13th EAWE PhD Seminar on Wind Energy
20-22 September 2017
Cranfield University, United Kingdom
Session XXXX Paper XXXXXXX

DESIGNING AXIAL-FLUX PERMANENT MAGNET GENERATORS FOR HUGH PIGGOTT WIND TURBINES

Grant Leishman
Wind & Marine Energy CDT,
University of Strathclyde,
Glasgow, UK
grant.leishman@strath.ac.uk

Dr. Alasdair McDonald
Institute for Energy and Environment,
University of Strathclyde,
Glasgow, UK
alasdair.mcdonald@strath.ac.uk

ABSTRACT

This paper details the construction of a design tool which estimates the performance and cost of axial-flux air-cored permanent magnet generator designs, the type of generators which are typically found in small scale micro wind turbines. The design tool is also used to optimise these generator designs to increase energy capture and reduce build costs. It is found that changing the design of the generator from the arrangement described in the Wind Turbine Recipe Book [1] can increase the power output of the generator whilst marginally reducing the build cost. An average of 7% additional energy production can be captured with the modified generator designs which have an average decrease of 4% in total build cost.

NOMENCLATURE

ϕ_{g}	=	Air-gap flux (T)	λ	=	Tip Speed Ratio
F	=	Magnetomotive Force (A-turns)	R_{max}	=	Maximum Blade Radius (m)
$\mathbb{R}_{\mathrm{m}}$	=	Magnet Reluctance (H^{-1})	P	=	Power (W)
$\mathbb{R}_{\mathrm{r}}$	=	Rotor Reluctance (H^{-1})	I	=	Current (A)
$\mathbb{R}_{\mathrm{g}}$	=	Air-gap Reluctance (H^{-1})	V	=	Voltage (V)
ω	=	Mechanical Rotational Speed (rad/s)	R_{w}	=	Winding Resistance (Ω)
u	=	Wind Speed (m/s)	E	=	Electromotive Force (V)
X	=	Reactance (Ω)			

INTRODUCTION

Small scale wind power is becoming ever more popular. As part of this there is interest in 'do it yourself' micro turbines with several guides on how to build your own wind turbine. One of the more well-known guides is A Wind Turbine Recipe Book - The Axial Flux Windmill Plans by Hugh Piggott [1]. It provides detailed, step-by-step instructions for constructing a range of small scale wind turbines using equipment that can be found in most workshops. The book also includes plans and parameters for an axial-flux air-cored permanent magnet generator. The generators detailed in the book have been designed with manufacturability in mind, and have been developed through experience. This is in contrast with the design process typically used in larger wind turbine generators, where there is a strong emphasis on electromagnetic modelling, design and optimization before prototyping and testing [2]. This research investigates the use of those methodologies in the case of small scale generators as used in the Wind Turbine Recipe Book. It goes on to model the potential cost and performance improvements.

In the spirit of the 'open-source' turbine design, the authors decided to embed the models in a generator design tool that could be used by non-specialist using a ubiquitous spreadsheet package and a free-to-download magnetic finite element software. This has been developed using Microsoft Excel [3] with links to a Finite Element Method Magnetics - FEMM [4] model to verify the calculated results.

METHODOLOGY

The initial stages of the project involved analysing the design plans set out in the Wind Turbine Recipe Book and then using the design plans as the framework of the design tool. The design tool has several sections; the first section takes into account the dimensions of the generator, most of which are found in the book, and then calculates areas and lengths which are required for the next stages. In the second stage, a magnetic circuit is constructed and analysed to investigate the magnetic flux density of the air gap in the generator. The third stage of the design tool develops the electrical circuit and performs analysis to calculate the power output of the generator at different wind speeds. The last stage links the power output of the generator to the construction and maintenance cost of the wind turbine, where an optimisation of each generator design is performed.

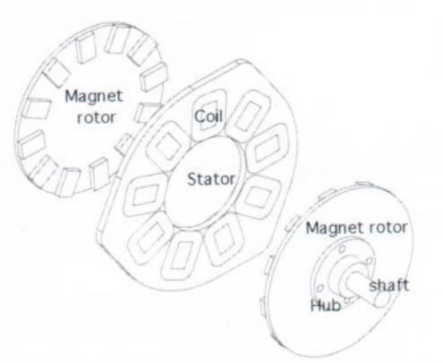

Figure 1. Standard Generator Configuration [1]

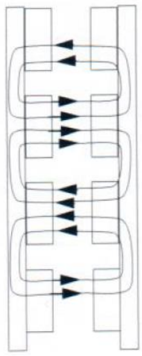

Figure 2. Path of Flux Flow [1]

