A novel axial flux permanent magnet generator for wind turbines

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Abstract

This paper presents the development of a framework used to optimize and experimentally validate a novel axial flux direct-drive (DD) permanent magnet generator (PMG) for the offshore wind turbine market. This technology aims to offer significant levelized cost of energy (LCoE) reductions via capital expenditure and operating expense (CAPEX and OPEX) savings – a key objective for the offshore industry. The DD-PMG technology uses ferrite magnets to create the magnetic field, which is a significant source of cost reduction. The use of ferrite could also eliminate an industry wide reliance on Neodymium Iron Boron (NdFeB), the scarce and expensive rare-earth magnet used in existing designs. Another advantage of a ferrite-based design is that it's less sensitive to the cooling problems that currently face existing DD-PMGs. This paper describes the development and testing of two prototype machines at nominal 2 kW and 70 kW power ratings. Moreover, the finite element analysis (FEA) and analytical steps employed to develop optimized designs together with the experimental verification are presented. The simulated and experimental results show good agreement which provides confidence in the design and modelling work completed.

1. Introduction

The growth in the deployment of wind power continues unabated with falling costs making it increasingly attractive [1]. A growing proportion of offshore wind turbine designs are now based on directly driven permanent magnet generators (DD-PMG). Direct drive machines can offer higher reliability and reduced maintenance cost because of the omission of the gearbox from the drive train [2, 3]. Some of the downsides of these generators include their large size (due to the high torque rating), requirements for large quantities of rare earth permanent magnets and the significant generator structures needed to maintain the small air-gap clearance against the large attraction forces between the rotor and the stator [4]. The generator designer needs to deliver a number of performance characteristics including high efficiency, low power losses at part load, high availability, low machine mass, reduced volume and low material and manufacturing costs.

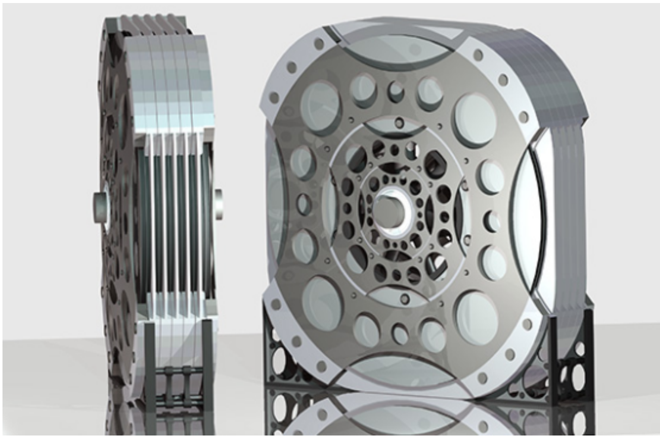

Figure 1. CAD representation of a compact MW range axial-flux direct drive permanent magnet generator (DD-PMG) technology.

Normally designers employ some element of computational optimization to achieve the best balance of these aspects [5]. Various researchers have approached the problem of formulating the objective function of such optimizations in different ways. In [6, 7] authors have shows an objective function that minimizes the cost of generator active materials (i.e. magnet, copper and iron), the generator losses and the importance of reducing the mass. A comparison of different types of generator in terms of annual energy yield per cost, which is analogous to payback period has been investigated in [8]. Objective functions to minimize costs and maximize efficiency which included not only minimizing active and structural materials cost but also minimizing cost of losses to get maximum return of investment have been addressed in [9]. An analytical tool that minimizes the generator's mass or cost by optimizing both the electromagnetic and structural design is presented in [10].

Over 10 GW of new capacity is expected in Europe alone in the next year [11]. Nevertheless, offshore costs remain higher than onshore with pressure to reduce both capital and operating costs. The direct-drive generators currently employed are slow speed (10 to 15 rpm for turbines of 5 MW or higher), high torque and physically large. These are radial flux machines typically using rare earth magnets, which offer high flux densities but are continuously expensive and the availability of rare earth materials is not secure [12]. In terms of availability and price stability, ferrite magnets can be a suitable alternative to Neodymium Iron Boron when mass (and inertia) of a generator rotor is of less importance [13].

