FEA Modelling of a Novel Tubular Linear Generator

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1. Introduction

This paper presents the finite element modelling of a novel tubular linear generator, designed for efficient wave energy conversion. The paper presents generator design considerations to meet the demands of the intended application. In addition, the paper concentrates on novel aspects of generator modelling using electromagnetic finite element analysis, which were adopted to fully characterise the generator performance at the development stage, hence alleviating the need for prototyping, the cost of which was unacceptable for this application.

2. Linear Generator Design

Figure 1 shows a section of a two-dimensional finite element model of the tubular generator.

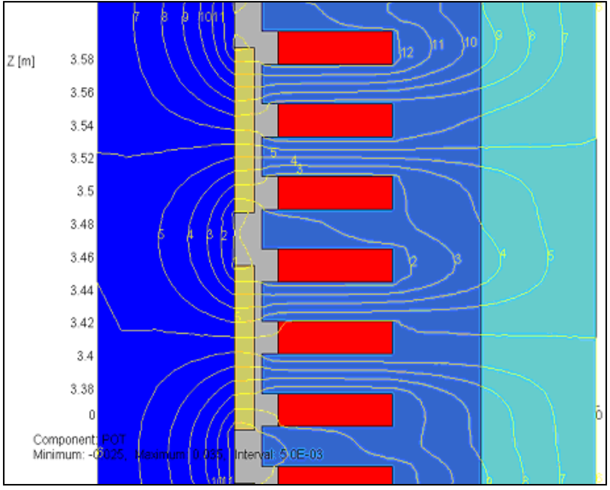


Figure 1. Section of a two-dimensional axi-symmetric model of the tubular generator

The tubular linear generator was designed to perform the mechanical / electrical energy conversion in a wave energy converter. The wave energy converter was of the type that produced an oscillating linear movement with a period of around 8-10 s.. The linear generator was required to operate with a peak mechanical force of 1 MN.

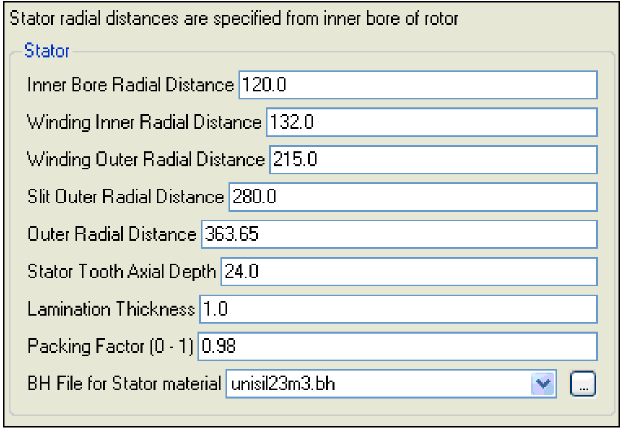
A tubular design was chosen rather than a more conventional flat linear machine for simplicity and strength in the mechanical structure and bearings. Ideally, stator laminations would be in the radial-axial plane to prevent the flow of azimuthal eddy currents, but this requires a tapering thickness to laminations to support each lamination subtending a constant azimuthal angle at all radii. Manufacturing could be made significantly easier if stator laminations could be built up in the same way as in a conventional rotating machine i.e. with laminations in the radial-azimuthal plane. Consequently, the flux path in the core-back of the tubular machine parallel to the axis, means that eddy currents can be induced in the plane of the laminations. It was therefore necessary to carry out detailed modelling of the eddy current behaviour to determine whether losses could be controlled to acceptable levels by introducing design modifications.

3. Linear Generator Modelling

3.1. Linear Generator 'Design Environment'

To enable the rapid generation of finite element models that incorporate significant design changes, parametric models driven from customised dialog environments were produced to give a 'Linear Generator Design Environment'. These capabilities were achieved by use of an advanced scripting language available in the software [1], [2]. Every aspect of the geometry and all analysis options were parameterised. Figure 2 shows part of a typical dialog with dimensions and material properties defined for the stator.

To reduce eddy current losses in the stator, the laminations were cut with radial slits – rather similar to Pistoye slits found in the teeth of large radial flux synchronous machines – which create a considerably longer eddy current path. The ability to define a Design Environment around the machine was particularly useful when features special to this machine (such as the slits) were parameterised and their values also given through the dialogs.


