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3D Modelling of the generator for OpenHydro's tidal energy system

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Abstract

OpenHydro is developing open centred submerged turbines for the extraction of energy from ocean tides. Power take off is via a surface-mounted, radial-flux, permanent-magnet generator mounted to the rim of the turbine blades. A number of full scale devices have been deployed globally, upto 2MW and 16m diameter. The aspect ratio of the machines mean that end effects are likely to be significant and hence 3D modelling is required to fully capture them. In this paper, alternative methods for modelling the existing machine design is discussed and compared. It is demonstrated that, although a full scale detailed FEA approach yields the best results, simplified FEA and even analytical approximations are best for the purpose of designing the machines.

1 Introduction

1.1 Tidal energy

Tidal energy is a promising resource for electricity generation. When compared to offshore wind, the higher mass density of water compared with air (800 times) results in tidal current generators having a higher power density. The resource is also more predictable than wind, allowing accurate estimates to be made of the energy available at a specific site.

There are two distinct forms of tidal power schemes, the first relies on a barrage across an estuary or bay to capture water at high tide and release it through hydro-electric turbines at low tide (or vice-versa or even both ways). Environmental concerns have inhibited this approach but a few schemes, notably La Rance in Northern France have successfully operated for many years. The second form employs free-stream turbines that intercept tidal currents in a similar manner to a wind turbine intercepting air currents. This is referred to as tidal-stream generation

Tidal-stream technology is being investigated worldwide and several prototypes are already online. South Korea, China, Australia, USA, and UK are among the countries that have started to assign tidal power sites. There are many methods of extracting energy from tidal current, using for example horizontal- or vertical-axis turbines and reciprocating devices where the water is shallow.

Ocean tides are periodic, the main periods being diurnal (24 hours and 50 minutes) and semidiurnal (12 hours 25 minutes). Different locations experience these periodic variations at different phase and so together tidal installations located around a coastline may provide a useful contribution without too much intermittency. Tidal generators convert the energy from the tidal movement into electric power. Greater tidal variation and higher tidal current velocities significantly increase the potential for electricity generation as power is proportional to the cube of the speed of the flow.

There are several areas in the world with very high potential for tidal energy to be harnessed. In Europe, UK and France have the best resources for tidal energy harnessing. The estimated power generation potential in UK is around 29 TWh/year [1]. India, China, Japan, Chile, the USA and South Korea are other countries with fast currents which could generate significant electric power.

Among the tidal stream devices, the SEAGEN turbine developed by Marine Current Turbines [2] is one of the best-documented. This is a horizontal-axis turbine resembling a submerged wind turbine. Development of the device has been well covered in the literature, e.g. [3].

The present paper concerns an open-centred turbine developed by OpenHydro [4]. This has reached a commercial level of development and deployment, but has not yet been discussed in depth in academic literature, except for information on the power converter [5].

2.2 OpenHydro turbine

The OpenHydro device is a bidirectional open-centred water turbine, mounted on a gravity base, converting the rotational energy into electrical power using an in house designed rim generator. Figure 1 is a schematic diagram of the 16m prototype that has been deployed off the northern French coast and Figure 2 shows the same machine during construction, Figure 3 shows an earlier 10m prototype mounted on its deployment barge before being lowered to the seabed in the bay of Fundy Canada. Smaller 6m research machines have been tested on a special-purpose R&D platform in the European Marine Energy Centre in Orkney, and have generated power into the UK grid.

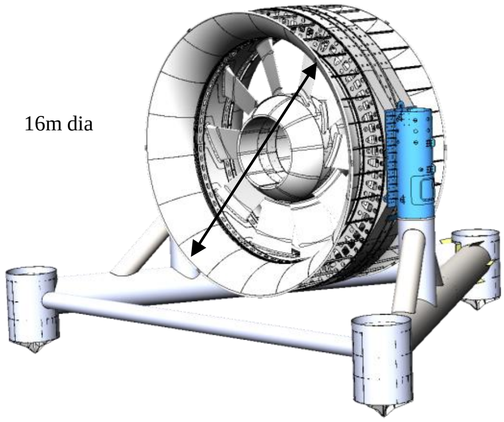

Figure 1: Open Hydro 16m commercial turbine

Figure 2: The 16m prototype during construction

Figure 3: A 10m prototype on its deployment barge

2 Permanent magnet rim generator

The generator is mounted at the rim of the turbine as illustrated in Figure 4. It has a radial-flux, surface-mounted, permanent-magnet Nd-Fe-B rotor. It was considered impractical to fit water seals, so the generator operates with a flooded gap. Both the rotor magnets and the stator winding are encapsulated for protection from the sea water.

