

Thermal and Structural Design of Axial Flux Permanent Magnet Generators for Locally Manufactured Small Wind Turbines

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Abstract — Locally manufactured small wind turbines (LMSWTs) used in off-grid battery based renewable energy systems, typically utilize coreless axial flux permanent magnet generators (AFPMGs) due to their simple manufacturing process. Commercial systems with high energy requirements for rural productive applications, use LMSWTs with high power AFPMGs which need to be designed for low cost and high efficiency, but also for low mass. In this paper, thermal and structural design aspects of AFPMGs are considered, with the aim of improving the heat dissipation capabilities of the stator and reducing the mass of the back iron disc of the rotor while minimizing disc deflection. Heat dissipation experiments are conducted for low and high power AFPMG prototypes, both in indoor laboratory conditions and in real operating conditions at the SWT test site. Finally, an electromagnetic design optimization is performed, in order to specify the ‘universal’ permanent magnet dimensions that can further reduce mass and cost for AFPMGs in the power range of 3kW to 7kW, used in LMSWTs with blade rotor diameters ranging from 4.8m to 7.8m.

Index Terms—Wind energy generation, Permanent magnet machines, Thermal analysis, Computational fluid dynamics, Particle swarm optimization, Finite element analysis, Manufacturing processes

I. INTRODUCTION

The UN Sustainable Development Goals (SDG) cover a range of social and economic issues, with SDG No7 calling for universal access to sustainable and affordable energy by 2030. In this aspect, low cost renewable energy technologies can make small scale electricity production more accessible to rural communities. In particular, the local manufacturing of such technologies can significantly reduce initial costs with the use of locally available materials, tools and manufacturing techniques and at the same time reduce maintenance costs [1] by providing appropriate training to the user community.

A widespread technology with such characteristics is locally manufactured small wind turbines (LMSWTs) [2]-[4]. Several design manuals [5] have provided a reference for NGOs and energy practitioners to manufacture small wind turbines for rural communities in developing countries, while global practitioners’ networks, such as the Wind Empowerment Association [6] have emerged out of the process.

The LMSWTs are battery charging variable speed machines which consist of a three blade wooden horizontal axis rotor [7] of constant pitch angle, of a coreless axial flux permanent magnet generator (AFPMG) with a double rotor single stator topology and utilize a passive mechanical furling tail system for rotor speed regulation. The use of AFPMGs is typical for such small scale wind energy applications [8]-[11], mostly due to simple manufacturing techniques required for constructing the stator and the rotor of the machine. Additional advantages are simple air gap regulation for improved turbine power matching [12] and lower cost of materials by comparison with their radial flux counter parts [13].

For rural off-grid systems with higher energy requirements used for commercial productive uses, LMSWTs of increased rated power of up to 10kW need to be designed. Several design aspects need to be considered while increasing the rated power of LMSWTs, such as the optimum turbine power matching in direct battery connection, the dissipation of thermal losses in the stator windings and the increased weight of the machine parts, amongst others.

In this paper, the thermal and structural design aspects of AFPMGs used in LMSWTs are considered with the aim of improving their heat dissipation capabilities and also reducing their total mass and cost. Common thermal design approaches for AFPMGs are considered such as lumped parameter thermal networks (LPTN) [14]-[16], 3D finite element analysis (FEA) [17]-[18] and computational fluid dynamics (CFD) analysis [19]-[22]. The results are compared with experiments for both laboratory and real operating conditions, while an appropriate thermal design approach is developed. A 3D structural FEA is performed on the back iron disc of the AFPMG [23] in order to achieve further reduction in mass while minimizing disc deflection, resulting in a novel disc design. An electromagnetic design optimization is performed using the Particle Swarm Optimization (PSO) [24]-[25], in order to specify the permanent magnet dimensions that can further reduce mass and cost while improving efficiency, for a range of high power AFPMGs used in LMSWTs.

In the following sections two types of AFPMGs typically used in LMSWTs are considered, namely a low power Type I generator and a high power Type II generator, whose characteristics can be found in Table I.