The Wind Turbine Recipe Book details the construction of several wind turbines which vary by rotor diameter. To begin, the design tool was initially developed using the 3m blade diameter turbine, then modified for the other wind turbine diameters described in the Recipe Book. From the input dimensions of magnets, coils & rotor diameter the according areas were calculated. Note, that the reluctance of the magnet depends on cross-sectional area which can be deciphered from analysing the flow of the flux within the generator, see Figure 2. In the recipe book there are several variations on wind turbine size and therefore generator design. The tool was developed using the 3m blade diameter wind turbine which has a 9 coil stator, 12 magnets per rotor, double rotor generator design. This standard generator design is shown in Figure 1.

Next, the magnetic circuit for the generator was developed to allow magnetic flux to be calculated. The magnetic circuit consists of a magnetomotive force(MMF) which is produced by the magnets, and a series of reluctances which hinder the flow of magnetic flux. The MMF is analogous to voltage in a standard electric circuit, reluctance is analogous to resistance and magnetic flux is analogous to current. Note, throughout this paper, 'air-gap' is referred to - this is the space between each set of aligned magnets and therefore consists of air and coil winding material. In addition to the air-gap reluctance there is also reluctance associated with the magnets and the rotor which they are fixed to. Once all of the generator components have been considered, the generator can then be modelled as a magnetic circuit as shown in Figure 3. Then, the air-gap flux can be calculated using $\phi_g = \frac{4F}{4\mathbb{R}_m 2\mathbb{R}_g \mathbb{R}_r}$ which is derived from Gauss's Law, Ampere's Law and the generator configuration shown in Figure 3. The air-gap flux density is then calculated by dividing the flux by the air-gap area. Once the flux density of the air-gap is calculated, harmonic analysis is used to find the fundamental air-gap flux - the first harmonic. The now fundamental air-gap flux density is a pure sinusoid, whereas the total air-gap flux density is more square in waveform. The fundamental air-gap flux density can be used to calculate the flux linkage of the machine, the amount of flux produced by the magnets which the coil receives. The flux linkage is used to calculate the coil pitch factor which in turn is used to calculated the electromotive force(EMF) induced on each coil of the machine. Additional parameters calculated are: resistance, inductance and reactance per coil. From all of the parameters calculated, an equivalent electrical circuit is developed and is shown in Figure 4. The equivalent electrical circuit is used to calculate the current, which will allow the voltage over the load to be calculated.

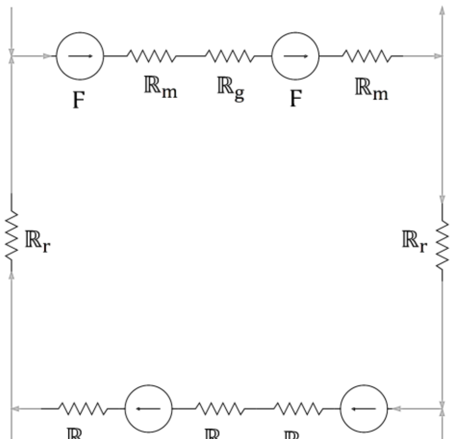

Figure 3. Magnetic Circuit of one pole

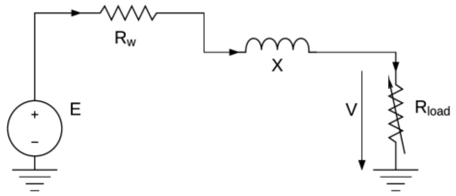

Figure 4. Electric Circuit

When both the voltage and current are known, the power can be calculated, $P = IV$. Additionally, losses from the windings $P = I^2 R_w$ and eddy current losses should be considered and deducted from the power calculated, the resultant power is then obtained. The resultant power is calculated at a range of wind speeds, a range of 1 m/s to 20 m/s is used in the design tool. The wind speed then determines the mechanical rotational speed of the rotor based upon turbine design parameters set out in the recipe book. The recipe book assumes maximum coefficient of power and an optimum tip speed ratio of 7; although the design tool can be adapted for different blade characterisations and control regulations. The mechanical rotational speed can then be calculated using $\omega = \frac{u\lambda}{R_{\max}}$.

