

# The use of concentrated windings for offset double stator linear induction motors

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## 1. Introduction

Concentrated windings are simple, cost-effective a.c. windings. However they cannot be applied directly to linear induction machines because they produce backward travelling fields, reducing the output force. Special arrangements are however possible and the paper describes a novel configuration in which concentrated windings are successfully used for double-sided machines. Here a longitudinal offset between the stators is used to cancel the unwanted fields. The resulting machines have reduced winding and construction costs and may form modular long-stator machines for launch and transport applications.

## 2. Primary windings for linear induction machines

### Double Layer Windings

Linear machines normally use double layer windings. In this arrangement the first or leading side of a coil occupies the top half of a slot whilst the second side is positioned in the bottom of a slot one coil pitch away from the first side. As successive coils are positioned in the stator the end windings at the sides of the machine overlap forming a bulky side region restricting the machine stack width for a particular overall width. When using double layer construction, winding linear machines is more difficult than winding conventional cylindrical versions because the winding has to terminate at each end of the machine and either half-filled slots or coil sides over the ends of the machine must be used. A simple 2-pole one slot per pole and phase double layer winding is shown in Fig.1. In this machine the 'half empty slot' technique is shown at one end and the two overlapping coil sides at the other.

### Concentrated windings

These are arguably the simplest form of ac winding and are commonly used for machines with permanent magnet excitation but very rarely for induction machines. A 4-pole linear motor primary such a winding is shown in Fig.2. The advantage of using this form of winding is immediately apparent. First there is no coil overlap at the sides of the machine leading to a larger active pole width for a given total machine width, if machines with fully formed end windings are considered. Secondly if open slots are used the coils can be totally pre-formed and easily inserted in the slots,

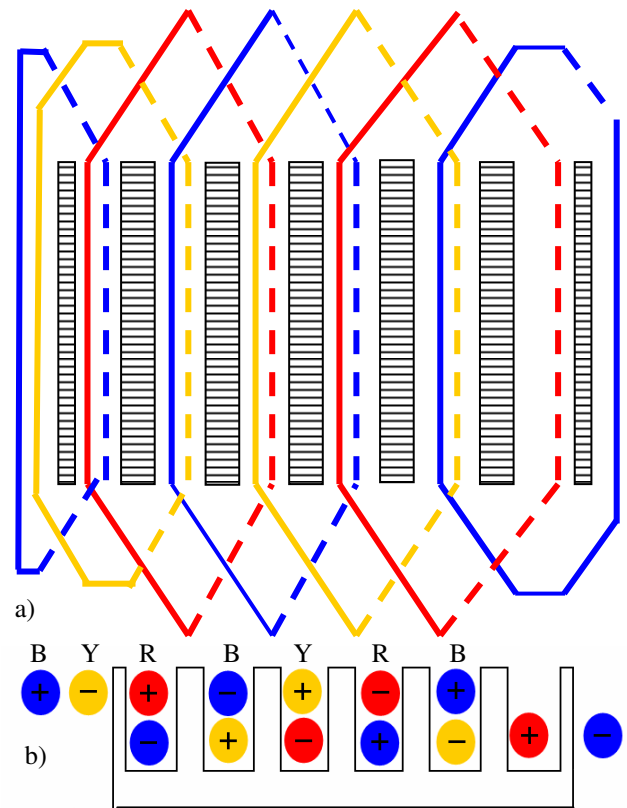


Fig 1. Two pole linear machine using a Double Layer Stator Winding

(a) Plan View

(b) Longitudinal cross section view

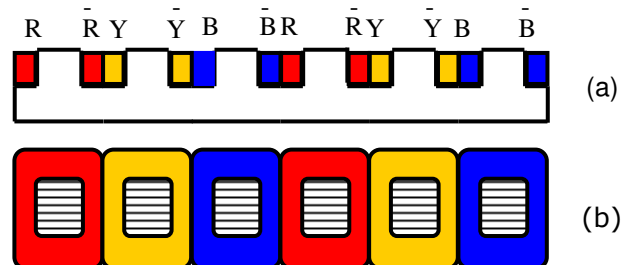


Fig. 2. Four Pole linear machine using a Concentrated Stator Winding

(a) Longitudinal cross sectional view

(b) Plan view

which leads to reduced labour costs and allows the easier production of high voltage windings.