TABLE I
BASIC CHARACTERISTICS OF THE TWO AFPM GENERATOR TYPES

AFPM generator	Type I	Type II
Rated power	600 W	3.2 kW
Rated speed	300 RPM	160 RPM
Rated current	7 A	41 A
Battery voltage	48 V	48 V
Rotor outer diameter	30 cm	70cm
Effective length inner $\varnothing$	20.8 cm	58.4 cm
Thickness of rotor discs	8 mm	10 mm
Number of poles	12	32
NdFeB magnet grade	N40	N45
Magnet dimensions	30x46x10mm	58x27x10mm
Magnet to pole ratio ai	0.48	0.43
Coil leg width	21mm	22 mm
Stator axial length	13 mm	15 mm
Number of turns	90	26
Copper diameter	1.5 mm	1.4 mm
No of parallel windings	1	4
Total Mass	17 kg	94 kg
Total Volume	3.9 dm ³	26.1 dm ³
Total Cost	360 €	1285 €

II. THERMAL DESIGN OF AFPM GENERATORS

Common methodologies for the thermal analysis of electrical machines are considered in this section, namely those of LPTN, FEA and CFD. The LPTN's main advantage is fast computational time, but the flow rate in the air flow field needs to be determined experimentally or through a CFD analysis. On the contrary, FEA and CFD analysis can model any machine geometry, but require high computational times and depend significantly on an accurate model setup. A FEA analysis can be used to model heat conduction in solids, whereas a CFD analysis can be used to model air flow in the machine air gap.

In the following sections these three approaches to thermal modeling of AFPM machines are studied and compared to experimental results for the two types of AFPMGs considered in this paper.

A. Lumped Parameter Thermal Model

LPTNs consist of thermal resistances and heat sources in a steady state analysis, which represent an electrical equivalent of a thermal circuit. In the simplified AFPMG lumped parameter model used in this section [26], half of the machine is modelled due to symmetry (Fig.1), air flow is considered to be laminar and radiation from the rotor disc to the surroundings and the conduction resistance between magnets and rotor discs are ignored. The air flow rate in the air gap depends mostly on the rotational speed of the rotor discs and on the magnet width-to-pole pitch ratio ai . Experimental measurements of the flow rate for various rotational speeds for AFPMGs can be found in [26]. In later sections, the flow rate is simulated using a CFD analysis.

The losses of the Type I AFPMG at rated power are calculated using analytical equations [26] and are validated with an electromagnetic FEA and experimental measurements in later sections of the paper. Losses at rated power are in total

109W, of which rotational losses ΔP_{rot} of 9W, eddy current losses ΔP_{eddy} of 3W and stator winding losses ΔP_{copper} of 97W. A flow rate of 0.007 m³/s is considered in the air gap. The losses of the Type II AFPMG at rated power are in total 869W, of which rotational losses ΔP_{rot} of 25W, eddy current losses ΔP_{eddy} of 19W and stator winding losses ΔP_{copper} of 825W. A flow rate of 0.025m³/s is considered in the air gap. The stator, air gap and rotor disc temperatures for both AFPMG types can be found in Table II.

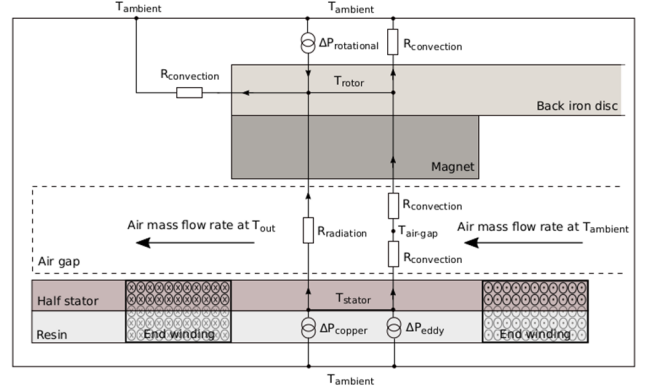


Fig. 1. Simplified lumped parameter thermal network of an AFPMG.

TABLE II
TEMPERATURES OF CONTROL VOLUMES FOR THE LPTN

AFPM machine	Type I	Type II
Stator winding (°C)	50.9	130.1
Air gap flow (°C)	26.2	30.3
Rotor disc (°C)	27.8	32.1

B. 3D Finite Element Thermal Analysis

As AFPM machines are intrinsically 3D, a thermal 3D FEA is conducted for both types of AFPMGs, in order to consider the 3D effect of heat flow. In addition, a 3D FEA allows for the visual inspection of critical regions of the winding where the heat needs to be dissipated effectively in order to avoid overheating.