Once the power is calculated at each wind speed, a wind speed probability function is applied to allow the annual energy to be calculated. In the design tool a Weibull distribution is used to give the probability of each wind speed occurring and therefore the probability of each power output occurring. The scale parameter is based on site specific information such as annual mean wind speed; the design tool uses an annual mean wind speed, an independent variable, of 6m/s. The predicted power output over all wind speeds is then multiplied by the amount of hours in a year to obtain the total annual energy produced. The final calculation performed by the design tool is to estimate a levelized cost of energy (LCoE) for the whole wind turbine. This involves calculating the total cost and total power produced over the lifetime of the wind turbine. The design tool estimates the LCoE over a ten-year period and includes costs associated with maintenance and turbine performance aspects such as degradation and turbine availability.

The finite element analysis solver tool, Finite Element Method Magnetics - FEMM [4] was used to model the generator and to test the outputs from the developed design tool. The model which was developed in FEMM consists of two poles of the generator, therefore eight magnets and three coils. Each coil consists of two blocks, a go and a return block which creates a complete circuit. Periodic boundary conditions were set at each end of the model to allow the effect of the whole generator to be modelled from two poles. Once the structure of the generator was developed it was then analysed to investigate the flux density of the air-gap between magnets, Figure 5 shows the model after an analysis has been run. Measurements of the flux from the model were taken and compared to the results produced from the design tool. The primary function of the FEMM model is to validate the design tool. Once the design tool was validated by the FEMM model, the optimisation of the generator designs could commence. The design tool has user defined inputs - including the turbine dimensions, power curve and wind resource estimates which are used by an automatic optimizer to find the best design. The results can then be expressed in the same format as the Wind Turbine Recipe Book. It was decided to limit certain independent variables (the dimensions of magnets and wire gauge) to those that are available 'off-the-shelf' in most countries, if the optimisation was undertaken without adding the constraint of specific magnet dimensions it is likely that the optimised magnet size would require custom manufacture, which would add expense. In terms of optimization, this then becomes quite a challenge as some variables that would be considered to be independent and continuous (in a large bespoke wind turbine generator design) become non-smooth and co-dependent. In terms of an objective function, the design tool uses the estimate of LCoE for the wind turbines. This takes into account costs associated with the materials as well as the performance of the generator. The Excel built-in solver tool was used for optimization. The evolutionary method was chosen as it allows the objective function to be solved for an integer value using non-smooth independent variables.

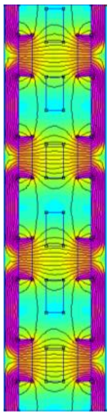

Figure 5. FEMM Analysis

RESULTS

Firstly, the validation of the design tool from the FEMM model. The design tool and FEMM model were both set-up as the 3.0m blade diameter wind turbine generator described in the Recipe Book, the magnetic flux density across the air-gap was measured, with FEMM giving 0.51T and the design tool giving 0.48T. This result shows that the design tool is within close proximity to the result given by the FEMM model and therefore is acceptable to be used to model the generators designed in the Recipe Book.

Then, plots were developed to illustrate the differences in the standard designs (STD) versus the optimised designs (OPT). Figure 6a shows the plot of power produced over a range of wind speeds for the 3.0m diameter turbine, it is noticeable that the optimised design produces more power, especially at lower wind speeds. Figure 6b displays the annual energy produced by each turbine model using both the standard and optimised generator designs. It is evident that the optimised designs outperform the standard designs yielding greater energy production and thus are more efficient. This is due to the optimised designs consisting of flatter coils which have more turns and generally use the magnetomotive force from the magnets more effectively. Plots of levelized cost of energy and total build cost are shown in Figures 6c & 6d respectively. Figure 6c shows that the LCoE of the optimised designs is lower than the standard designs for all turbines modelled. This is due to the optimiser selecting magnet dimensions and costs which are more favorable for the design and also selecting winding wire and coil dimensions which make better use of the magnetomotive force of the magnets. Figure 6d displays the build cost for each turbine model, the build cost of the optimised design is similar for the smaller rotor diameters and less for the larger diameters. This is a result of the optimiser selecting less expensive materials to use within the generator, but importantly it does not compromise the generator performance.

