LINEAR SYNCHRONOUS MACHINE PERFORMANCE IMPROVEMENT WITH FLUX BARRIERS

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Abstract

Linear synchronous motors can be used for large scale electromagnetic launch. The machines are short time rated and can therefore use substantial values of stator current loading. This leads to high values of armature flux and the risk of demagnetising the excitation magnets. In order to mitigate this risk by reducing the armature flux, quadrature axis flux barriers can be positioned in the permanent magnet backing iron. These reduce the armature field but leave the permanent magnet excitation field largely unchanged. In addition to improving the force due to the larger usable stator current loading, the barriers are beneficial in reducing the synchronous reactance and hence improving the power factor and reducing the Volt Amps per Newton of useful force (VA/N) of a linear motor. The paper explores the use of these barriers for a typical configuration and shows the performance improvements that can be obtained.

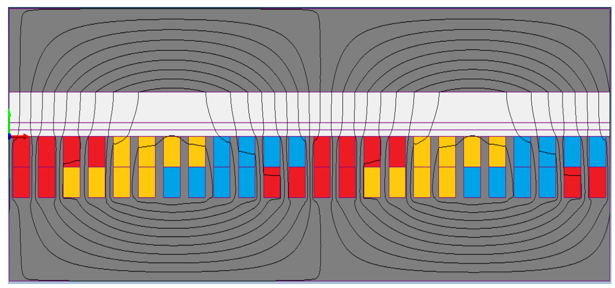
1 Introduction

Linear Synchronous Motors (LSMs) using permanent magnets (PM) are capable of producing high thrusts suitable for large scale electromagnetic launch projects [1]. These machines are short time rated with the current on time typically less than a second so that the stator current loading can be high. This leads to one of the principal disadvantages of the use of PM LSMs for high energy launch, which is the risk of irreversibly demagnetising the magnets due to high armature fluxes occurring in the machine.

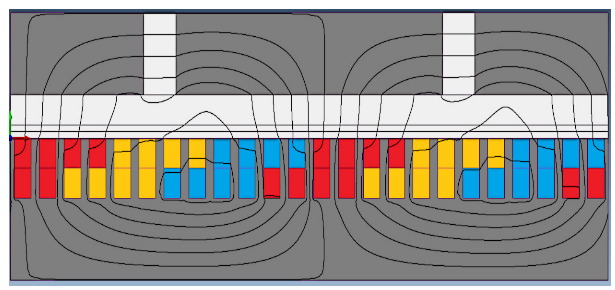
2 The Machine Action

This paper describes a novel PM linear synchronous motor of the surface magnet type that uses quadrature axis flux barriers [2,3] to reduce the armature flux. This in turn allows the use of a higher current loading and so allows a significantly greater output force and performance without the risk of demagnetising the excitation magnets.

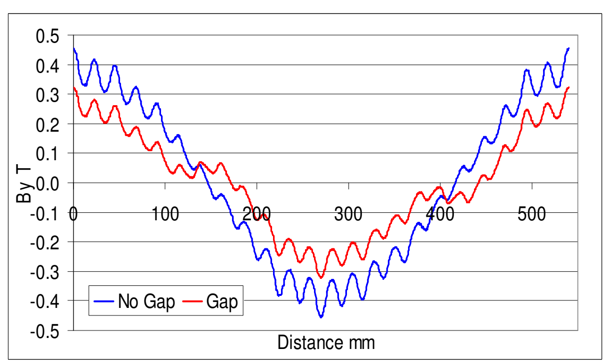
The effect of the flux barriers can be explored using 2D finite element analysis (undertaken using Infolytica's MAGNET software) of a two pole section of a machine. The models are of a scale suitable for aircraft launch, initially using 66kA/m current loading. The position of the stator current wave is chosen to yield maximum tangential force. Figure 1 shows the effect on the armature flux of a quadrature axis flux barrier without excitation magnets.