This is of particular interest, as conventional linear motors may have major issues at high voltage owing to the overlapping of phases. Finally the winding produces no difficulties at the ends of the machine since all the slots are filled and there are no coil sides around the ends. This is important when a long stator assembly is needed, for instance in a launcher application, as stator modules can be butted up to each other to form a true continuous stator.

The mmf produced by the double layer winding is an approximately sinusoidal travelling wave of the pole number for which it is wound. The harmonic content is small and only odd harmonics are present. In contrast the mmf produced by the concentrated winding has a very high harmonic content and in particular produces a large backward going field of twice the pole number for which it is wound. For example with no rotor conductor present, the 4-pole stator of Fig. 2 produces both a forward going 4-pole ampere conductor wave and a backward going 8-pole ampere conductor wave of equal size.

### 3. Application of the windings to linear machines

As in rotary machines the double layer winding can be used freely for both permanent magnet and induction machines. The largely sinusoidal nature of the mmf ensures a good performance. In rotary machines, the concentrated winding is useful currently only for permanent magnet machines. This is because an induction motor with a sheet rotor can respond and produce force from any harmonic and therefore in the concentrated winding case a large negative force is produced by the backward going fields that detract from the wanted positive force. In contrast a permanent magnet rotor can produce force only from a field that has the same pole number.

It is the objective of this paper to describe a new double-sided stator arrangement in which the backward going harmonic fields from the stators are eliminated, while allowing maximum force to be produced from the forwards going harmonic field.

### 4. Double-sided machines with offset stators

The harmonic elimination technique is simple; all that is required is to offset the stators so that the unwanted fields from the two sides are in opposition whilst the wanted fields reinforce. The arrangement is shown at Fig. 3, displaying the red phase mmfs from the two sides and the resultant mmf pattern. It can be seen that the result is a symmetrical waveform that does not contain even harmonics and will not produce backward going fields. It follows that the machine can operate successfully with a plate rotor. The arrangement described uses the common form of concentrated winding in which a three-coil array produces a 2-pole winding. The action has been illustrated by way of mmf

patterns however the harmonic performance is shown in Fig.4. Here the harmonic spectrum produced by a non offset pair shows the unwanted high 8-pole component in addition to the wanted 4-pole whilst the addition of the offset between the two stators cancels the 8-pole harmonic leaving a good 4-pole harmonic.

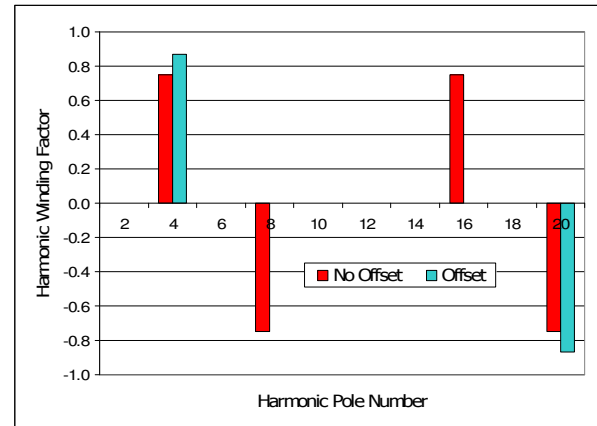


Fig. 4. Showing the harmonic behaviour of the 6 slot 4-pole concentrated winding machine offset machine of Fig 3

The action has been described by means of the simplest form of concentrated winding that is one that uses 3-coils to produce 2-poles.

However other forms of concentrated winding are known [1] and can be used with appropriate offsets, for harmonic cancellation, in arrangements similar to that of Fig. 3. A 12 slot 10-pole machine is shown in Fig.5.

Fig.6 shows the harmonic spectrum of the 12 slot 10 pole winding and it will be observed that a single stator produces a large unwanted 14-pole field as well as the wanted 10-pole. The stators are therefore offset by one pole-pitch on the 14-pole wave so that the unwanted 14-pole field is cancelled yielding the spectrum shown in the figure.