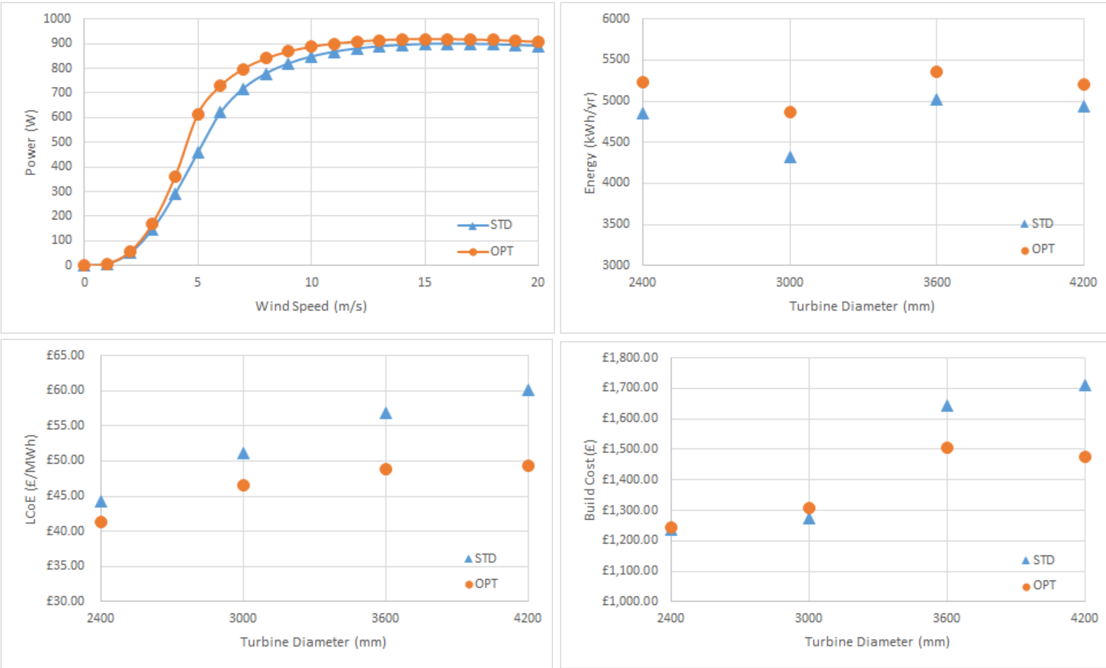

Figure 6. Top left: (a) Power Curve 3.0m, Top Right: (b) Annual Energy, Bottom Left: (c) Levelized Cost of Energy, Bottom Right: (d) Turbine Build Cost

CONCLUSIONS

In conclusion, the design tool developed represents a valid model of the wind turbine generators detailed in A Wind Turbine Recipe Book - The Axial Flux Windmill Plans by Hugh Piggott [1]. The design tool also allows each generator design to be optimised in terms of magnets, coil size and winding wire used and selects these components from readily available 'off-the-shelf' sizes, keeping the cost of the generator down. The optimisation process of the generator allows for greater power output and a lower levelized cost of energy, making the generator more efficient. Some improvements could be made to the model to yield more accurate results, such as including the flux leakage within the magnetic circuit and to have a more accurate representation of the power curve would provide a more reliable output from the design tool. In all cases the optimiser selects a different magnet to the standard design and in most cases also modifies the coil parameters. Broadly speaking, the optimised generators are less expensive as well as more efficient, especially at lower wind speeds. The coils are flatter with more turns and generally use the magnet MMF more effectively. Overall, the optimised generator designs exceed the standard designs in both LCoE and power production therefore, proving the requirement for an optimised generator design. All of the designs tools created for this project can be found at [6].

ACKNOWLEDGEMENTS

This work has been funded by the EPSRC, project reference number EP/L016680/1.

REFERENCES

[1] Piggott, H. A Wind Turbine Recipe Book: The Axial Flux Windmill Plans Metric Units Edition, Hugh Piggott, 2014.
[2] McDonald, A.S., Keysan, O. How electrical machine and drivetrain design can influence Offshore Wind Cost of Energy, UK Magnetics Society Seminar: Electromagnetics in Renewable Energy Generation, 8th July 2015, Edinburgh, UK
[3] Microsoft (2017) Microsoft Excel [Computer Program]. Available at https://products.office.com/en-gb/excel (25/07/17)
[4] Meeker, D. (2016) Finite Element Method Magnetics: FEMM 4.2 [Computer Program]. Available at http://www.femm.info/wiki/Download (25/07/17)
[5] McDonald, A.S. (2017) EE975 - Power Electronics for Energy and Drive Control, University of Strathclyde.
[6] Leishman, G., McDonald, A.S. (2017). Designing Axial-Flux Permanent Magnet Generators for Hugh Piggott Wind Turbines - KnowledgeBase, University of Strathclyde. [online] Pure.strath.ac.uk. Available at: https://pure.strath.ac.uk/portal/en/projects/designing-axialflux-permanent-magnet-generators-for-hugh-piggott-wind-turbines(79e59356-e772-4efb-b4b7-b3bc18559de5).html [Accessed 11 Sep. 2017].