(a) FEA Plot armature flux with no flux barrier



(b) FEA Plot armature flux with quadrature axis flux barrier

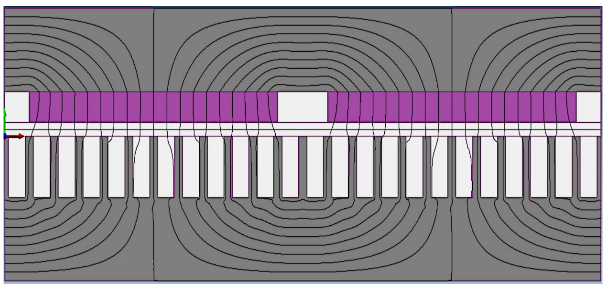


(c) Graphs of normally directed armature air gap flux density with and without the quadrature axis flux barrier

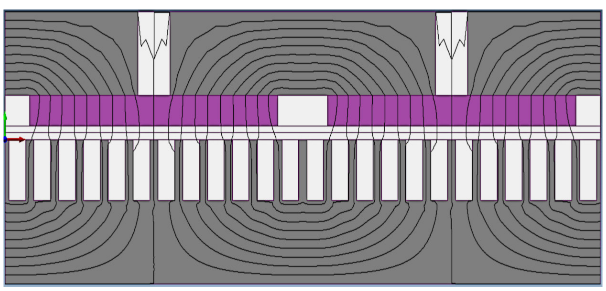
Figure 1: Showing the effect of a quadrature axis barrier on the armature flux

Figure 1(a) illustrates the armature field without the barrier, in contrast with Figure 1(b) where a barrier is employed. It will be observed that the armature field is considerably reduced by the barrier. Figure 1(c) plots the normally directed air gap flux density at the centre of the air gap, confirming the reduction in armature field.

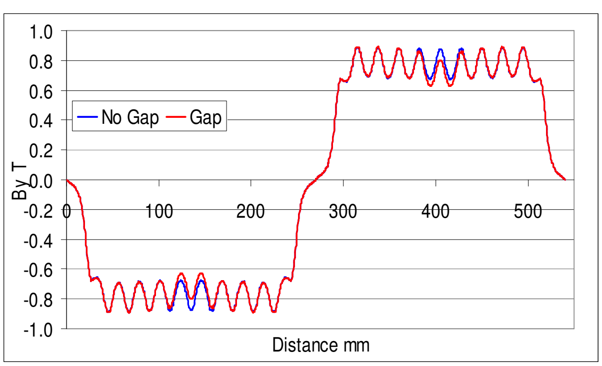
The effect of the flux barrier on the permanent magnet (PM) flux, again using the FEA method, is illustrated by Figure 2. Figure 2(a) shows the magnet excitation field without the barrier and Figure 2(b) the field when the barrier is present. It can be seen that because of the orientation of the barrier the field is only marginally reduced by the barrier. This is confirmed by Figure 2(c) which shows a plot of the normally directed flux density at the centre of the gap.



(a) FEA Plot permanent excitation flux with no flux barrier



(b) FEA Plot permanent magnet excitation flux with quadrature axis flux barrier



(c) Graphs of normally directed PM excitation air gap flux density with and without the quadrature axis flux barrier

Figure 2: Showing the effect of a quadrature axis barrier on the permanent magnet excitation flux

In this case, the width of the flux barrier has been made equal to the width of the airgap plus the magnet depth. This seems to be a reasonable approximation based on the compromise of reducing armature flux whilst maintaining sufficient backing iron for proper operation. The shape of the flux barrier was maintained as a straight sided slot for ease of production, especially if this is to contain non magnetic material for structural purposes.

The use of trapezoidal iron secondary pieces that are wider at the magnet surface would further reduce armature flux without significantly affecting excitation magnet flux. Optimisation of the flux barrier shape and size will be undertaken for the general case in future work.

