Parallel And Flux Forced Windings In Discontinuous Machines

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***Abstract*—Linear Induction Motors commonly have the coils of each phase connected in series. The effect of this connection type is that equal currents flow throughout the phase winding, whilst the voltage across coil groups connected in series may vary significantly. As flux is proportional to voltage, the air gap flux may also significantly vary over the length of the machine. This can be an issue particularly where a conductive plate is traveling between a series of discontinuous machines at high speed, for example in electromagnetic launch systems. The plate entry into each discontinuous machine can cause significant drops in flux with a consequent large variation in thrust. With a machine using phase groups connected in parallel, the voltage is now forced whilst the current is variant. This has the effect of maintaining the air gap flux on entry and so producing a more consistent force profile, a significant benefit for high speed launch applications.**

Keywords-Linear Machines; Linear Induction Motors; High Speed Launch

I. INTRODUCTION

The windings for most Linear Induction Motors have all the coils for each phase connected in series. Flux varies along the stator, being close to zero at the input edge. This limits the output force and can produce force perturbations if the stator is discontinuous.

The problematic flux behavior can be improved if sections of the winding are connected in parallel, and the potential advantages of this connection type will be established.

II. THE BEHAVIOR OF SIMPLE VOLTAGE & CURRENT FORCED MAGNETIC CIRCUITS

The principle behind the work can be explained with the aid of simple magnetic circuits, shown in Fig 1-4. The current in the coil is the same for Fig. 1 and Fig. 2. Fig. 1 shows the conditions with a simple air gap. In Fig. 2 a conductive plate secondary is inserted into the air gap and it will be observed that the flux is reduced to a small value in comparison to the air gap case by the presence of induced currents within the plate.

Very different behavior results if the coil is connected to a constant voltage source as shown in Fig. 3 with a simple air gap and Fig. 4 with an air gap including a conductive plate. Here the flux is largely the same regardless of the presence or absence of the conductive plate.

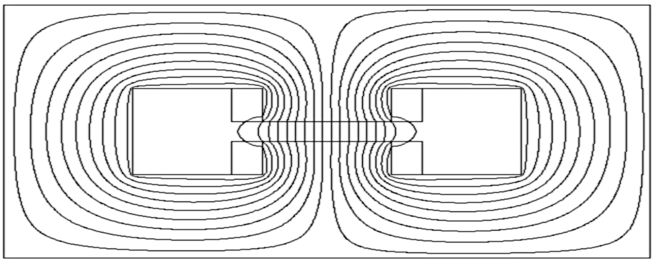

Figure 1. Magnetic circuit behaviour with a fixed current supply

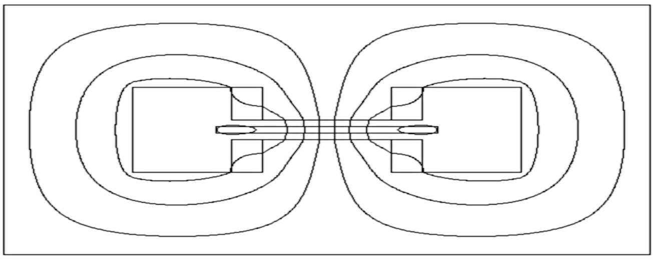

Figure 2. Magnetic circuit behaviour with a fixed current supply and a conductive sheet in the airgap

