlap. Here the end winding is compact and stator sections can be butted together. However modular windings do not produce high quality travelling fields. Two space harmonics of closely the same magnitude are produced that travel in opposite directions, giving induced currents and opposing forces with little net force in plate rotors. The difficulty can be resolved if a wound secondary with a double layer winding is used instead of a plate. Here a substantial induced emf and current is produced only by the field for which the secondary is wound, so that force is produced only in one direction. The use and properties of modular windings for short rotor machines are explored using finite element analysis and the results are validated by practical tests. It is concluded that inexpensive modular windings can be used with wound secondaries to good effect particularly in long stator situations; for example, for electromagnetic launch and urban transport systems.

Index Terms—Linear induction motors, wound rotors.

I. INTRODUCTION

LINEAR induction motors commonly use conventional double-layer stator windings. These provide an excellent traveling field with little harmonic content. However, when applied to linear stators they must use either half empty slots or coils that overlap at the ends of the stack. In addition, the end windings at the sides of the machine tend to be bulky. Fig. 1 illustrates a stator using an 8 pole double-layer winding in 24 slots.

This uses half empty slots at one end and coils overlapping the stack end at the other. It is the objective of this work to use windings with nonoverlapping planar coils. Following the nomenclature of [1] these are termed "concentrated" if the older repeating coil sequence of R Y B is used and "modular" if the newer winding sequences such as those given in [2] are used. Only modular windings are considered in this paper. An 8/10 pole 9 coil modular winding equivalent to that of Fig. 1 is illustrated in Fig. 2.

Modular windings lead to machines that are inexpensive to wind, compact, and that can be stacked end to end since no overlapping coils or half filled slots are needed. This is a particularly useful feature when long stators for EM launchers or urban transport schemes are considered.

II. THE USE OF MODULAR WINDINGS

There are two modular windings that are apt for use for long stator linear induction motors. The first of these uses nine coils and the second 12 coils. They have high winding factors and 14 poles or less so that they can be used to form compact separate stator blocks for use in modular stator constructions. The
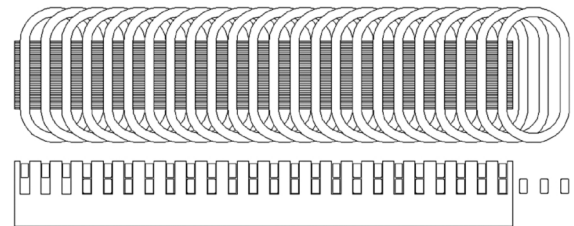
Fig. 1. 8 pole double layer winding layout.
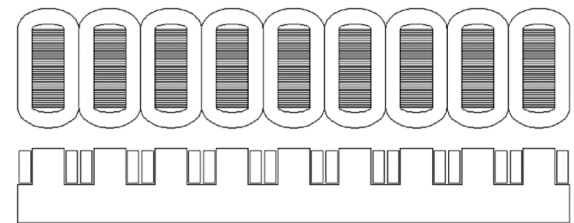
Fig. 2. 8 pole modular winding layout.

TABLE I
COIL CONNECTIONS FOR TWO MODULAR WINDINGS

Nine slot 8/10 pole modular winding									
Coil Number	1	2	3	4	5	6	7	8	9
Coil phase & connection	R	-R	R	B	-B	B	Y	-Y	Y

Twelve slot 10/12 pole modular winding											
Coil Number	1	2	3	4	5	6	7	8	9	10	11	12
Coil phase & connection	R	-R	-B	B	Y	-Y	-R	R	B	-B	-Y	Y

winding connection sequences for these two windings are as shown in Table I.

While modular windings are excellent mechanically, they have the drawback of a high harmonic content in the mmf wave. In the table the nine slot winding is designated 8/10 poles because it produces two high mmf components of approximately equal value at 8 and 10 poles. These travel in oppo-

Fig. 3. 9 coil stator air gap flux and harmonic components at (a) 0° and (b) 120°.

Fig. 4. 12 coil stator air gap flux and harmonic components at (a) 0° and (b) 120 °.

directions. Similarly the 12 slot winding produces high 10 and 14 pole harmonics.