Initial and boundary conditions, including all heat transfer coefficients are calculated based on the LPTN described in the previous section, while material properties are derived from relevant literature [27]. In addition, radiation between the rotor and stator is considered to be negligible, due to its small effect compared to conduction and convection heat transfer modes.

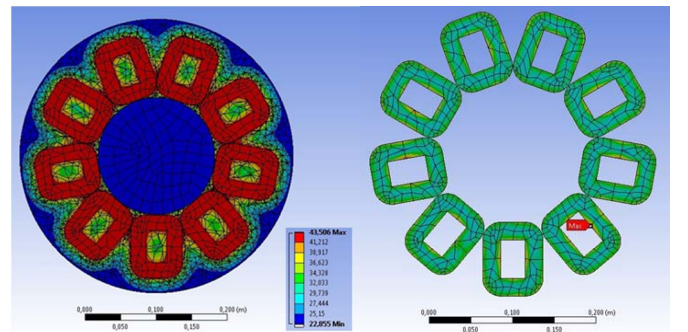


Fig. 2. (a) Temperature distribution (°C) in the resin encapsulated stator winding (left) and (b) total heat flux (W/m²) distribution (right) of the AFPMG Type I.

The results obtained from the thermal 3D FEA in terms of temperature distribution in the stator winding and the total heat flux can be seen in Fig.2, whereas the variation of the winding temperature over a period of 25 mins can be seen in Fig.6. The Type I AFPM generator winding reached a temperature of 43.5°C whereas the Type II AFPM generator winding reached a temperature of 129.5°C after 25 mins of operation at rated power.

In both cases the maximum heat flux concentration was observed in the inner walls of the winding hole, Fig.2 (b). This occurs due to the limited ability of the resin in the hole to transfer heat to the air gap. An improved design approach for better cooling of self-ventilated AFPM machines for high power applications, such as the Type II AFPMG considered in this paper, would be to remove the resin from the inner hole of the winding. This design approach increases the coil surface area which is able to transfer heat to the air gap, the fluid of which is of significantly lower temperature than that of the resin, and significantly increases the overall heat dissipation capability of the stator.

C. CFD Thermal Analysis

A CFD thermal analysis can be used to simulate the air flow in the air gap of an AFPM machine, while at the same time provide temperature distribution results which include the flow of air in the air gap. A CFD model of the Type II AFPMG was developed, as higher stator temperatures were simulated in the 3D thermal FEA and also recorded in experimental measurements presented in later sections.

The CFD model consists of a fluid domain enclosure and a solid domain for the stator. Because of the axisymmetric periodicity of the geometry and the limitation of available computational resources, only 1/6th of the AFPMG was modeled. A structured grid consisting of 3.600.000 elements was created with the ICEM CFD software with a distribution of 25 elements along the axial direction of the air gap between rotor and stator. The air density was considered to be independent of temperature increase, so buoyancy effects were neglected. The conservation of mass and momentum equations for the fluid domain were solved separately from the conservation of energy equation, which was solved for both fluid and solid regions. Steady state analyses were run on commercial CFD software using a pressure-based coupled solver. A realizable k-ε model was adapted for modeling turbulence with an enhanced wall treatment model used for the boundary layer near the walls, and a proper element distribution was developed near the wall so as to achieve y^+ values close to 1 in these regions. A transient analysis with a time-step independence study was conducted for the energy equation. Radiation between the rotor and stator was again considered negligible in relation to convective heat transfer, as was the heat transfer from the fluid to the rotor disks. The criteria for convergence were that the scaled residuals' values of the flow variables to be in the order of 10^{-5} and 10^{-12} for the energy equation for each time-step. Moreover, the monitored velocity magnitude at a point inside the air gap, the mass flow rate between inlet and outlet, and the fluid region's volume-average static pressure had to be independent of the number of iterations.

The velocity magnitude and the temperature distribution contours for a section of the AFPMG can be seen in Fig.3. The

mean temperature in the coil leg, where the temperature sensor has been placed, is measured to be 120°C. The velocity vector around the stator and rotor can be seen in Fig.4.