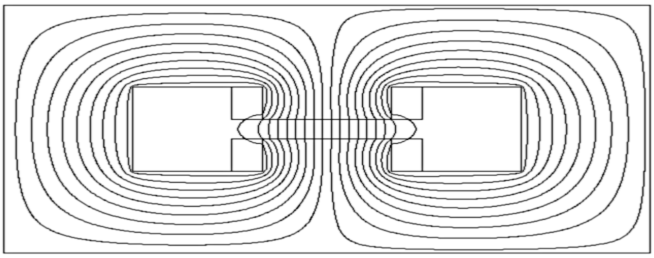

Figure 3. Magnetic circuit behaviour with a fixed voltage supply

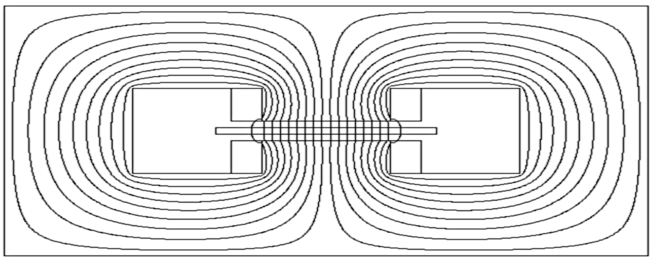

Figure 4. Magnetic circuit behaviour with a fixed voltage supply and a conductive sheet in the airgap