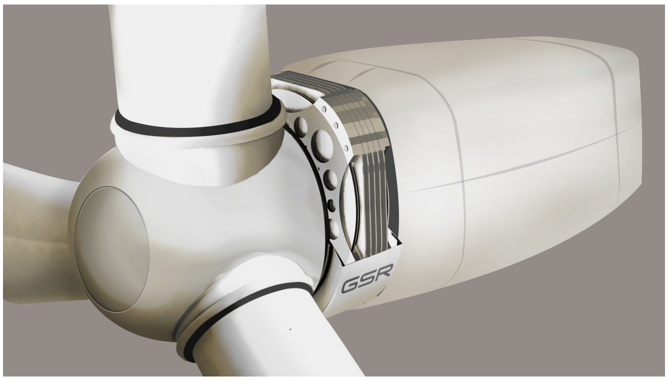

Figure 2. A novel concept for a low-cost axial-flux generator for wind energy conversion system (WECS) applications.

A performance comparison between radial-flux and axial-flux permanent magnet machines has been investigated [14], but different machine topologies are not very straightforward to compare. Nevertheless, attempts have been made to address variations which occur if electromagnetic, thermal and mechanical aspects are taken into account [15–18].

This paper describes a concept for a ferrite magnet generator for an offshore direct-drive wind turbine (Figure 1) depicted in Figure 2, and initial testing of a new design of low-cost axial-flux generator to support this. This paper also examines the process of optimizing a low speed generator design for wind turbines, exploring modelling approaches, software tool development/validation and experimental tests conducted at the Offshore Renewable Energy Catapult (OREC) test facilities.

2. Methods and Approach

The GreenSpur approach utilises an axial flux machine, which can offer comparable torque density to the radial flux counterpart [19]. Axial flux machines show promise but to date there has been limited development of these machines [20–24]. The decision to use ferrite magnets is the second major difference. The deployment of wind turbine generators in recent years has employed the use of rare-earth permanent magnets which has increased significantly. The large price fluctuations encourage us to look at alternative magnet materials. Some sample comparative data are given in Table 2., showing that the remanent flux density of ferrite magnets is lower than that of rare earth magnets, as is well known, whilst the cost of ferrite magnets is much lower – about one forthieth (at the current pricing levels) by weight – and they are readily available.

Magnet material	**Ferrite**	**NdFeB**
Grade	Y30	N40H
Remanence, min (T)	0.4	1.25
Normal Coercivity, min (kA/m)	240	923
Intrinsic Coercivity, min (kA/m)	245	1355
Density (kg/m^3)	5000	7600
Cost per kg	£ 1	£ 40

Table 1. Example magnet properties for ferrite and rare earth magnets [25].

In addition they have a much higher Curie temperature, 450 °C as against 310 °C, and significantly higher maximum operating temperatures (∼300 °C as against commonly ∼80 to 120 °C) [25]. The machine design is effectively ironless, reducing the magnetic forces to be sustained.

The machine has alternating stator and rotor segments, there being one more rotor segment. The machine's power rating can be extended by increasing the number of rotor/stator pairs or, of course by increasing the outside diameter of the machine. The rotor discs contain the magnets and the stator discs contain the coils. A stator disc surrounded on each side by the magnets from neighbouring rotor discs is termed one stage of the machine. Specifically, a stage incorporates a full stator disc and half of the rotor discs either side of it, such that it represents an axially-repeatable unit as shown in Figure 3.