3 Effect on the Machine Performance

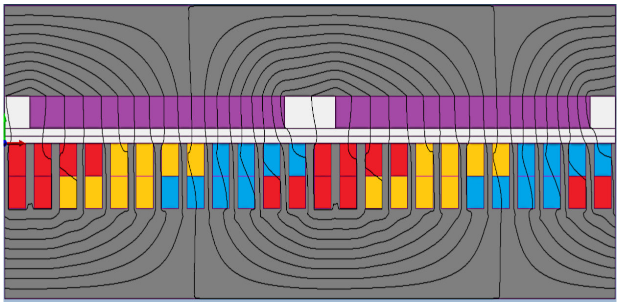
The flux barrier improves the machine performance by reducing the armature flux with only a small reduction in the excitation flux. The reduction in armature flux provides three benefits:

-The demagnetising effect of the armature flux is reduced. Demagnetisation can occur when the armature field becomes strong enough to reverse the magnet field, typically in extremities such as the corners and edges of the excitation magnets. Decreasing the potentially demagnetizing armature field for a given value of current means that a higher value of stator current loading and hence force can be achieved without risking irreversible reduction of the magnet flux.

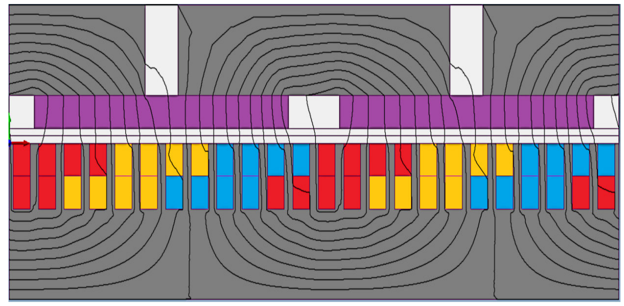
-The synchronous reactance is reduced due to the reduction of armature flux. This means that the machine current usage at a fixed voltage is reduced and the overall VA/N and power factor are improved.

-For a given value of current loading, the tooth fluxes are reduced due to the reduction in armature flux.

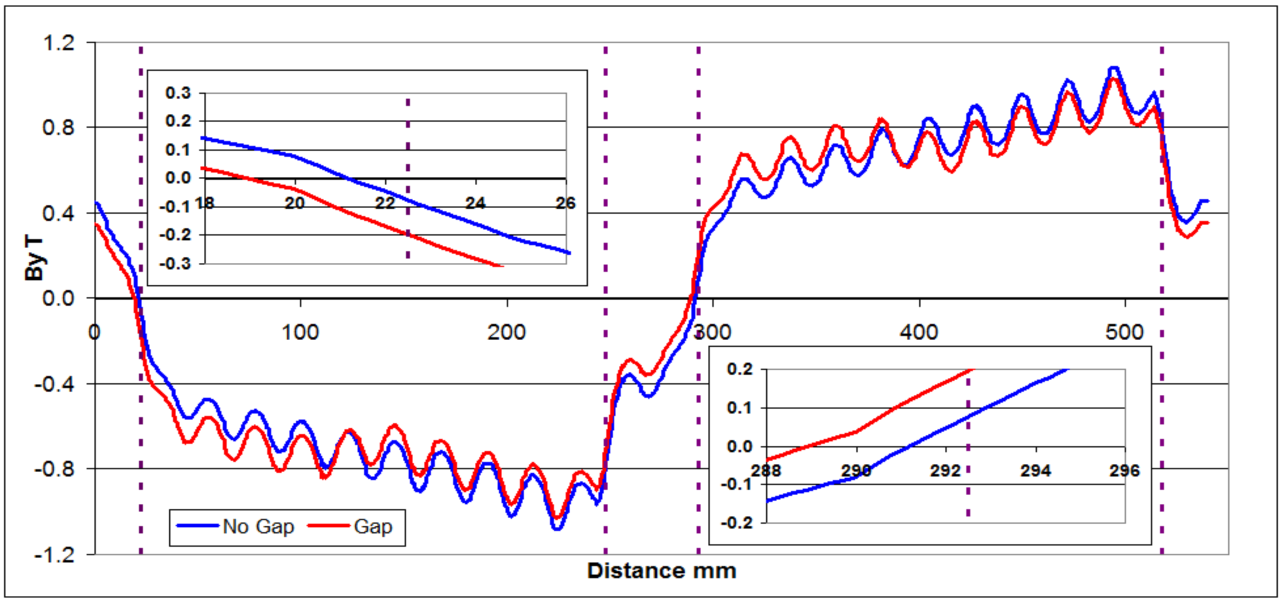
Figure 3 shows the total machine behaviour including both excitation and armature fields. The edges of the excitation magnets where demagnetising effects may occur are indicated by the dotted lines on Figure 3 (c), with close ups at two points to show the resultant flux at the magnet edges. It can be seen that the magnet edge flux at this current loading is greater with the flux barriers than without, indicating that significant extra current loading may be achieved without risk of demagnetization.