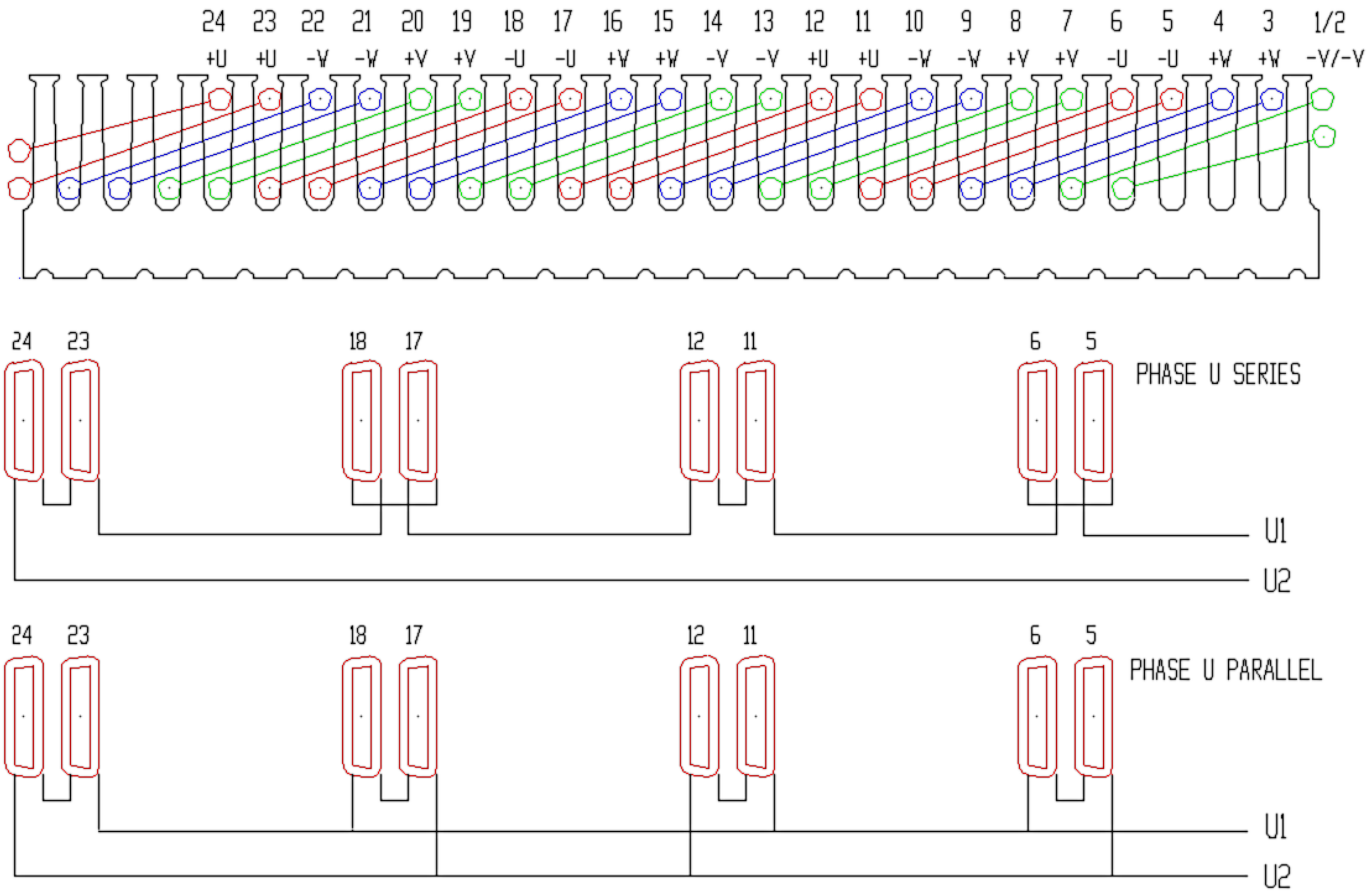

Figure 5. Series and parallel winding connections for one phase of a stator

III. Application of Forced Voltage And Forced Current to Linear Stators

In linear machines, coils of a phase are generally connected in series, as shown in Fig. 5. This has the effect of forcing an equal current through each phase group of coils, whilst allowing the voltage (and hence flux) per phase group to be variant as in Fig. 1-2.

In an alternative configuration [1][2] also shown in Fig. 5 the phase groups of each stator can be connected in parallel with one another with the effect of forcing an equal voltage and so an equal flux in each phase group, whilst allowing the current per phase group to be variant as in Fig. 3-4.

The behaviors of linear machines using both series and parallel connections, the differences in behavior between the two connection types and the advantages of using parallel windings are explored below.

IV. The Behaviour Of A Short Stator Machine With A Series Connected Winding

The behavior of a machine with a series connected winding and discontinuous stator is complex; the amplitude of the flux linking the stator varies along its length rather than being constant as in a conventional cylindrical machine. This means that the voltage across the coil groups varies along the length of the winding. To appreciate the action the rotor can be represented by a series of bars in the form of a squirrel cage. A loop formed by two of the bars, neglecting fringing effects, has zero flux linked with it immediately before it enters the stator and it follows that the flux just inside the stator is also zero. To achieve this the rotor loop acquires an induced current largely equal and opposite to the stator current. The rotor current and flux following this condition as the loop progresses along the stator depends on several factors including the rotor velocity.

The case for synchronous rotor speed will be considered first. The gap flux can be considered to be made up of a first component due to the stator currents and a second due to the rotor. The stator flux is a constant amplitude travelling wave in quadrature with the stator current wave. Since there is no slip between the rotor and the stator wave there is no mechanism to maintain the rotor current induced at entry and it decays as the rotor progresses. This decay takes the form $J_r = J_o \varepsilon^{-t/\tau}$ where τ is the rotor coupled time constant. The corresponding rotor flux produced by the rotor current is again a decaying travelling wave of the form $\varepsilon^{-t/\tau}$ that is equal and opposite with respect to the stator flux wave at entry.

The above treatment is extended in [1] & [2] to the case of a general rotor velocity and shows that the air gap flux is given by:

$$B_g^2 = \frac{(\rho J_s)^2}{(\sigma u_s)^2[1+(c_0/\sigma)^2]}\{1-2\varepsilon^{-a_0 x}\cos b_0 x+\varepsilon^{-2a_0 x}\} \quad (4)$$

Where

$$a_0 = \frac{n\pi}{\tau\omega(1-\sigma)} \quad (5)$$

$$b_0 = \frac{\pi\sigma n}{1-\sigma} \quad (6)$$

$$c_0 = \frac{1}{\tau\omega} \quad (7)$$

$$x = \frac{s}{np} \quad (8)$$

$$\tau = \frac{4p^2\mu_0}{\pi\rho_r g} \quad (9)$$

and

J_s = stator current loading

n = number of poles on the stator

p = pole pitch

σ = slip

s = distance along the stator

g = magnetic gap

ρ_r = rotor surface resistivity

The references further go on to find expressions for the quantities such as force, losses etc. However the theory assumes steady state operation and is necessarily approximate. It neglects the plate leakage inductance and assumes that the flux is in paths at right angles to the pole surfaces. However the only rigorous technique available for the analysis of an accelerating short rotor in a discontinuous set of stators is time stepping finite element analysis, which is comparatively slow compared to simple analytical methods. The simple theory is therefore useful as a method to gain some physical insight and as an approximate confirmation of finite element results in simple cases.