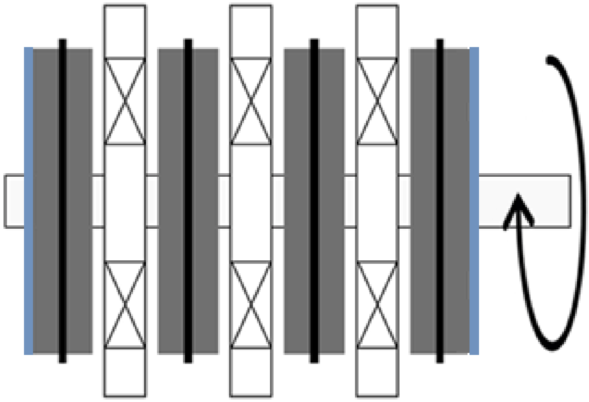

Figure 3. Diagrammatic longitudinal section through the machine.

A machine can have an arbitrary number of stages as required by the particular application. The stages on either end of the machine will require suitable end-plates. An example stator disc is shown in Figure 4, which comprises a number of coils (circular for simplicity) arranged contiguously around the circumference of the machine. The GreenSpur design allows for the coil shape to be optimised with the only restriction being that the coils should not overlap.

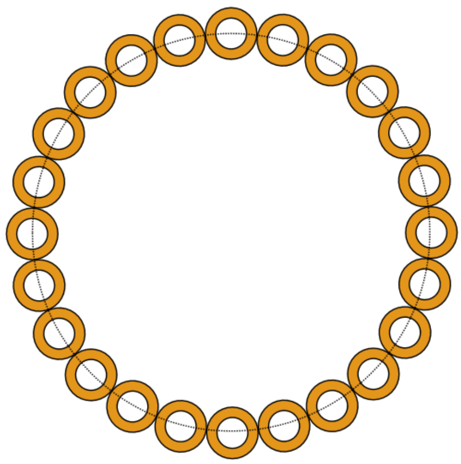

Figure 4. An example stator disc representation.

At the present time, the software tool allows either circular or elliptical coils to be investigated as detailed in Section 3. It is technically feasible to expand this to a greater range of coil geometries such as trapezoidal, which allows a greater degree of versatility in terms of coil profile arrangements.

The rotor discs carry ferrite permanent magnets; these are fixed back–to–back either side of a steel disc. Viewed in an axial direction this gives alternating N and S poles. In axial section through a rotor disc there is say an N pole, the S pole being against the steel disc and an N pole against the other side of the disc with an S pole facing the air-gap. There are double rotor discs at each end having only magnets facing inwards.

3. Modelling Approach

For computational speed, a combination of finite-element and analytical techniques are used in the analysis as appropriate. A 3-D finite-element model with suitable boundary conditions illustrated in Figure 5 is first solved to determine a flux-cut versus position profile for one coil in the machine.

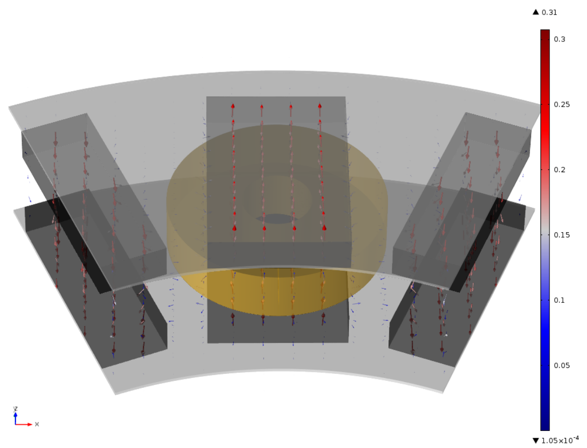

Figure 5. 3-D finite element analysis of ferrite generator design using COMSOL Multiphysics package.

This is subsequently post-processed to give an emf versus time profile for the given speed. Inductance and resistance parameters for the selected coil geometry are computed and the resulting coil equivalent circuit is then analytically solved to determine the machine output at the given loading condition. The 3-D finite-element model is also used to evaluate the effect of current in the coil on the flux density within the magnets, and this forms the basis of a maximum allowable current calculation. To construct and solve the 3-D finite-element model, the software tool utilises the established COMSOL Multiphysics external software package.