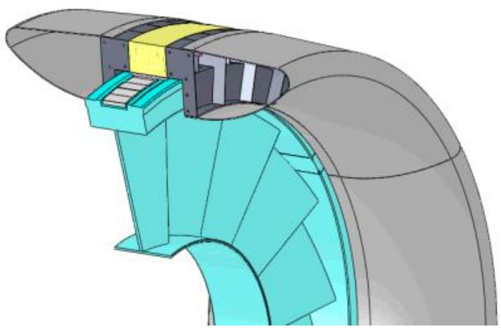

Figure 4: The arrangement of the PM rim generator

The rotor magnets are simple rectangular blocks mounted on short sections of back iron to facilitate assembly and to make it possible to provide all-round protection from the water. The stator winding comprises a number of discrete coils housed in waterproof non-metallic enclosures and connected in series and parallel groups within each of the three phases. The airgap (water gap) diameter of the generator in the commercial prototype is approximately 14m. The machine has no shaft and so the bearing system is also of very large diameter. The radial clearance between rotor and stator is necessarily large and since the magnets are surface mounted and the stator winding is slotless, both enclosed in thick protective enclosures, the total magnetic gap is unusually large. Initial electromagnetic design and analysis of the generator has been based on 2D analytic and 2D finite element models, Fig. 5. However, the very large magnetic gap means that the effects of the ends of the magnets and the stator laminated core extend a long distance axially into the active part of the machine. As a result there is a large difference between the emf expected from a simple application of the 2D results and the emf measured in practice.

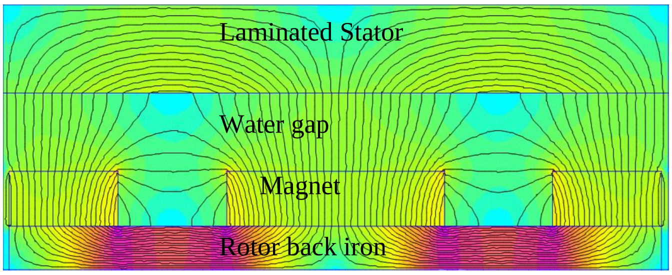

Figure 5: 2D FE model

Also, the large magnetic gap causes leakage flux to extend axially a long distance outside the gap where it may impinge upon steel parts of the rotor and stator structures.

The generator is used in conjunction with a power-electronic frequency converter and so it is necessary to have an accurate prediction of the generated emf to ensure that the generator and converter are correctly matched and that there is no danger of the converter being overloaded during short periods of very high flow through the turbine.

A number of *ad-hoc* empirical adjustments have been made to the 2D analysis to take account of the end effects on the magnetic flux distribution and the resulting reduction in open-circuit emf, but a comprehensive 3D FEA model would be preferred. In this paper, the development of a suitable 3D model is described.

3 Full 3D FEA model of 16m machine

3.1 Development of FEA model

Modelling of the 16m diameter machine was based on a full 3D solid model CAD file provided by OpenHydro. The model was imported to Infolytica MagNet and meshed suitable for a 3D transient solver. Although it was possible to run the model and solve in this form, computational time was prohibitively slow due to the model size, the slight curvature of the airgap at this radius and inclusion of a number of detailed mechanical components. Components which were problematic to mesh but had little or no influence on the magnetic circuit were replaced with simplified indicative geometries, for example those in Figure 6.

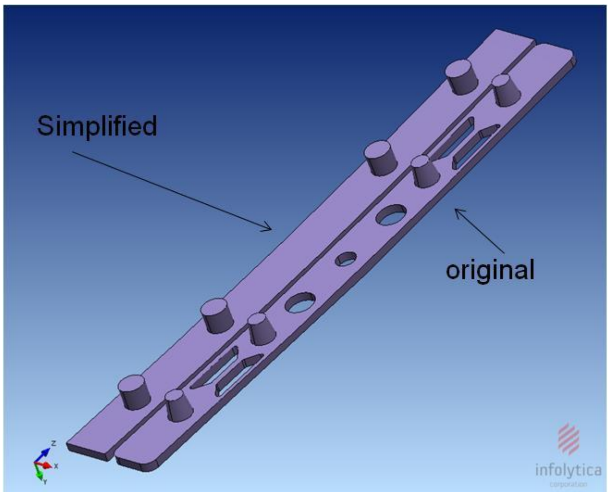

Figure 6: Example of mechanical component simplified for the purpose of meshing

One of the aims of this work was to quantify the effect of the large surrounding support structure on the magnetic performance of the generator. Figure 4 shows the general layout of the structure and it can be seen to occupy a large amount of space which in turn leads to a very large amount of superfluous detail in the mesh. To increase computational speed, the axial length of the surrounding structure has been reduced, some of the major items remote from the magnetic gap have been removed and the region next to the flat end surface of the rotor structure has been removed from the model. Magnetic performance was affected by less than 0.3% by all of these changes together. The final model covers four poles across two magnet modules and three stator coils and includes the gaps between rotor back iron sections that occur at intervals of two poles.