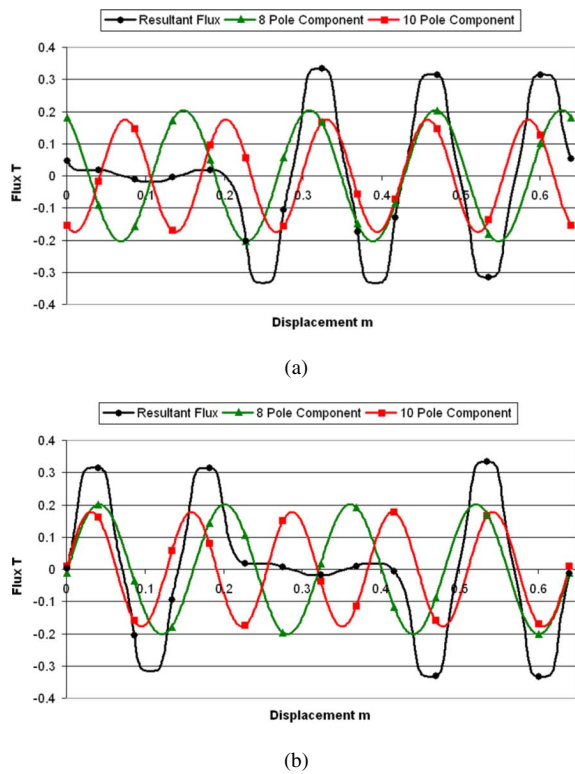The behavior of the 9 slot winding is illustrated by Fig. 3, which shows the open circuit air gap flux produced by finite element analysis of a model using a stator of the form of Fig. 2. The 8 and 10 pole components of the wave are also shown on the figure. The two separate instants in a cycle are shown to illustrate that these main components travel in opposite directions.

Figures for the 12 slot winding corresponding to Table I appear as Fig. 4.

The windings are typically in use for machines with permanent magnet excitation [1]. For both windings a magnet array can be provided to cooperate with either pole number of mmf to produce force; the second mmf wave then merely produces air-gap flux which gives extra leakage reactance.

If for example in the 9 slot case an 8 pole magnet array is chosen then net force will result only from the 8 pole mmf and the 10 pole mmf will only add reactance.

The situation is radically different for induction machines. If an inductive plate rotor is used then all the flux waves produce secondary eddy currents and force. For both windings the forces from the two oppositely directed high value harmonics oppose each other and the net force is severely reduced.

III. NEW PRINCIPLE

The situation can be improved by using a double layer wound secondary. This, like the permanent magnet secondary, will respond substantially only t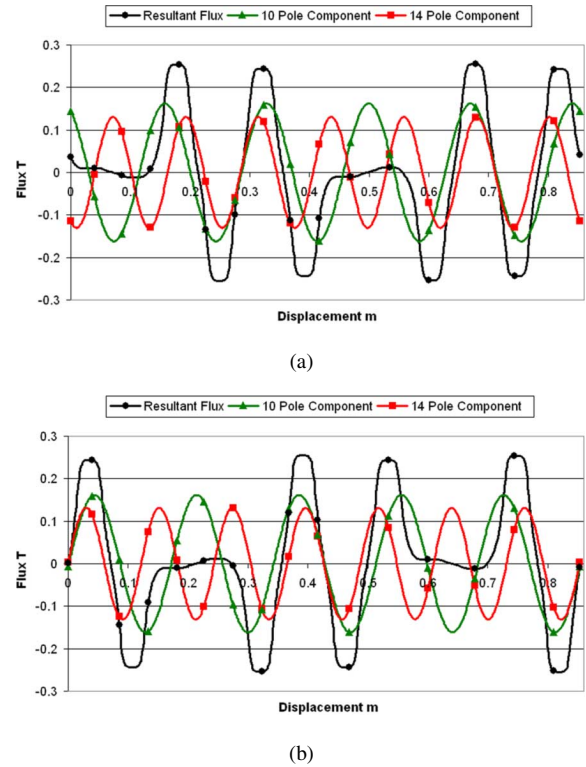o the pole number for which it is wound since the winding factor controlling the induced emf is small except for the fundamental.

In order to avoid force perturbations due to magnetic locking the secondary slots can be skewed. Alternatively a solution which is simpler mechanically can be adopted, using a fractional slot winding so that the mutual slotting pattern repeats only in the secondary length.

The new principle of using a wound secondary so that simple modular primary windings may be used is described in the patent of [3].

IV. WOUND ROTOR ACTION

The wound rotor in the machine described above is used as a selector so that only one harmonic is effective. However, wound rotors can improve the behavior of linear motors apart from this effect [4].