A software tool has been developed to assist in the modelling. The tool is centred around a graphical user interface (specific to the GreenSpur machine design) comprising several input boxes which are filled by the user. The program then computes the expected performance of the machine and displays the results to the user. The process consists of two computation stages: the Finite Element Analysis (FEA) stage and post-processing stage in the following sequential order:

- User inputs parameters required for FEA (Overall machine details, Magnet details, Coil initial details, Holding plate details and FEA options), then the user clicks 'Compute FEA' as shown in Figure 6.
- User inputs parameters required for post-processing (Coil winding details and Machine loading details), then the user clicks 'Calculate Results' as shown in Figure 7.
- The simulation program uses data from the FEA computations combined with the post-processing parameters to analytically calculate the performance of the machine.
- Results are displayed to the user as depicted in Figure 8.
- Finally, the user can change the post-processing parameters and re-calculate the results without re-running the FEA.

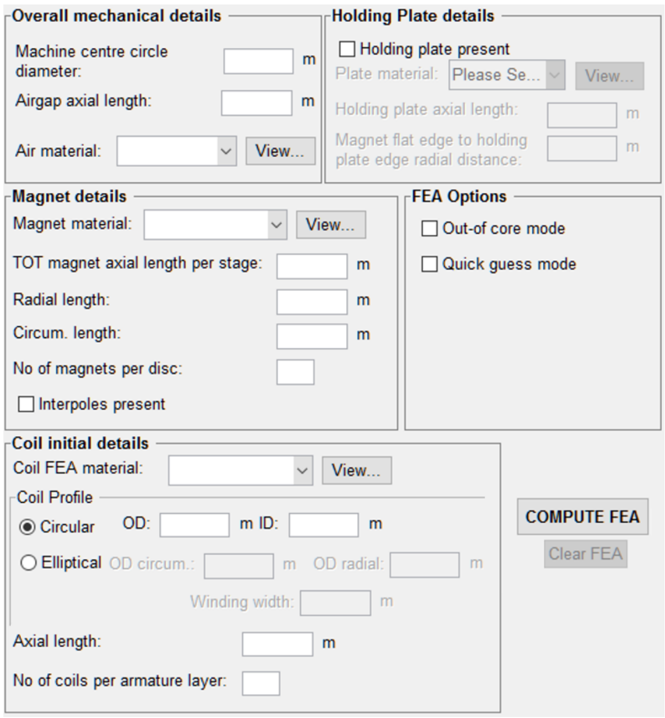

Figure 6. Input parameters required for FEA computation stage.

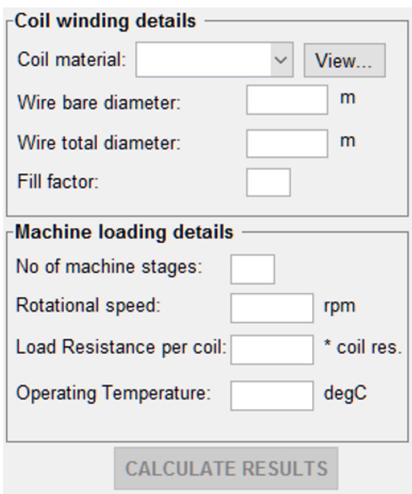

Figure 7. Parameters required for the postprocessing computation stage.