Fig.6 shows the results of a finite element calculation of the flux envelope of a series connected short stator machine at near synchronous speed and Fig.7 the comparative result using equation (4) and it can be seen that the agreement is good for the case chosen. Essentially this confirms the physical approach that the field at the entry edge will be close to zero if a plate with zero current enters.

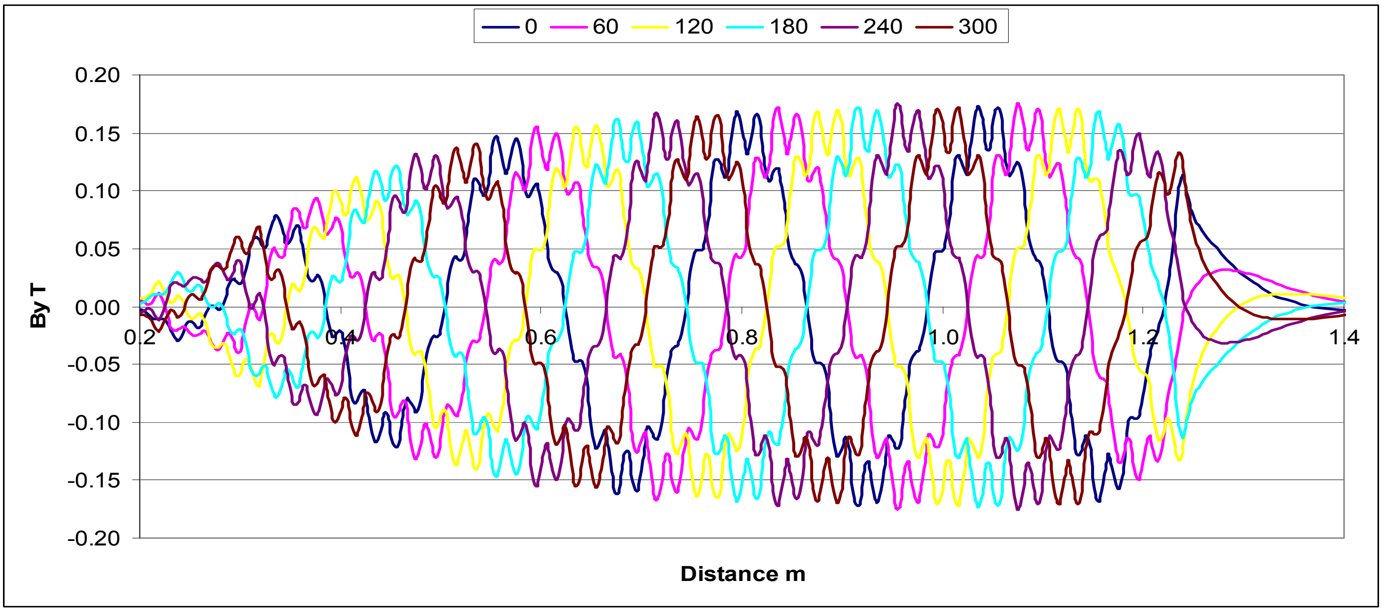

Figure 6. Air gap flux for a series connected winding at calculated from FEA at various instants in a cycle