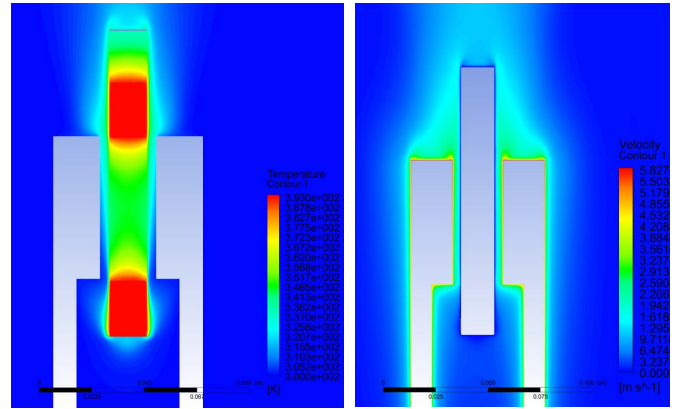


Fig. 3. (a) Temperature distribution contours in the resin encapsulated stator winding (left) and (b) velocity magnitude (right) of the Type II AFPMG.

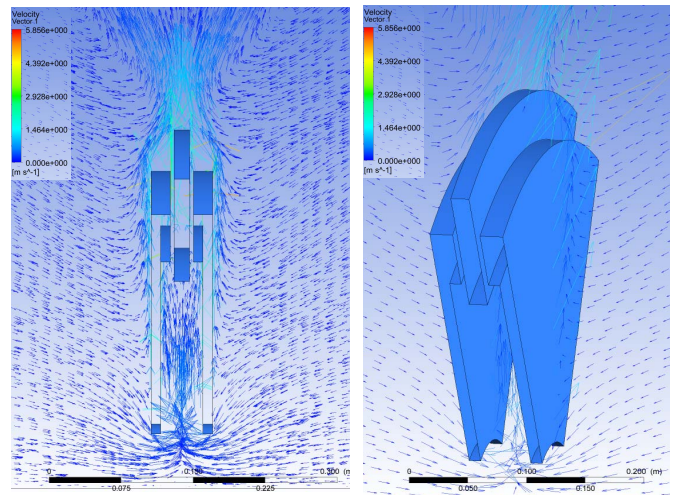


Fig. 4. Velocity vector around the stator and rotor of the Type II AFPMG.

D. Experimental Measurements

In order to evaluate experimentally the thermal behavior of AFPMGs operating in LMSWTs, both indoor laboratory bench tests were conducted and outdoor field tests in real conditions of operation.

1) *Laboratory Testing of AFPMGs:* The test bench for AMPM machines of the NTUA, Fig.5, was used in order to verify experimentally the thermal design methodologies used in previous sections of the paper.

Both AFPM generator types were connected with a 48VDC battery bank, via an uncontrolled three phase diode bridge rectifier, and driven with a variable speed DC motor, while all electrical measurements were recorded with a power analyzer. The mechanical torque at the shaft was measured with a torque meter. The phase resistance of the stator windings for each AFPMG type were measured at room temperature, and were found to be 0.66Ω for Type I and 0.16Ω for Type II.

During the local manufacturing of both AFPMGs under test, a PT100 temperature sensor was inserted in the winding at the middle of the coil leg, so for both machines the winding temperature was recorded at rated power. The winding

temperature reached 51°C for the Type I AFPMG and 136°C for the Type II AFPMG, after 60 mins of operation at rated power.

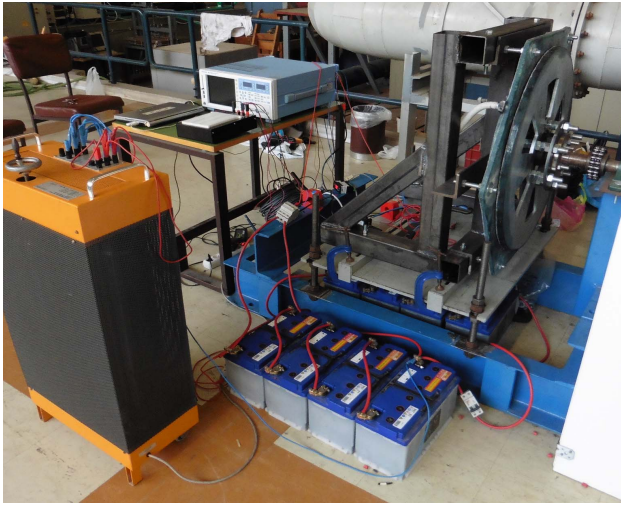


Fig. 5. The experimental setup for the Type II AFPMG.