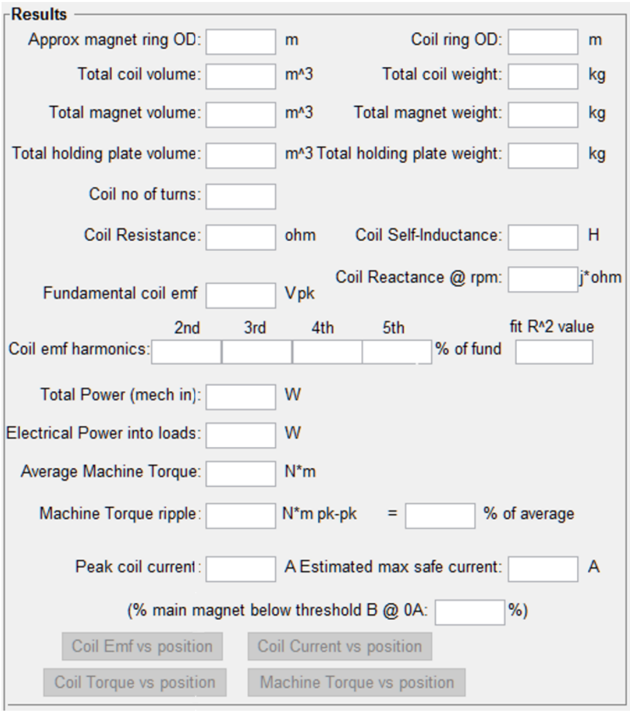

Figure 8. Performance of the machine displayed to the user following the two stage computation of FEA and postprocessing.

The fidelity of the finite-element model can be adjusted according to the desire for trend exploration versus detailed design. The effective electrical loading conditions applied to the generator can be varied to explore varying efficiencies of conversion, and the coil wire diameter can be adjusted according to the desired emf.

The output pane reports the electrical output power, mechanical input power, currents, torques and voltages within the machine as illustrated in Figure 8. It also outputs the volumes and weights of the main components of the machine to assist with calculations of material cost for a given design.

4. Machine Construction

An initial prototype rated at 2 kW (Figure 9) has been constructed to demonstrate the GreenSpur concept design. Using the design tools and experience from the 2 kW prototype, a 70 kW demonstrator was subsequently designed, built and tested by GreenSpur Renewables at the Offshore Renewable Energy Catapult test facilities in Blyth as shown in Figure 10. The finite element analysis in comparison with practical performance from the two prototypes are presented in Section 5.

The stator discs embody (optimally) profiled coils which have been wound on a special former enabling a high packing factor to be achieved and close to full utilisation of coil slot volume. So far the number of coils has been a multiple of three to allow the use of a conventional three-phase converter but other arrangements are possible. The detailed design of the coils has been carried out using the developed software tool with the aim of achieving the highest emf per turn in the first instance, subject to mechanical constraints on the airgap and for a given magnet thickness. The magnet and/or coil thickness can then be varied with the overall aim of achieving the maximum output for minimum material cost and weight.

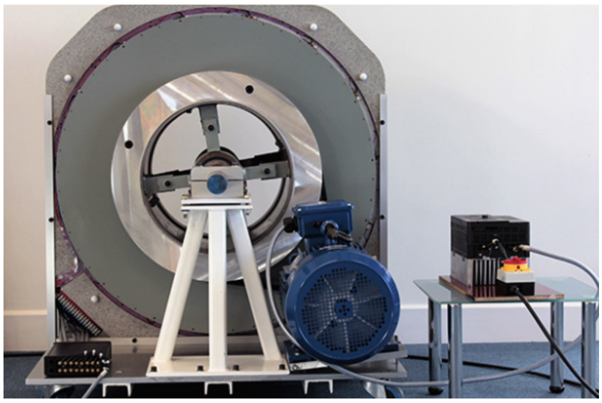

Figure 9. 2 kW DD permanent magnet generator prototype under test.

Figure 10. 70 kW directly driven permanent magnet generator prototype under test at the Offshore Renewable Energy Catapult (OREC) test facilities.

The designs developed to date show relatively high usage of inexpensive ferrite magnets and relatively low use of expensive copper and assist in achieving a low-cost design. Headline parameters for the machines built to date are shown in Table 4.