Stator radial distances are specified from inner bore of rotor

Stator

Inner Bore Radial Distance 120.0

Winding Inner Radial Distance 132.0

Winding Outer Radial Distance 215.0

Slit Outer Radial Distance 280.0

Outer Radial Distance 363.65

Stator Tooth Axial Depth 24.0

Lamination Thickness 1.0

Packing Factor (0 - 1) 0.98

BH File for Stator material unisil23m3.bh

Figure 2. Sample dialog for defining model

These slits limit the usefulness of two dimensional modelling as eddy currents are no longer confined to the azimuthal direction and a three dimensional solution must be obtained. The model extended over half of one azimuthal pitch of the slitting (between the centre of one slit and the centre between a pair of slits). On each of these boundaries the flux will be tangential and appropriate boundary conditions were applied to imply the remainder of the 360 degrees. In the axial direction, the model covered one pole pitch with negative periodicity boundary conditions applied to imply that the pole pitch is part of an “infinite” system in the axial direction. However, the coils in the model are connected into a circuit that has the correct number of pole pitches for the finite length machine.

3.2. Effective Modelling of Electric and Magnetic properties of Materials

The laminations in the machine are quite thick (1 cm) and it was initially hoped to model each lamination discretely, but this resulted in extremely large models which significantly limited the ability of the designer to examine multiple designs.

ELEKTRA-TR [1] includes an option for inclusion of laminated and anisotropic material properties within magnetic / conducting regions of the model. In laminated volumes, the region is treated as a bulk (solid) material but has properties that simulate the laminated nature [3]. Specifically, the anisotropic permeability and conductivity tensors of the bulk material in the plane of the lamination and perpendicular to it are set from the isotropic material properties and the packing factor. The bulk model was originally validated for thin laminations and the normal assumption is that the conductivity in the perpendicular direction is zero. To obtain valid parameters for the thicker laminations in the linear generator, test models were constructed that compared a small volume of the bulk material with equivalent explicitly modelled laminations. It was found that a perpendicular electrical conductivity about 4 orders of magnitude lower than the intrinsic material value in the bulk representation gave equivalent eddy current losses to the explicitly modelled laminations.

3.3. Achieving Motion … without Movement.

Modelling true linear motion in three dimensions is computationally expensive, as it requires re-meshing in 3D at each time step. An alternative method was proposed that emulates the movement by replacing the moving magnets on the rotor with a set of solenoid coils that switched on and off in sequence. The validity of this was initially tested in two dimensions (where re-meshing at each time step is much less expensive). Firstly the necessary excitation level in the coils was established by comparison of the static field distribution with coils or magnets present. Then, the conductors were excited at distinct time intervals to simulate the rotor moving at a specified linear velocity. The open circuit stator voltage was computed and this was compared to the results obtained with true reciprocating linear motion.

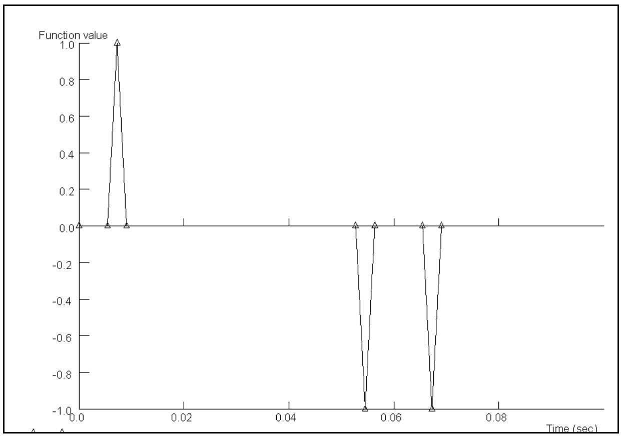


Figure 3. Typical pulse shape for switched coils

Several investigations of the necessary pulse shape for the currents were made and it was determined that a triangular pulse starting to switch on one time-step before the magnet arrived at the position where its edge would coincide with the position of the coil and completing switch off one time-step after the coincidence position gave the closest comparison. Figure 3 shows a typical switching sequence for one of the coils (where it was necessary for it to represent both a north and south pole passing the coil position and the south pole returning due to the reciprocating motion). Figures 4 and 5 compare the open circuit voltages for the true linear motion with the switched coil approximation.