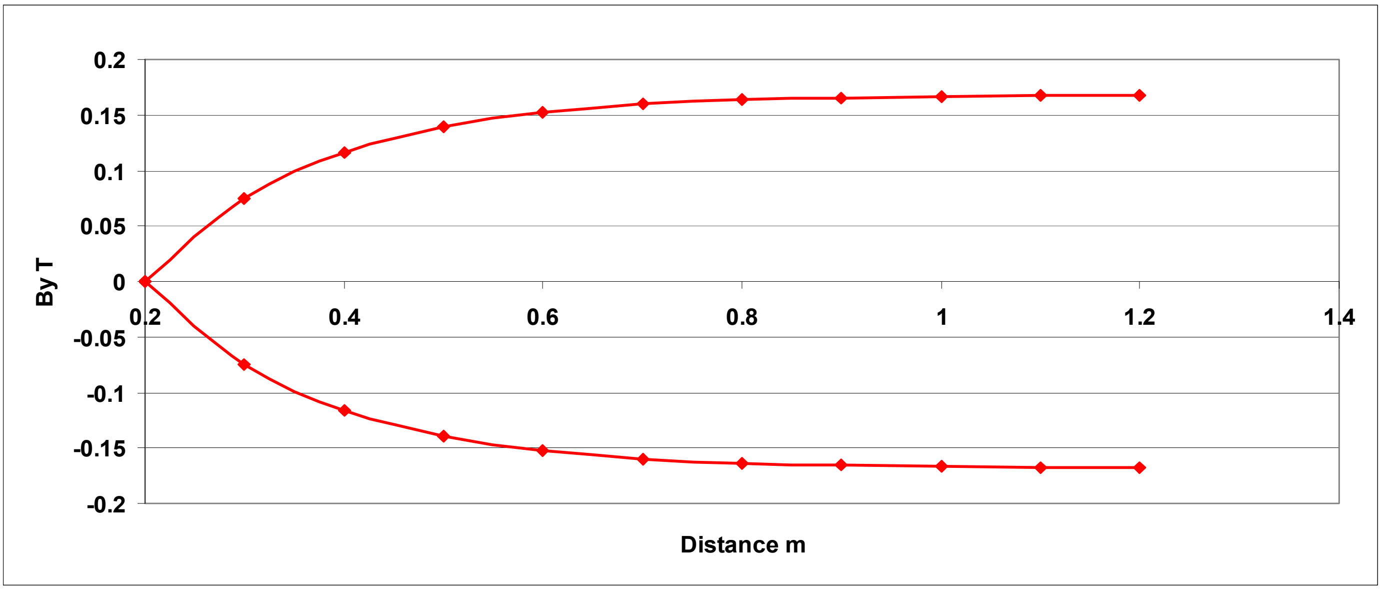

Figure 7. Peak airgap flux for a series connected winding calculated using equation (4) at various instants in a cycle

V. The Behaviour Of A Short Stator Machine With A Parallel Connected Winding

The principle behind the parallel connected winding can be found by reference to Fig 3-4. The flux remains largely the same regardless of the conductive plate in the airgap. This can be explained by the use of the voltage equation which with $\phi = \Phi \sin \omega t$ becomes $e = \omega \Phi N \cos \omega t$ for sinusoidal quantities, when the coil resistance is assumed to be small.

It can be seen that the flux is proportional to the applied voltage irrespective of any external conditions and it is often said that the flux sets the voltage. For example if the gap size of Fig. 3 were doubled then the flux would still have the same value as before. Looking at Fig. 3 if a conductive plate secondary is inserted then the voltage will again set the flux with an increase of coil current to compensate for the current in the plate.

In one parallel configuration [3] the phase groups of each stator are connected in parallel with one another with the effect of forcing an equal voltage and so an equal flux in each phase group, whilst allowing the current per phase group to be variant. An air gap flux envelope plot for the winding used for Fig.5 but connected in parallel rather than series is shown at Fig.8.