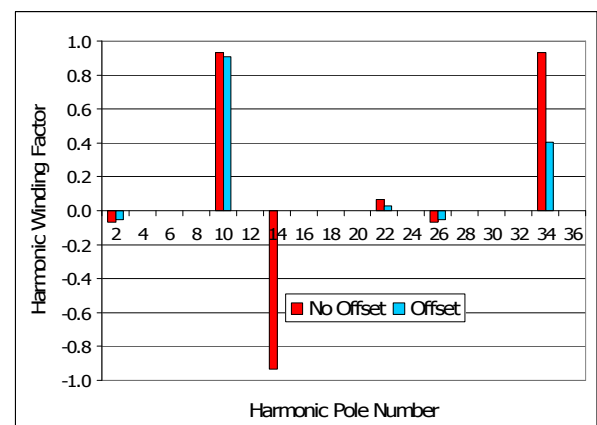


Fig. 6. Showing the offset and non offset harmonic behaviour of the 12 slot 10-pole concentrated winding machine of Fig 5

## 5. Finite element Modelling

2D finite element analysis (FEA) was undertaken of various offset motor configurations, using the University of Bath MEGA package.

2D electromagnetic fields can be modeled using the magnetic vector potential,  $\mathbf{A}$ . The governing equation is:

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

where:

$\mu$  is the permeability in henries/meter

$\mathbf{A}$  is the magnetic vector potential in webers/metre

$\sigma$  is the conductivity in siemens/metre

By using the finite element method together with the Galerkin weighted residual procedure this can be transformed into a system of equations.

A Minkowski transform was used to simulate the effects of a rotor of constant cross sectional area moving at constant velocity past short stators. The use of this technique means that a time-stepped scheme is unnecessary and one solution gives the steady-state result. The Russell & Norsworthy Factor was used to modify the rotor resistivity in order to simulate the secondary end ring effects [2].

A view of the stator and rotor mesh that was used is shown in Fig. 7.

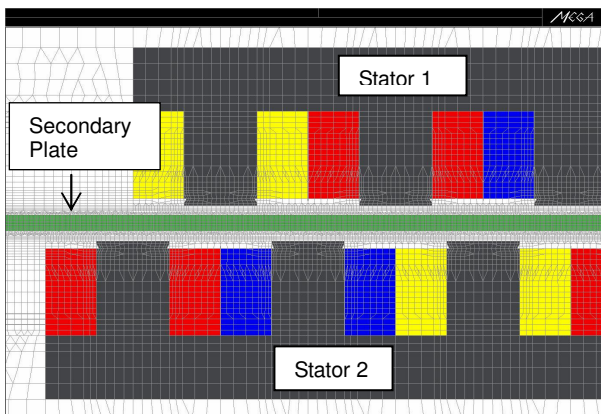


Fig. 7. The finite element mesh

## 6. Experimental Machine

An experimental offset double-sided concentrated winding machine has been made and tested using the technique described in reference [3]. The force produced is compared with first a non-offset double-sided machine using conventional double layer windings and secondly with the calculated output from the time-stepped finite element analysis of the concentrated offset machine. It will be observed from Fig. 8 that the performance of the offset machine using concentrated windings compares well with the behaviour of the non-offset conventional machine using

double layer windings.

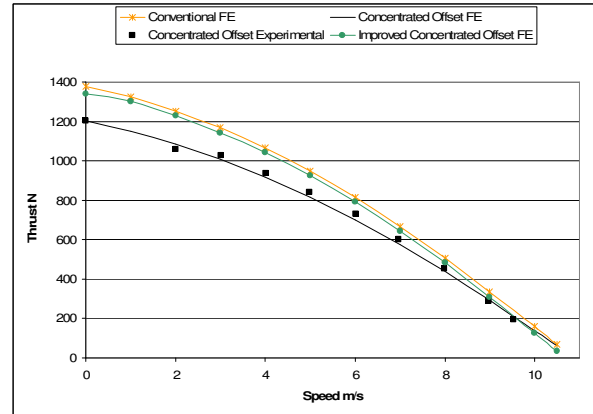


Fig. 8 Motor pair thrust speed comparisons

In an improved version more conductors can be packed in the slots due to the simple non-overlapping winding, and the slot turns and slot profile can be modified to improve machine performance. An improved machine has been designed with similar force to the conventional but reduced assembly costs. The improved machine has been finite Element modelled in Fig. 8.