The action of the wound rotor machine is different to that of the plate rotor machine because of edge effects. In a long stator arrangement, the stator current is forced to be virtually constant by the impedance of the winding outside the active region. The flux density is, therefore, smaller inside the plate region where plate currents oppose the stator current than it is outside. As the edge of the plate moves between the flux densities in the two regions, currents are induced at the plate edges that try to prevent the flux density change. These currents detract from the performance. Conversely in the wound rotor case since a series 3 phase set of coils take up position along the length of the secondary, the winding current is the same along its length and there are no space transient effects.
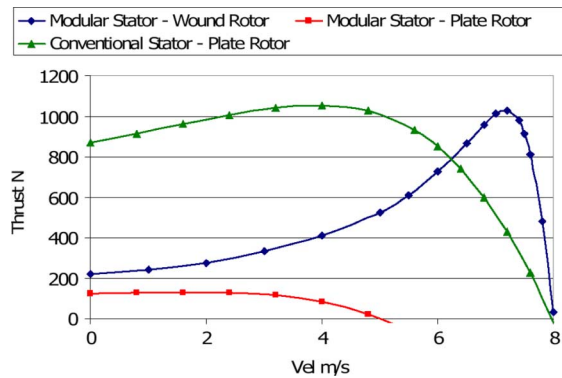
Fig. 5. Thrust speed curves for modular stator with both plate and wound rotors, and conventional stator with plate rotor.

TABLE II
COIL CONNECTIONS FOR THE WOUND ROTOR

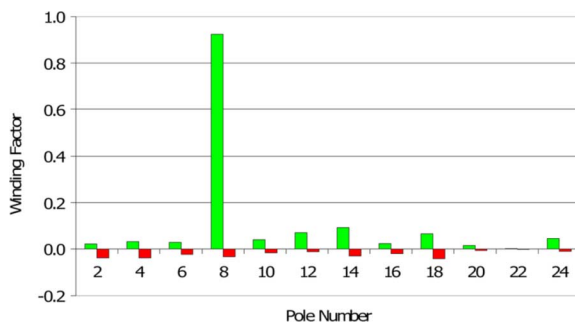| 8-pole 32 slot fractional slot rotor winding							
Coil Number	1	2	3	4	5	6	7	8
Coil phase & connection	R	R	-B	Y	-R	B	B	-Y
Coil Number	9	10	11	12	13	14	15	16
Coil phase & connection	R	-B	Y	Y	-R	-R	B	-Y
Coil Number	17	18	19	20	21	22	23	24
Coil phase & connection	R	-B	-B	Y	-R	B	-Y	-Y
Coil Number	25	26	27	28	29	30	31	32
Coil phase & connection	R	R	-B	Y	-R	B	B	-Y

Fig. 6. Winding factors of the wound rotor.

V. ANALYTICAL RESULTS

Fig. 5 compares the response of an 8 pole short plate rotor first to a double layer winding with small harmonic content and secondly to the 9 coil modular winding described previously.

It will be seen that the plate rotor performs poorly with a modular wound stator due to the backward going harmonic. These results were obtained by time stepped FEA modelling using the MEGA package as detailed in the Appendix. The results for a wound secondary are also shown in Fig. 5. Here, the fractional slot 4 slot per pole winding using 3 slots pitched coils shown in Table II was used.

The winding factors of each pole number for the rotor winding are shown in Fig. 6. The sign of the winding factor indicates direction of travel for each harmonic.

It can be seen that this rotor has a large 8 pole winding factor, with only very small winding factors for harmonics of other
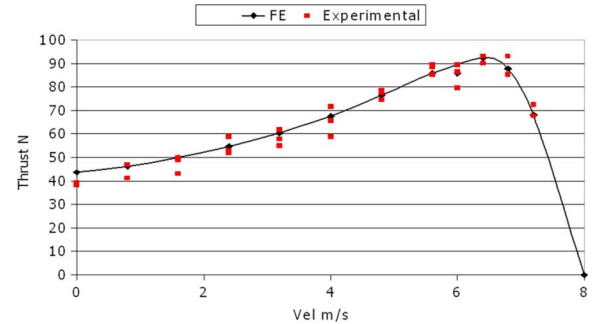

Fig. 7. Wound rotor experimental and FE results.

pole number, particularly the 10 pole harmonic, as this is the significant negative harmonic of the stator.

The response of the winding is excellent; the peak force is closely the same as when a double layer stator and plate rotor is used but the peak is closer to the synchronous speed and since secondary efficiency is given by 1/slip this indicates a much better secondary efficiency (92% compared to 52%).

Further comparisons can be drawn from Fig. 5 with regard to the performance of wound and plate rotor machines with short rotors. As argued previously, the stator current is approximately constant in a short rotor induction motor. In this circumstance the peak of the force speed curve occurs at a slip of approximately R_2/X_m, where R_2 is the referred secondary resistance and X_m is the magnetizing reactance.