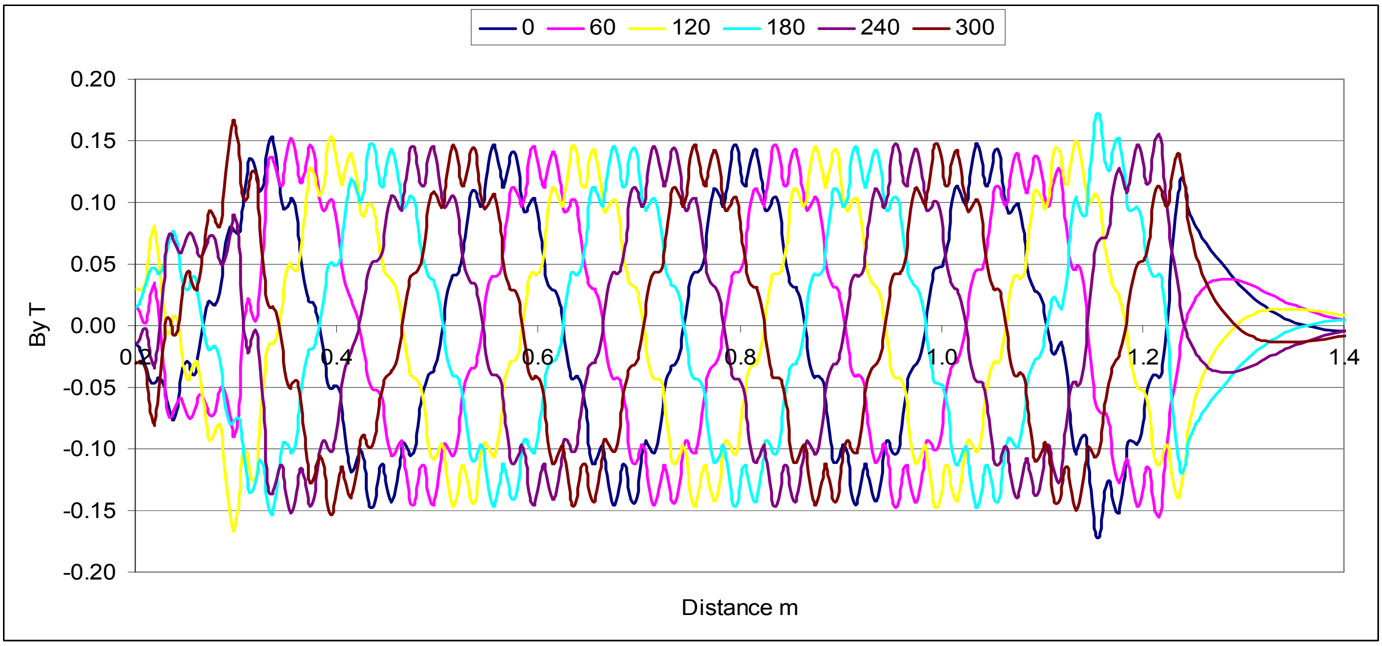

Figure 8. Airgap flux for a parallel connected winding at calculated from FEA at various instants in a cycle

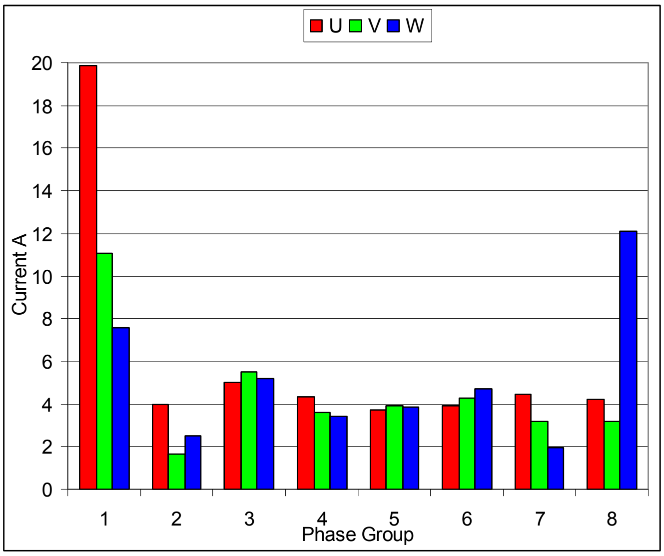

Figure 9. Current density plot for each phase group of a parallel connected stator

Fig. 8 serves to demonstrate the effect of this connection type on the air gap flux. It can be seen that whilst the flux is significantly tapered at the conductor entry edge in the series case Fig. 5, it tends to be constant in the parallel. The flux at the machine ends is much less varied and reaches its maximum over a significantly shorter distance due to the flux forcing effect of the parallel connection.

The current drawn by the various parallel connected coil groups for each phase is shown at Fig. 9. It can be seen that there is a significant variation in current draw along the stator in order to force constant flux. The current draw at the entry end and to a lesser extent at the exit end is notably greater than that in the middle groups of the stator. The current imbalance makes this method mainly applicable to areas where long term rating is not an issue, for example, in high speed short term rated launch equipment.