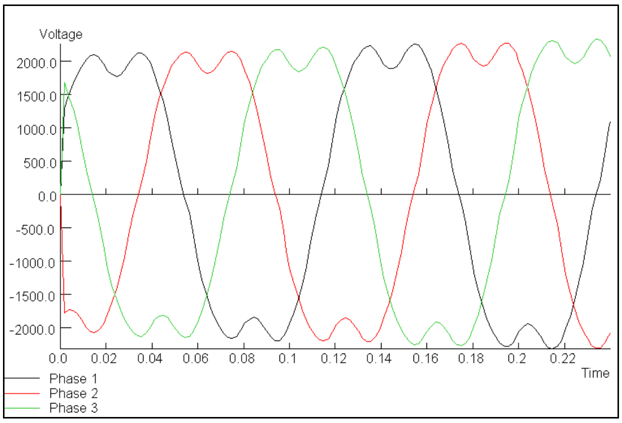


Figure 4. Open circuit voltage from linear motion

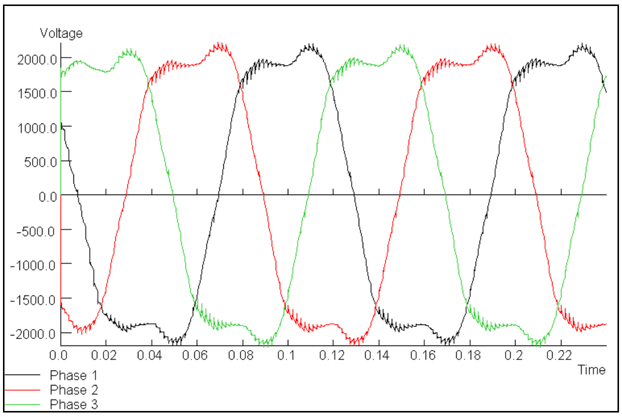


Figure 5. Open circuit voltage from switched coils

Small oscillations associated with the switching can be seen but the overall comparison is acceptable. The same triangular pulse scheme was therefore used in the three dimensional modelling.

3.4. Results

The initial design configuration was created using the customised dialog and the open circuit model operating conditions defined. Figure 6 shows the open circuit phase voltages. The waveform shows a considerable flat top with the same double peak seen in the 2D results (that ignores the slitting). This waveform is equivalent to a fundamental (8 Hz) line voltage of 3.2 kV, as expected.

This is a time-stepping simulation so there are initial transient components associated with initial switch on. This can be seen in the voltage waveforms but are clearer when computing the power dissipation in the stator due to the eddy currents (shown in figure 7). When steady state operation is achieved, the power loss will be of the form of a DC with double frequency ripple (+ higher harmonics). Figure 7 shows that the average value is settling to around 35 kW.

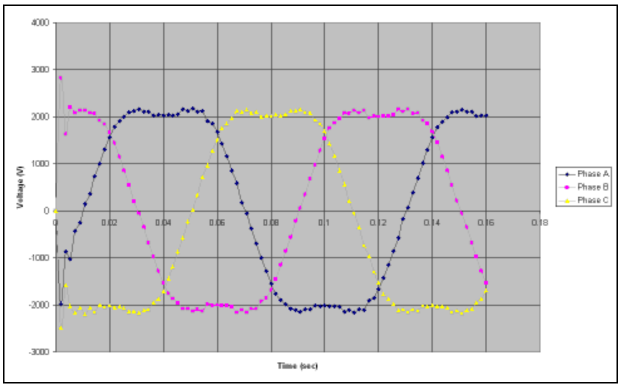


Figure 6 Open circuit voltages in 3D model with slitting

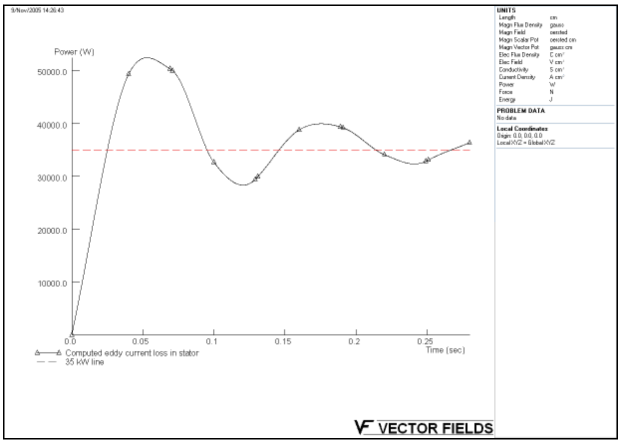


Figure 7 Power dissipation in stator on open circuit

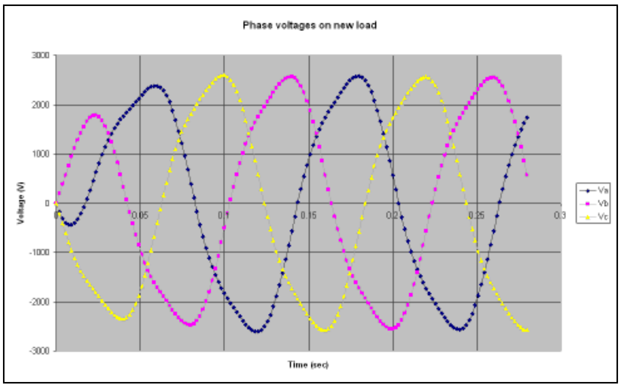


Figure 8. Phase voltages at 0.85 p.f. lead

The same design configuration was then examined at the (expected) worse case load conditions – 0.85 p.f. lead. Figures 8 and 9 show the stator phase voltage and currents respectively, and figure 10 shows the power dissipation. Under these operating conditions power dissipation in the stator rises to around 47 kW, which is about 2.4% of output power. This is unsurprising as the lamination is not in the correct direction to eliminate eddy currents in the stator.