The comparison of experimental, 3D FEA and CFD winding temperature results, after 25 mins of operation at rated power, can be seen in Fig.6 for the Type II AFPMG, while the comparison of experimental, 3D FEA, CFD and lumped parameter modeling results for all AFPMG Types can be seen in Table III.

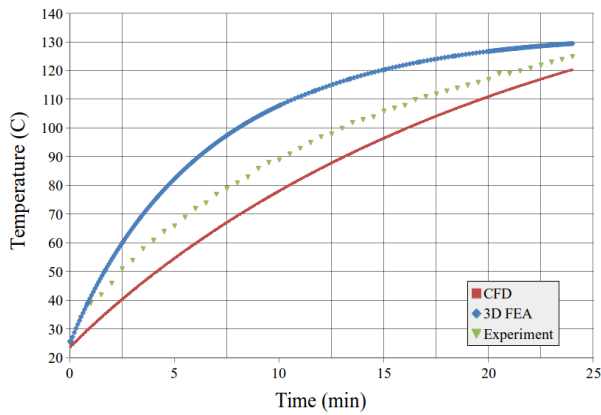


Fig. 6. Comparison between experimental measurements and simulated data from the 3D FEA and CFD models for the Type II AFPMG.

TABLE III
TEMPERATURES (°C) OF THE STATOR WINDING

AFPM machine	Type I	Type II
LPTN model	50.9	130.1
3D FEA model	43.5	129.5
CFD model	-	120
Bench test data	47.9	125

The LPTN model has an error of 6% when compared to experimental data for Type I AFPMG and 4% for Type II AFPMG. The 3D FEA has an error of 10% when compared to experimental data for Type I AFPMG and 3.5% for Type II AFPMG. The CFD model has an error of 4% when compared to experimental data for Type II AFPMG. The above percentages are considered acceptable for the current study,

but are strongly dependent on the duration of the experimental tests. In addition, the transient response of the CFD model matches more closely the experimental results than the 3D FEA, as seen in Fig.6, due to the better approximation of the air flow in the air gap and of the convective heat transfer coefficients.

As there is no current literature to suggest the standard duration of stator temperature tests for small wind turbine generators, further outdoor experiments were conducted in the NTUA small wind turbine test site.

2) *Field Testing of AFPMGs*: In order to identify the actual behavior of an AFPMG as part of a small wind turbine in real conditions of operation, the Type I AFPMG was coupled to a three blade rotor of 2.4m diameter and installed at the NTUA small wind turbine test site, in order to validate experimentally the stator temperature during real conditions.

As can be seen in Fig.7, the temperature of the stator raises gradually from ambient temperature to rated temperature, as the wind speed increases from cut-in to rated wind speed, following the increase in winding current and power production up to rated conditions. As the wind speed increases further the furling mechanism of the tail vane regulates power production by gradually deflecting the blade rotor from the wind, so power, current and thus stator temperature are reduced at higher than rated wind speeds. In high wind speeds the stator temperature is reduced close to the ambient temperature as power production is low and the cooling effect of the wind against the AFPMG has increased, as LMSWTs do not carry a casing for the AFPM generator.

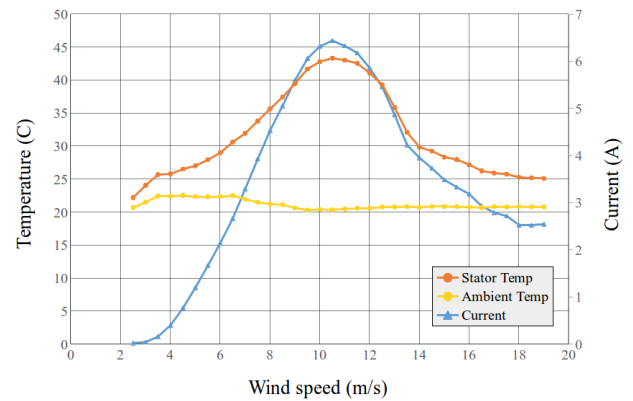


Fig. 7. Stator temperature, ambient temperature and winding current against various wind speeds for the Type I AFPMG.