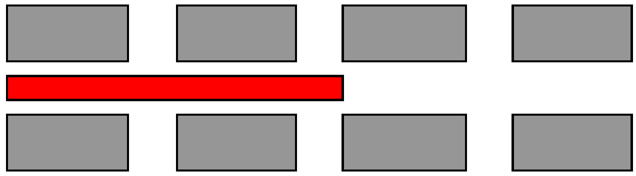

Figure 10. Typical electromagnetic launch layout with multiple stators

IV Application to Electromagnetic Launch.

The effect of parallel connection on the motor flux for a short stator machine has been shown. The situation in electromagnetic launch arrays, for example the one sketched at Fig. 10, is considerably more complex.

In this configuration, multiple disjointed stators are acting on both sides of a rotor that is longer than an individual stator unit but shorter than the overall track

Whilst there are similarities between single stator performance and full track behaviour other important effects are found only in a track situation. For example the plate can enter a powered stator when it is still carrying current from the previous stator. With a track using series connected stators, the effects on the gap fluxes during the transition is shown at Fig. 11. It can be seen that the flux under the section of plate entering the right hand stator is significantly reduced compared to that in the rest of the machine. This reduction in flux consequently reduces the force on the plate, causing significant force perturbations and reducing performance as the plate travels between machines.

An identical launch track has been modified to use parallel rather than series connection and the flux conditions are shown for comparison in Fig.12. It can be seen that the flux at the entry edge of the plate is much closer to that found throughout the machine when compared to the series connected case. The parallel connection of the launch track has effectively reduced the loss of flux as the reaction plate enters a stator, thus ameliorating the large force perturbation present in the series connected version.