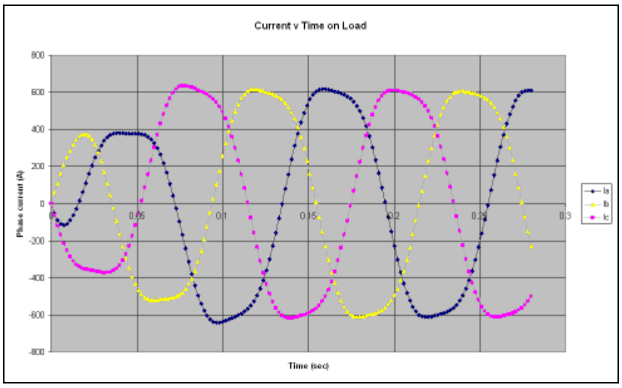


Figure 9. Phase currents at 0.85 p.f. lead

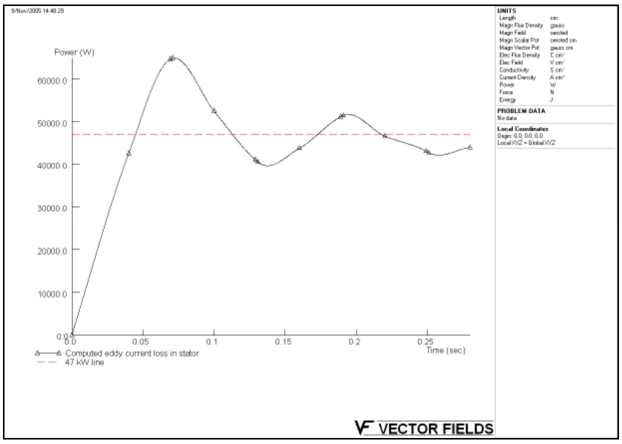


Figure 10. Power dissipation in stator at 0.85 p.f. lead

At this load operating condition it can be seen that the stator voltages and currents still contain a high harmonic content, although the flat top seen on open circuit voltage is less evident. The armature reaction MMF opposes the field MMF from the permanent magnets reducing the saturation in the stator.

Figure 11 shows a typical instantaneous eddy current density distribution on load. The highest density is observed at the back of the slits but, of course, this is confined to a small volume and total losses are actually higher on the edges of the teeth than in the core back.

4. Future work

Further design configurations, which can be simply generated using the linear generator environment dialog, should be examined in order to further reduce the stator power loss.

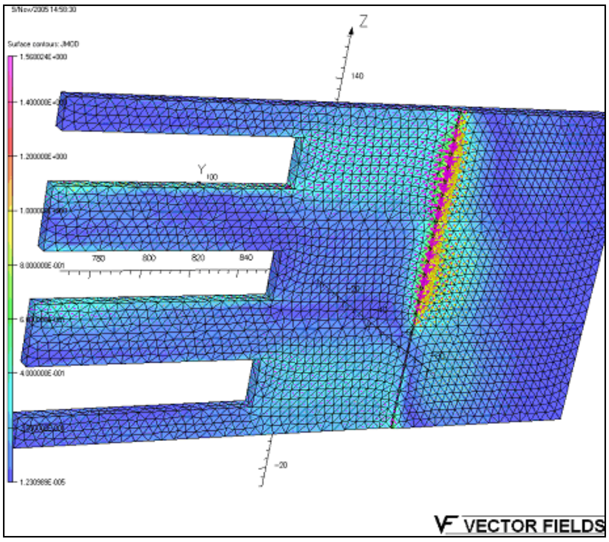


Figure 11. Instantaneous eddy current distribution at 0.85 p.f. lead

5. Conclusion

Successful three-dimensional finite element modelling of a novel linear generator on open circuit and on load was achieved in an industrial environment by creating a 'design environment' around the linear generator model and by employing novel techniques for the analysis. This alleviated the need for overly expensive (computationally) models but still achieved accurate results.

References

[1] www.vectorfields.com

[2] A. Michaelides & C.P. Riley, *'Use of Advanced Scripting Language in the Modelling of Dynamic Systems'*, Proc. LDIA 03 Conference, Birmingham, September 2003.

[3] C.S. Biddlecombe and J. Simkin, "Enhancements to the PE2D Package", IEEE Trans. Mag., Vol. Mag-19, No. 6, November 1983