Parameter	Prototype 1	Prototype 2
Nominal power	2 kW	70 kW
Rated speed	30 rpm	60 rpm
Number of rotor discs	4	4
Number of stator discs	3	3
Outer diameter	0.99 m	1.48 m
Overall active length	0.36 m	0.537 m
Coils per stage	15	21

Table 2. Machines built to date (ratings and dimensions).

5. Software Tool Validation and Test Results

Coils for the same angular position were connected between the stages, forming a machine with 15 coils (2 kW) and 21 coils (70 kW), respectively. Each coil was individually loaded with a resistive load. The quantitative and qualitative comparison between the experimental measurements and the results predicted by the program developed are shown in Table 5. (emf versus position for a coil moving at 33 rpm), while the corresponding captured plots for the phase terminal voltage and phase current are depicted in Figure 12. Due to time constraints and suitable loads being unavailable the 2 kW prototype was not tested to its full nominal power rating. Agreement is within 7 % in this comparison, with the exception of the coil inductance which is within 10 %.

Quantity	Predicted	Measured	Unit
Speed	33	33	rpm
No load phase voltage	343	320	V-peak
Loaded phase voltage	297	305	V-peak
Output power	1400	1370	W
Phase inductance	1.431	1.578	H
Phase resistance	66.9	66.3 to 67.5	Ω
Load resistance	441.5	360 to 510	Ω

Table 3. Comparison between predicted and measured results of the 2 kW DD-PMG prototype.

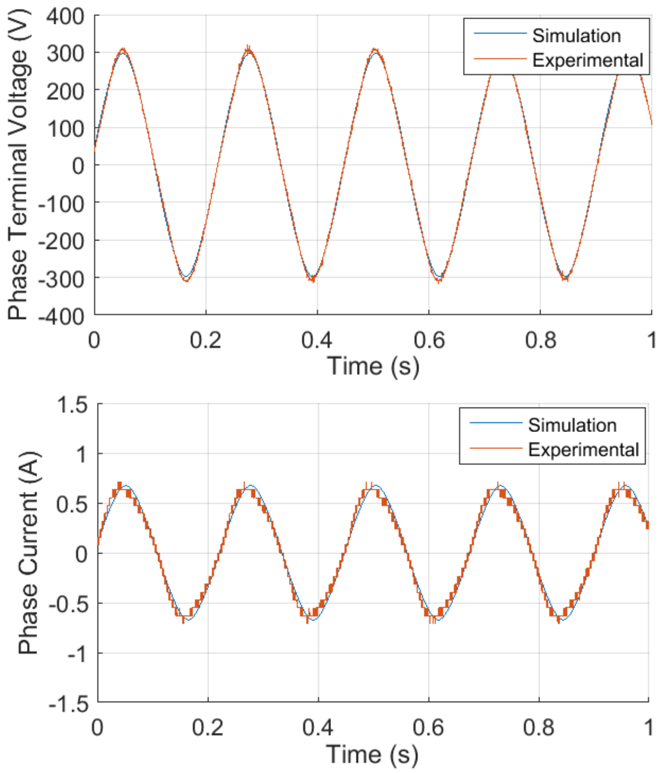

Figure 12. Simulation and experimental waveforms of 2 kW machine operating at 33 rpm.