Rated conditions for the Type I AFPMG, as described in Table I, are reached at a wind speed of 10.5 m/s and the average stator temperature at rated current is measured to be 43.4°C. In Fig. 8, the maximum and minimum values for each wind speed bin are presented showing the behavior of the small wind turbine as the rotor is accelerating and decelerating. As the maximum operating temperature of the AFPMG stator is of interest during the design phase, the maximum values will also be taken into consideration. As before, at rated conditions the maximum stator temperature is measured to be 52.2°C.

The percentage differences between the LPTN model, the 3D FEA and the AFPMG bench test, for both the mean and the maximum values of the stator temperature as measured in the field tests, are shown in Table IV. The magnitudes of the errors are considered acceptable for the current study and suggest that

both a LPTN model and a 3D FEA can be used to predict temperatures in the AFPMG stator winding.

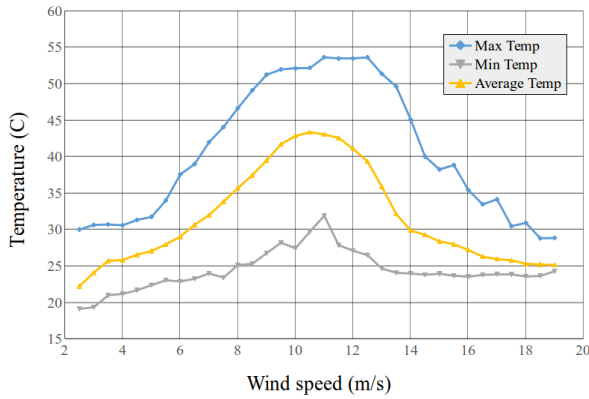


Fig. 8. Stator temperature as the blade rotor is accelerating (min values) and decelerating (max values) for the Type I AFPMG.

TABLE IV
PERCENTAGE DIFFERENCES WITH FIELD TEST MEASUREMENTS

Stator temperature	Mean (43.4°C)	Max (52.2°C)
LPTN model	14.7 %	2.5 %
3D FEA model	1 %	20 %
Bench test data	9.5 %	9 %

In addition, the 9% difference between the stator temperature when measured in the laboratory test bench and when measured in real operating conditions, suggests that the cooling effect of the wind does not contribute significantly to the cooling of the stator windings, although AFPMGs in LMSWTs operate without any casing.

III. STRUCTURAL DESIGN OF AFPM GENERATORS

As AFPM generators increase in power rating so does the outside diameter of the back iron disk with $D_{out} \propto \sqrt[3]{P_{out}}$ [26], resulting in significant increases in mass, especially for high power AFPMGs. For rated power of up to 10kW the rotor disc diameter for LMSWTs can increase up to more than 1m and weight more than 100kg. With machine parts of this size, the installation of a LMSWT becomes more demanding in terms of human resources and equipment required for lifting, while also significantly increasing the cost of the tower.

Reducing the mass of high power LMSWTs can be achieved by redesigning the rotor discs to include air ducts, which can significantly reduce the weight of the rotors and also improve the cooling capabilities of the AFPM generator. In the following sections, the structural design of the back iron disc of AFPMGs is considered so as to introduce the maximum amount of air ducts, while at the same time prevent extreme deformation of the disc due to the attractive forces between the rotor discs in double rotor single stator AFPM topologies.

Minimizing the disc deflection is significant as this determines the mechanical clearance gap between stator and rotors at the outer diameter of the machine. Apart from preventing friction between the stationary and moving parts of the machines, this gap also regulates the discharge of air in the air gap during operation and thus affects the self-ventilation of the machine and cooling of the stator. In addition, increased deflection of the discs can lead to fractures of the permanent

magnets that are fixed on its periphery, or in extreme cases to their detachment.