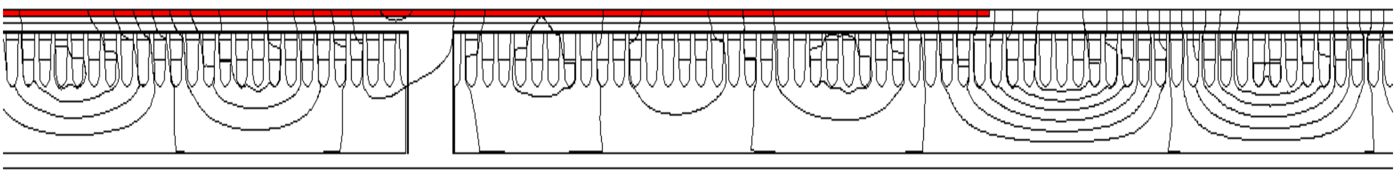

Figure 11. Flux contours for a series connected machine from FEA

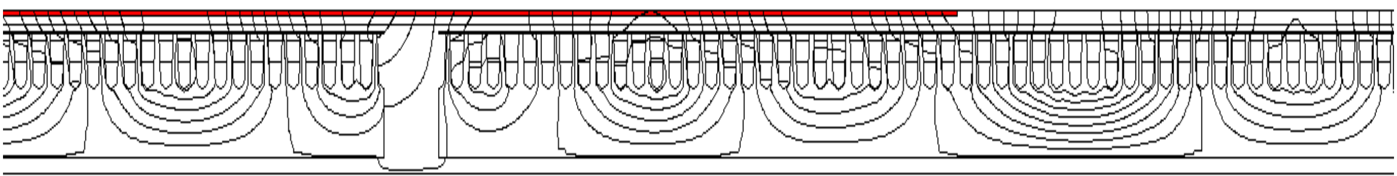

Figure 12. Flux contours for a parallel connected machine from FEA

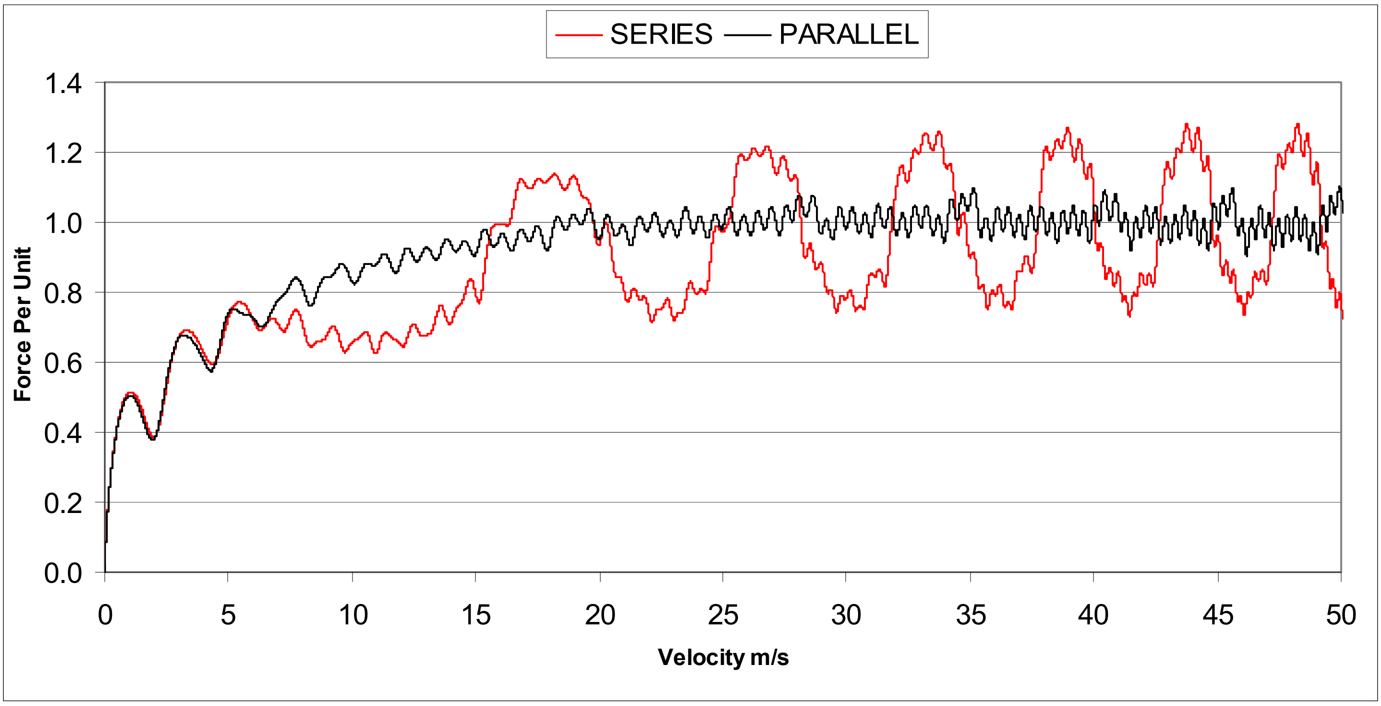

Figure 13. Force per unit for a launcher connected in series and parallel

The method of using parallel connected machines to force the flux in the air gap has been successfully employed for high speed launch. Fig. 13 shows the per unit thrust for a high-speed launch system with otherwise identical stators connected in both series and parallel.

In the series case, it can be seen that large perturbations in force are present, corresponding to the transition points at which the leading edge of the rotor travels between adjacent but discontinuous stator blocks, arranged as in Fig. 10. This behavior is a direct result of the reduced leading edge flux in transient conditions seen in Fig. 6.

Fig. 13 also shows the same discontinuous stators with phase groups connected in parallel. It can be seen that the large force perturbations present in the series connected case are removed by this method, as the leading edge flux is maintained at its maximum value as shown in Fig. 8.

V Conclusions

The use of parallel connections provides significant benefits for machines such as high speed launchers, where a long track of discontinuous stators is used with a rotor that is longer than an individual stator but much shorter than the overall track.

The parallel connection method forces the airgap flux to be constant along the full length of the stator, which prevents significant force perturbations due to flux variation that are present in the series connected case due to the transition of the moving rotor between discontinuous stators.

VI References

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[3] E. R. Laithwaite, “Induction Machines For Special Purposes”, Newnes, 1966, Chapter 3 pp. 51-56