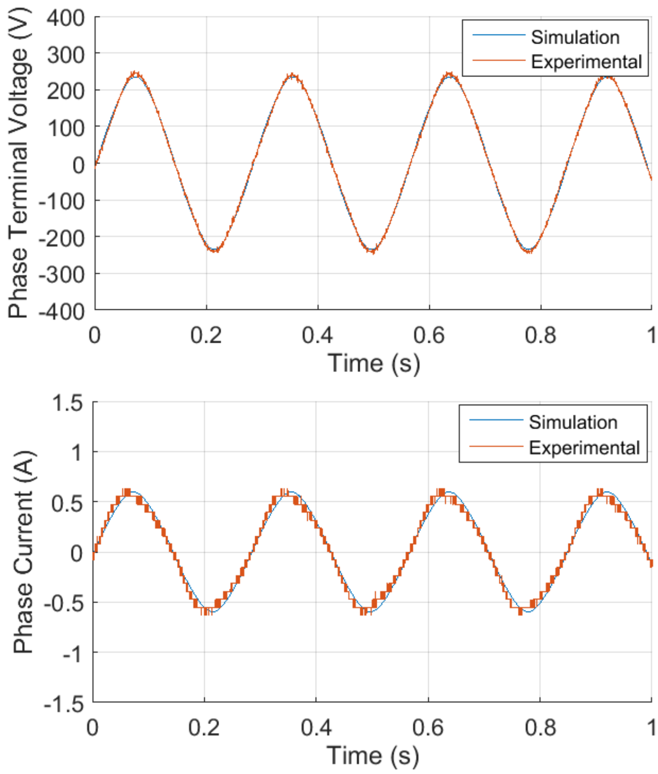

Figure 11. Simulation and experimental waveforms of 2 kW machine operating at 26 rpm.

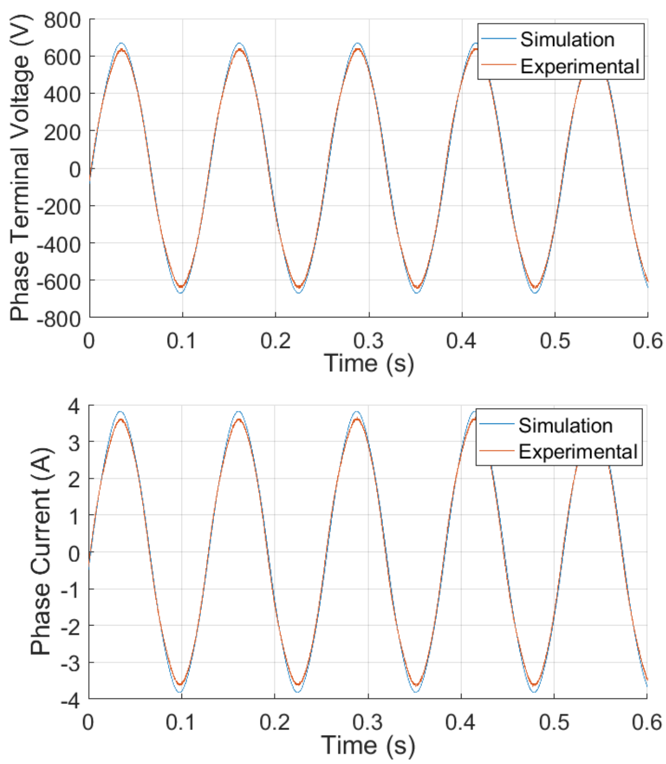

Figure 13. Simulation and experimental waveforms of 70 kW machine operating at 43 rpm.

Further loading conditions at various speeds have been captured and benchmarked against the FEA design tool outputs as depicted in Figures 11-12 for the 2 kW generator. A good degree of agreement is observed in the terminal voltage waveform shape. The experimental current waveforms show some distortion compared to the simulated sinusoidal shape as light bulbs were used for the load and these varied in resistance over the cycle. A similar procedure was carried out for validation against the 70 kW demonstrator machine. A sample of simulation and experimental test results operating at 43 rpm under a part-load (purely resistive) is depicted in Figure 13. The simulated and experimental results for both terminal voltage and current show a good agreement.

6. Conclusion

Two prototypes of the proposed axial-flux ferrite based direct-drive permanent magnet generator for application in wind power generation have been investigated (a smaller 2 kW machine and larger 70 kW machine). Comparison of the software tool outputs to those measured experimentally shows a good level of agreement within a reasonable tolerance band for both machine prototypes. Furthermore, the practical design, build and testing of the proposed design has been conducted at prototype scale. The experimental verification of the software tool has provided confidence in the design and modelling work completed, and a 250 kW generator is currently under investigation as part of the Innovate UK grant.

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