A. 3D Finite Element Mechanical Stress Analysis

A 3D FEA was used for a linear static analysis of mechanical stress in the elastic range. Only one rotor disc was modelled due to symmetry, using 10-node and 8-node elements, while a variable mesh was used, dependent on disc geometry and areas of high pressure concentration. The axial load from the magnet pull was distributed uniformly on the magnet.

Initially the standard air duct design of the Type II AFPMG was modeled and the simulated results for disc deflection were compared with experimental measurements (Fig.9a). The maximum disc deflection in the 3D FEA simulation was found to be 1.68mm, whereas the deflection in the Type II prototype was found to vary on the disc periphery between 1.35 and 2.1mm, due to the low precision of local manufacturing. For an average of 1.73mm of disc deflection, the simulation results vary by 3% from the experimental measurements. The maximum stresses were concentrated at the inner corner edges of the air ducts (Fig.9b), so appropriate fillets were designed to distribute them more evenly, while the stress values recorded were evaluated using the ASME code (VIII Division 2 Part 5).

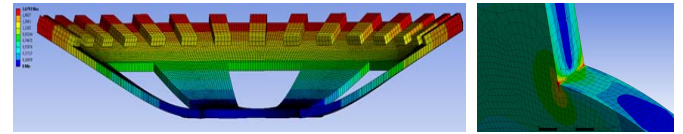


Fig. 9. (a) Rotor disc deflection (left) and (b) stress concentration in the air duct (right) of the Type II AFPMG.

The air ducts were further designed using the 3D FEA model developed in order to minimize the mass of the rotor disc, while at the same time avoiding failure of the material due to high stresses and avoiding deflection of the magnet surface. High power AFPMGs up to 7kW used in LMSWTs were considered, with disc diameters of up to 90cm. The air duct dimensions were parametrized and different designs were executed with the aim of satisfying the above requirements, resulting in the rotor disc design of Fig.10 (b).

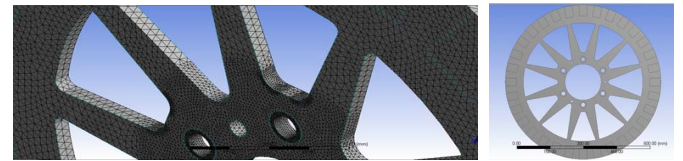


Fig. 10. (a) Detail of the mesh (left) and (b) the design geometry of the air ducts (right) used for high power Type II AFPMGs.

The proposed air duct design provides a reduction in back iron mass of up to 35% for high power AFPMG designs when compared to rotor discs without any air ducts. For the case of the Type II AFPMG described in this paper, which carries a generic air duct design, a mass reduction of 28% was achieved, reducing the back iron disc mass from 36kg to 26kg.

IV. ELECTROMAGNETIC DESIGN OF AFPM GENERATORS

The Particle Swarm Optimization (PSO), a common stochastic global optimization method for multi-criteria

optimizations in electrical machines, is coupled with a 2D electromagnetic FEA, in order to optimize the high power Type II AFPMG design for cost, efficiency and mass. The dimensions of a universal magnet are optimized for a set of high power machines ranging from 3kW to 7kW with blade rotor diameters ranging from 4.8m to 7.8m respectively.

Appropriate calibration of the inertia constant w , the particle's self-acceleration constant c_1 and the particle's social acceleration constant c_2 is required in order to achieve fast convergence. In this analysis the values of $w=0.7$, $c_1=0.3$ and $c_2=0.7$ have been used. Four design variables were optimized, namely the magnet width w_m , the magnet length l_a , the magnet thickness h_r and the stator thickness t_w , all taking values from a wide solution space. The number of poles varied according to the AFPMG power rating from 24 to 44, and the magnet grade was chosen to be N45 for Neodymium block magnets.

The objective function (5) was minimized, by reducing the total cost $GenCost$ and mass $GenMass$ of the generator while increasing the generator efficiency η at rated power. The weight coefficients k_m , k_c and k_e were introduced in order to vary the importance of all three performance criteria in the optimization.

$$F = (1 - \eta) \cdot k_e + GenMass \cdot k_m + GenCost \cdot k_c + P(x) \quad (5)$$

Appropriate penalty functions $P(x)$ were created for candidate designs with stators that would overheat and rotor discs that would weigh more than 75kg, so as to allow lifting by two people and so facilitate the installation of LMSWTs in remote areas.