(a) FEA Plot total flux with no flux barrier



(b) FEA Plot total flux with quadrature axis flux barrier



(c) Graphs of normally directed total air gap flux density with and without the quadrature axis flux barrier

Figure 3: Showing the effect of a quadrature axis barrier on the total flux

3.1 Armature flux demagnetisation

In order to establish the allowable level of current loading for cases with and without flux barriers, the magnet edge flux for the negative excitation magnet was plotted for various levels of current loading, the results of which can be seen in Figure 4.

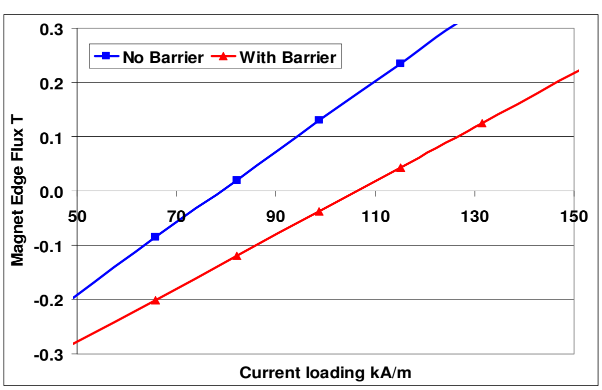


Figure 4: Current loading and consequent negative field magnet edge flux for various values of current loading.

For the purposes of this comparison it was assumed that the commonly employed straight line demagnetization characteristic could be used for the magnet material with values of remnant flux density and relative permeability set at 1.39T and 1.04 respectively. These values are appropriate to NdFeB.

From Figure 4, it is apparent that the flux barriers make a significant difference to allowable loading. Leaving an arbitrary 0.05T safety margin, the maximum rms current loading is 71kA/m for the case with no barriers, and 96kA/m for the case with flux barriers. It can be seen that whilst the total flux at the magnet edge is driven into the region where the flux is in the opposite direction to the magnet flux by the current loading of 96kAt/m when there is no barrier, this current loading can be withstood when the barrier is present.

3.2 Force output

The increase in current loading to 96kA/m implies a proportional tangential force increase of 35%, which has been verified by FEA.

3.3 Synchronous reactance

At 96kA/m current loading using a flux barrier the synchronous reactance is reduced by 11% compared with the machine at 71kA/m without a barrier.

3.4 Tooth fluxes

The maximum tooth flux when using 96kA/m and a flux barrier is equal to that produced by 71kA/m and no barrier as the current loading in each case has been chosen to produce a consistent gap flux.

4 Conclusions

The flux barrier method has been shown through FEA modelling to significantly improve the performance of LSMs. This method produces a significantly greater force for a given machine size by allowing the use of a significantly greater current loading without the risk of demagnetising the excitation magnets and with the same maximum tooth flux. Further, this method reduces the synchronous reactance.

References

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