3.2 Effect of surrounding support structure

In one version of the machine, the turbine blades are supported by steel reinforced GRP, onto which the individual magnet modules and back iron are mounted. Similarly the stator back iron is mounted on a structure that includes some GRP. As the magnetic properties of the steel / GRP combination are unclear, to ensure a conservative calculation of the effect of the surrounding structure on the magnetic circuit, it was assumed to be a thin walled (6mm) steel shell. The effect of the surrounding structure relating to the rotor and stator is given in Table 1. The total effect of including both is to reduce the peak flux linkage by 1.5%.

Rotor Material	*Stator Material*	*Peak Linkage per turn (%)*
Steel	Steel	98.49
Air	Steel	99.80
Steel	Air	99.75
Air	Air	100

Table 1: Effect of surrounding structure on peak flux linkage through the coil

3.3 Model validation

The simulation was run transiently for 12.5 msec for a constant speed. The phase voltage results are shown in Figure 7. The dotted lines show the results of modelling the coils as a solid copper, whereas the solid lines assume stranded wire. The difference in induced voltage between the two cases, stranded and solid indicates that the solid copper carries very large eddy current whose magnetic effect is to oppose the mmf of the magnets. The loss due to such large eddy currents would be completely unacceptable. The sensitivity of slotless windings to eddy currents induced by the airgap flux is well known and it calls for windings to be assembled from conductor of small cross section or even from Litz wire.

The predicted phase voltage is 12.5% lower than the prediction based on the simple 2D model indicating that the end effect is very significant as expected in view of the large magnetic gap. However, the measured open circuit emf is 23% below the 2D model result. The residual diference of

10% remains the subject of investigations. It is noteworthy that the magnetic gap dimensions for a machine 14m diameter are subject to quite large tolerance and measurement of voltages under field service conditions at sea is far from straightforward.

The waveforms shown in Figure 7 are very close to pure sinewaves. This is confirmed by measurement. The absence of harmonics is a result of the large magnetic gap attenuating space harmonics in the distribution of magnet mmf and of the distribution of turns within the slotless winding attenuating the emf induced by the space harmonics.

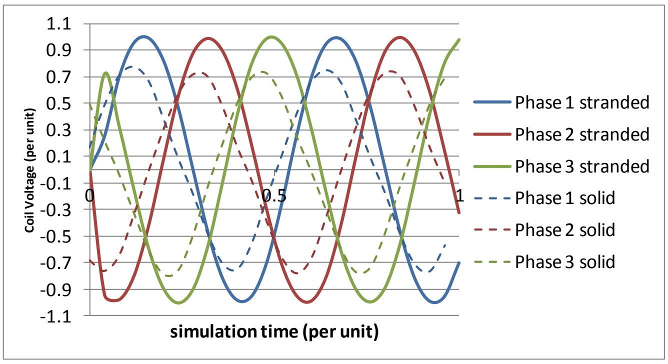

Figure 7: Line to line voltage.

4 Single pole pair linear 3D FE model

4.1 Model development

The majority of mechanical features were shown in the full 3D model to have little or no effect on the generator magnetic circuit, yet drastically increase computation time for the 3D simulation. A simplified model has been developed using just a single pole pair with a single rectangular coil with rounded ends to represent the winding. This generic model can be adapted to give a good representation of all the relevant alternative geometries and is solved in a reasonably short computation time.

Variable	Description
x_1	Magnet thickness
x_2	Water gap
x_3	Coil radial thickness
x_4	Coil to stator iron gap
x_5	Total magnetic gap
x_6	Coil inner width
x_7	Coil outer width
x_8	Coil overhang from from stator back iron
x_9	Stator core overhang from magnets
x_{10}	Magnet width
x_{11}	Magnet axial length

Table 2: Key design dimensions

The model ignores curvature and includes only the active magnetic parts. The primary input parameter is the pole pitch and the other principal geometric variables are defined in Table 2 and are expressed in dimensionless form with respect to the pole pitch. Figure 8 illustrates the layout considered. The model also includes the small gaps between adjacent rotor back iron sections which are found to have a small effect on the flux density waveform.