The thermal and structural design approaches of previous sections of this paper were taken into consideration while designing the AFPMGs. The stator design with no resin in the coil hole was used, so as to increase the coil's surface area and its cooling abilities in the section with highest heat flux concentration. In addition, the back iron disc design with air ducts was used in the rotors in order to reduce the total weight of the machines.

All candidate designs created during the PSO optimization were simulated using a 2D magnetostatic FEA in order to evaluate the flux density in the air gap. A 2D FEA can predict experimental results with an accuracy of 3% [28], for double rotor single stator coreless AFPM generators, and can easily be coupled with a PSO optimization, producing acceptable computational times, due to its reduced number of elements when compared with a 3D electromagnetic FEA.

Once the optimization results were obtained, the optimal generators of the 3kW to 7kW power range were simulated using a 2D electromagnetic FEA in order to verify their performance and fine tune the designs (Fig. 11).

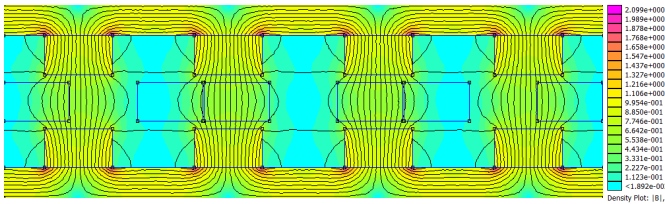


Fig. 11. A type II AFPM generator simulated with the 2D FEA software, FEMM.

A. Universal Magnet for High Power AFPMGs

Acquiring the appropriate size and grade of magnet in the market, is one of the challenges faced by local manufactures of small wind turbines. Due to the small quantity of production, a bulk order of custom made magnets from overseas suppliers is usually unaffordable for the local manufacturer. This supply chain issue can be overcome with the use of the same magnet dimensions for a variety of AFPM generator designs that are used for a specific power range and a specific range of rotor blade diameters. In this manner, apart from allowing the local manufacturer to place larger orders, in time these magnet dimensions become widely available in the market, which reduces their price due to mass production. For these reasons, a "universal" magnet is designed, which is a magnet that can be used with good performance criteria in the complete range of rotor diameters under investigation.

The universal magnet grade and dimensions for the power range under investigation were found to be NdFeB N45 75x25x15mm, using the PSO optimization described in the previous section. The performance of high power AFPMGs using the universal magnet with blade rotor diameters ranging from 4.8m to 7.8m are shown in Table V.

TABLE V
PERFORMANCE OF GENERATOR DESIGNS FOR HIGH POWER AFPMGs USING THE UNIVERSAL MAGNET FOR DIFFERENT ROTOR DIAMETERS

Rotor Diameter (m)	Rated Power (kW)	Efficiency (%)	Cost (€)	Mass (kg)
4.8	2.5	75	1285	52
5.4	3.2	76	1520	68
6	3.9	77	1825	99
6.6	4.7	76	2055	125
7.2	5.5	76	2375	155
7.8	6.5	75	2600	175

V. CONCLUSIONS

This paper focuses on the thermal and structural design aspects of high power AFPMGs used in LMSWTs for rural off-grid systems with high energy requirements. Different thermal design methodologies, such as lumped parameter modelling, 3D FEA and CFD, have been investigated and compared with experimental results, allowing for the development of appropriate thermal models for LMSWTs. An improved stator design with air ducts in the center of the concentrated windings has been proposed for better cooling of the stator. In addition, the thermal behavior of an AFPMG has been investigated in real conditions of outdoor operation in a LMSWT, providing a reference for the duration of indoor laboratory experiments. Further, the structural design of the back iron disc of high power AFPMGs has been investigated and an improved design has been proposed which achieves a 35% reduction in mass with minimal disc deflection. Finally, with the use of a PSO and an electromagnetic FEA, the dimensions of the permanent magnet that minimizes mass and cost and maximizes efficiency has been investigated, for a range of high power AFPMGs between 3kW to 7kW, with the aim of overcoming supply chain issues faced by local manufactures and small wind energy practitioners.

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