## 7. Conclusions

A novel form of double-sided linear induction machine has been described which uses concentrated windings. The arrangement eliminates the backward going harmonic produced by the concentrated windings so that a plate secondary can be used. Comparisons have been drawn between the thrust produced by the arrangement and a similar double-sided machine made from stators using conventional double layer windings and it is shown that comparable results are obtained. It is shown that finite element analysis can be used successfully to model findings from an experimental machine

## 8. 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] Russell, R.L. and Norsworthy, K H. "Eddy Current and Wall Losses in Screened Rotor Induction Motors" Proc. I.E.E. Paper No. 2525 U, Apr 1958 (105 A, 163)
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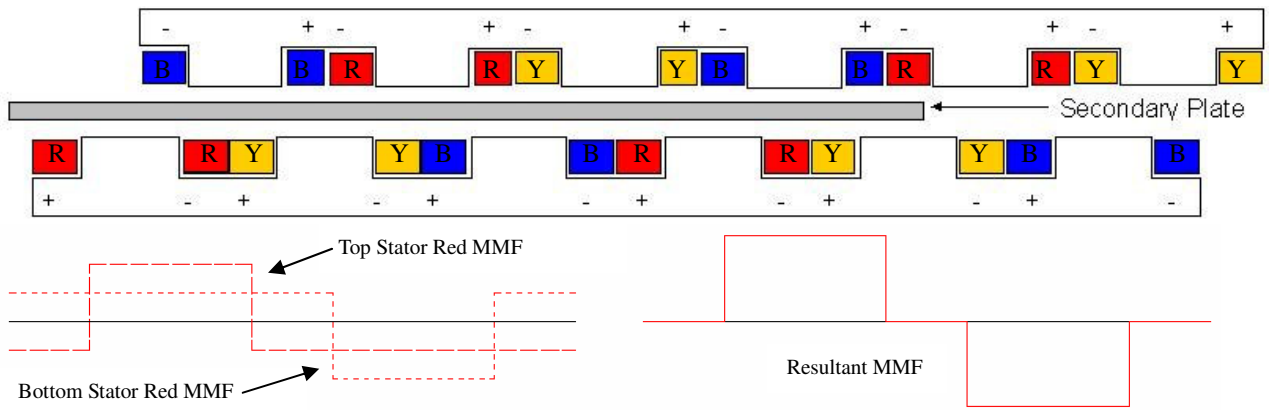


Fig. 3. Offset Stator machine and component mmfs

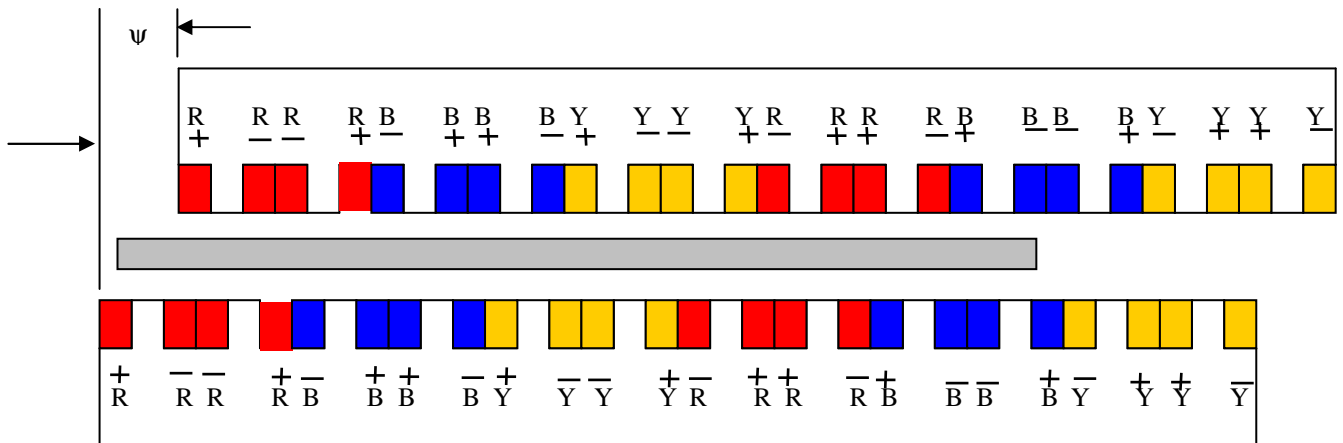


Fig.5 12 slot modular winding stators offset by one pole-pitch of the 14 pole ( $\psi$ )