The force speed curve for the wound rotor has a high force low slip characteristic with a peak that implies that the ratio of R_2/X_m is low. Therefore, the magnetizing reactance is high and the rotor resistance is low. In contrast, the plate rotor shows a drooping characteristic indicating that the magnetizing reactance is lower and the rotor resistance is higher. The difference in the characteristic of course follows from the physical arrangement. The magnetizing reactance is governed by the inverse of the magnetic gap. This is small in the wound rotor case since it is set by the clearance. In contrast the magnetic gap is larger in the plate rotor machine since it is governed by the clearance plus the plate thickness. It follows that the magnetizing reactance tends to be larger in wound rotor machines. The secondary resistance in the wound rotor case is set by such factors as the slot dimensions and can be arranged independently of the magnetizing reactance and designed to be small. However in the plate rotor machine the secondary resistance and magnetizing reactance are closely linked. For example, if the plate thickness is increased to produce a lower resistance the magnetic gap is also increased reducing the magnetizing reactance. This tends to keep the ratio of R to X_m the same and it is difficult to change the shape of the force speed curve. It follows that the wound rotor machine will always have a design advantage and be more easily arranged to have a low peak slip high peak efficiency characteristic.

VI. EXPERIMENTAL MACHINE

A test rig has been constructed to prove this principle using 9 slot 8/10 pole stator winding sections. This cooperates with a short wound rotor carrying the fractional slot double layer 8 pole winding described above. Tests were performed using the standstill variable frequency principle [5] to estimate the dynamic response of the system and the results are plotted on Fig. 7 for

comparison with FE standstill variable frequency results. It will be observed that the correlation is excellent.

VII. CONCLUSION

The work has shown by time-stepped finite element modelling validated by experimental results that simple modular windings in which the coils do not overlap can be used for linear induction motor stators when wound rotors are employed. The new arrangement enables inexpensive stator modules to be used in EM launch and urban transport systems.

APPENDIX
FINITE ELEMENT MODELING

The device was modeled using 2-D finite elements using the University of Bath MEGA Finite Element package.

The governing field equation (not in the coil regions) is

$$\nabla \times \frac{1}{\mu}\nabla \times \mathbf{A} + \sigma\left(\frac{\partial \mathbf{A}}{\partial t} - E_r\right) = 0 \qquad (1)$$

$$\int \sigma E_r dS = 0 \qquad (2)$$

where

μ is the permeability in henries/meter;

A is the magnetic vector field potential in Webbers/meter;

σ is the conductivity in Siemens/meter;

E_r is the additional field (a single unknown) in the rotor plate required to constrain the total current to zero.

In the coil regions, the governing equation is

$$\nabla \times \frac{1}{\mu}\nabla \times \mathbf{A} - I_c t_c = 0 \qquad (3)$$

$$L\int t_c\frac{\partial \mathbf{A}}{\partial t}dS - V_c = 0 \qquad (4)$$

where

I_c is the unknown current in each filament of the coil c in amps;

t_c is the turns density of the coil;

V_c is the voltage across the coil in volts;

L is the length of the machine (into the page) in meters.

This approach allows the coils to be connected to external circuits using the unknowns I_c and V_c [6]. In this case the stator currents were prescribed sinusoids. Each rotor coil becomes 2 regions (in and out flowing current). These coil regions where joined together appropriately. The movement of the rotor was modeled by a special sliding surface FEA scheme. In this arrangement, the stator and rotor of the motor are represented by separate meshes joined by the interface. Due to symmetry in the plate model case only a half of the machine needs to be modeled, i.e., one stator and a half of the plate secondary. The common interface was located at the middle of the clearance gap between the rotor surface and the adjacent stator surface of the half model. In the wound rotor case this symmetry does not
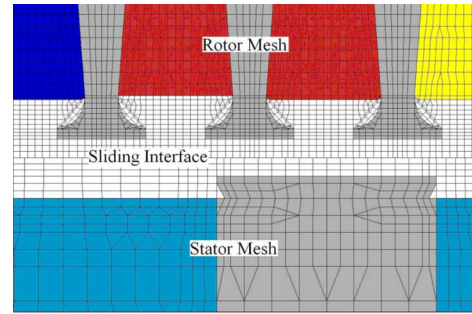

Fig. 8. A finite element mesh.

exist. A view of the stator and rotor mesh for the wound rotor case is shown in Fig. 8.

The stator and rotor mesh can slide freely relative to each other along the interface and in so doing enable the dynamic motion of the rotor to be handled without the need of any re-meshing.

A further improvement to the 2-D finite element modeling comes from the use of the Russell & Norsworthy Factor to modify rotor resistivity in order to simulate the secondary end ring effects present in the practical case [7].

The relative motion of rotor means that the field is no longer harmonic in time. The motor was simulated using a full time transient nonlinear solver.

ACKNOWLEDGMENT

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