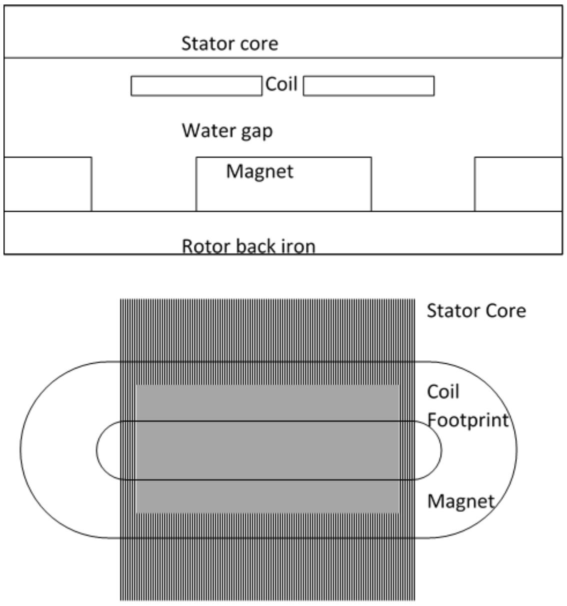

Figure 8: Model layout considered

4.2 Validation of simple model

The single pole pair FE model was scaled to represent the 16m machine. It is hence possible to compare the accuracy of the simple and detailed models. Figure 9 shows flux linkage versus coil position plots for both FEA models. There is an over prediction of 2.57% peak flux linkage for the simplified model. As shown in Table 1, over half this error (1.5%) is due to exclusion of the surrounding steel reinforced GRP structure. The remaining error is believed to be the result of effects from other structural elements such as bolts combining to provide leakage paths to the magnet flux. The phase error between the two models in Figure 9 is believed to result from the assumption of a linear airgap.

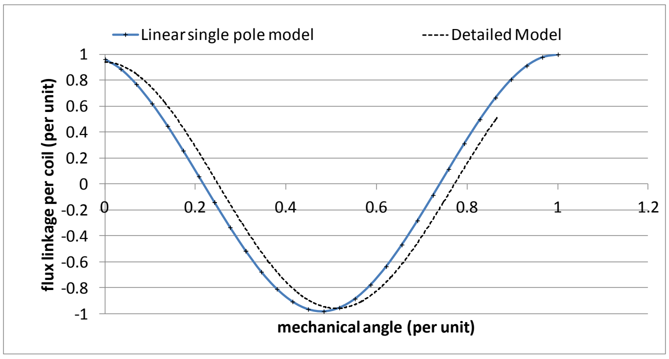

Figure 9: Comparison of flux linkage for full and single pole pair linear models.

4.2 Flux distribution and end effect

The flux density plot of Figure 4 showed the variation in airgap flux density over a full pole pair in the radial / circumferential plane. The machine has a very large magnetic gap compared with both the pole pitch and the axial length and so there is expected to be significant variation in the flux pattern with the axial position. The radial component of the flux density at the mean coil radius is plotted in Figure 10 for a hypothetical machine having thin magnets. The plots are taken along circumferential lines located axially at:

Line 1 the end of the rotor back iron
Line 2 the end of the magnets
Line 3 halfway between line 2 and the mid plane
Line 4 the generator mid plane

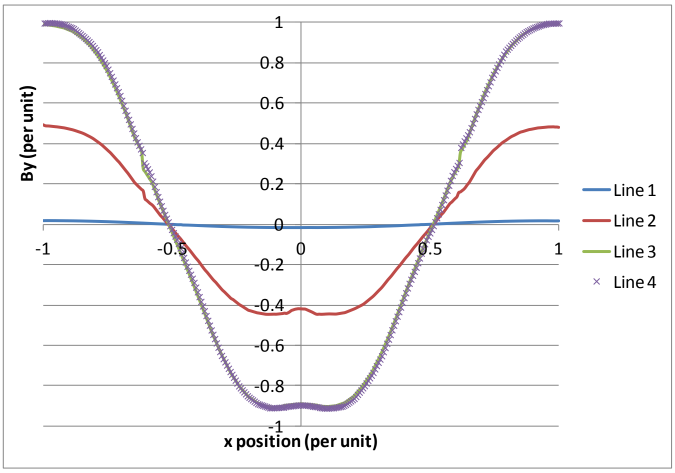

Figure 10: Radial flux density at the coil axis at the coil mean radius

Figure 10 corresponds to the case where the gap between adjacent sections of back iron occurs at a pole axis and the corresponding magnet has been divided accordingly. The dip in the flux density is localised and so has only a small effect on the amplitude of the fundamental component, the harmonics introduced into the flux distribution do not produce significant emf because of the distributed nature of the stator winding.

The flux density at Lines 3 and 4 are coincident, indicating that for this case the end effect does not extend more than halfway toward the mid plane, although for other cases the end effect can be more extensive. The plot for Line 2 indicates the magnitude of the end effect which is about 50% in common with the outcome of most end effect studies.

The axial variation of the fundamental component of the flux distribution from this 3D model is shown in Figure 11.

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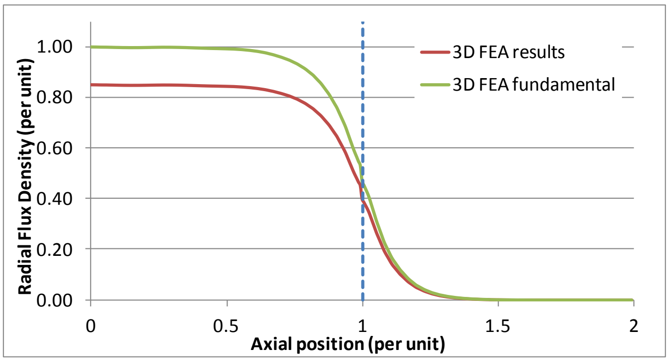

Figure 11: Axial variation of fundamental flux amplitude. The dotted line represents the edge of the magnet.

5 Regression analysis of simplified model

The simplified linear model has been created and validated against the full 16m model and may now be used to characterise the effect of pole dimensions on predicted peak flux linkage. There are numerous well documented approaches to machine design using multiple results from FEA models, such as optimisation routines or simply investigating the effect of individual parameters on machine performance. In a wider design context, where the generator is physically integrated a large and complex system, it is useful to replace the FEA results with simple algebraic approximations.

Linear regression provides a simple method for developing such an expression and is an alternative to storing large look up tables of data [6]. By way of example, this method was used to propose a linear relationship between the dimensions of Table 2 and the peak flux linkage per coil. Machine geometry was transformed into the non dimensional ratios based on the dimensions of Table 2 and practical physical limits were applied. A random number generator was then used to create a number of random sized machines within a realistic design envelope.

70 machines within the physical limits were created and solved for peak flux linkage by the single pole pair linear model. The 70 data points have been used to calculate the 11 coefficients of a linear equation of the form flux linkage $=Ax_1+Bx_2+Cx_3$ ….for all 11 dimensional ratios. Figure 12 shows a plot of the linear equation predicted results versus the actual FE results for all 70 machines. If the model was an ideal fit, this would be a perfect straight line at 45^0. Employing a higher order polynomial could easily give results suitable for a design office type environment.

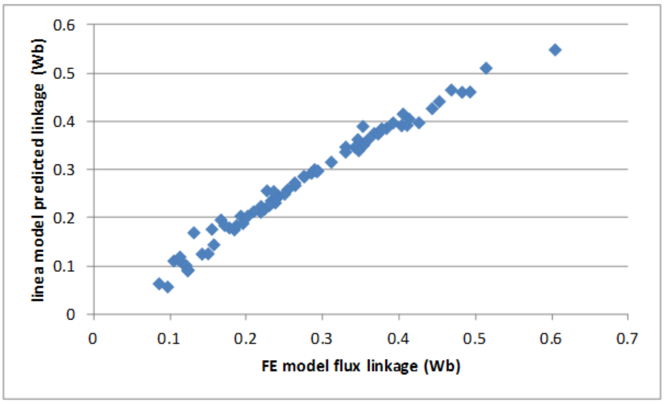

Figure 12: Plot of linkage predicted by linear equation verses FEA generated results.

6 Conclusion

The OpenHydro open centred tidal turbine uses a generator with a surface mounted PM rim generator. A fully detailed FEA model of the 16m version of the generator has been built and used to investigate the affect of mechanical support structure on induced emf. The predicted emf is much closer to the measured value than can be achieved directly by the earlier 2D model. A simplified 3D FEA model of a single linear pole has been developed and used to investigate the end effect of the machine. The linear model has also been used to generate flux linkage results suitable for developing simple relationships between geometry and machine performance. 70 sample machine geometries have been created and used to show that even a simple linear relationship between emf and dimensions is possible indicating that a higher-order algebraic model should provide a close approximation to the real machine suitable for rapid use by the machine designer.

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