Design of Axial Flux Permanent Magnet Generators Using Various Magnetic Materials in Locally Manufactured Small Wind Turbines

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***Abstract* — Locally manufactured small wind turbines are most frequently used in off-grid battery based renewable energy systems and typically utilize coreless axial flux permanent magnet (AFPM) generators. Due to reports of neodymium magnet corrosion, the performance of coreless AFPM generators is investigated with the use of both neodymium and ferrite magnetic materials. Generator designs are conducted for rotor diameters between 2.4 and 4.2m, applying a Particle Swarm Optimization (PSO) in the generator design process, while the final designs are verified and fine-tuned with Finite Element Analysis (FEA) simulations. Optimal magnet dimensions are derived for both magnetic materials and for each rotor diameter, while a 'universal' magnet design is compared with commercially available magnets. Experimental comparison of a ferrite and a neodymium magnet generator design for a 2.4m rotor is conducted, proving that ferrite magnet AFPM generators are suitable for locally manufactured small wind turbines, making them less prone to corrosion, but also heavier in weight.**

***Index Terms*—Wind energy generation, Permanent magnet machines, Ferrites, Neodymium, Battery management systems, Particle swarm optimization, Finite element analysis, Manufacturing processes**

I. INTRODUCTION

Low cost renewable energy technologies can make small scale electricity production more accessible to rural communities. 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 by providing appropriate training to the user community.

A widespread technology with such characteristics is locally manufactured small wind turbines [1]-[3]. Available design manuals [4] have been a reference guide for locally manufactured small wind turbines, with many NGOs and technical groups using them in order to locally manufacture small wind turbines for rural communities in developing countries. The small wind turbines in question are variable speed machines which consist of a three blade wooden horizontal axis rotor of constant pitch angle, of a coreless axial flux permanent magnet (AFPM) generator with a double rotor single stator configuration and utilize a passive mechanical furling tail system for rotor speed regulation. The use of AFPM generators is typical for these small scale wind energy applications [5]-[8], mostly due to the simple manufacturing techniques required for constructing the stator and the rotor of the machine. Additional advantages are a simple air gap regulation process and the lower cost of materials by comparison with their radial flux counter parts [9].

The majority of these generators are manufactured with neodymium magnets (NdFeB), mostly due to their high energy density, but such magnetic materials have also been associated with problems of an economic, social, environmental and functional nature. The price of rare earth metals like neodymium (Nd) and dysprosium (Dy), which are contained in NdFeB magnets, has been highly unstable in the past years, with the price for Nd increasing more than 1000% from August 2009 to August 2011 [10]. In addition, environmental and social concerns have arisen [11] due to the processes used when extracting and refining such metals. Neodymium magnets are also prone to electrochemical corrosion due to the presence of small amounts of acid, alkali or water. For locally manufactured small wind turbines, which usually do not carry a casing around the generator, corrosion poses a threat, especially when operating in humid coastal environments. Users of such small wind turbines have reported that corrosion can occur during the first years of operation, causing the magnet rotors to swell and leading to the premature failure of the AFPM generator.

For the aforementioned reasons, many approaches have been proposed for reducing dependence on rare earth materials [12], such as introducing an iron core in the stator of the AFPM machines [13] in order to reduce the amount of magnetic material required. Yet, a coreless stator is still used in the majority of applications, due to the absence of cogging torque which enhances power production in low wind speeds, although attempts have been made to reduce it [14].

In this paper, alternative magnetic materials to replace neodymium in AFPM generator design are investigated, and specifically, the current design approach [15]-[18] of using ceramic magnets (hard ferrites) is developed further. Small wind turbines in the 0.8 to 3kW power range are designed (rotor diameters 2.4m to 4.8m respectively) using both neodymium and ferrite magnets, while maintaining the same performance characteristics for the AFPM generator. The Particle Swarm Optimization (PSO) is used, a common method for multi-criteria optimizations in electrical machines [19], in order to optimize the generator design for cost and efficiency, along with the FEMM Finite Element Analysis

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(FEA) [20] open source software to simulate the generator designs. Once the optimal magnet dimensions have been found for both magnetic materials and for each rotor blade radius, a universal magnet is designed for each material, which can provide similar performance characteristics for the whole range of rotor blade radii. Finally, the universal magnet is compared with commercially available magnets for both materials, and for the whole range of rotor blade radii.

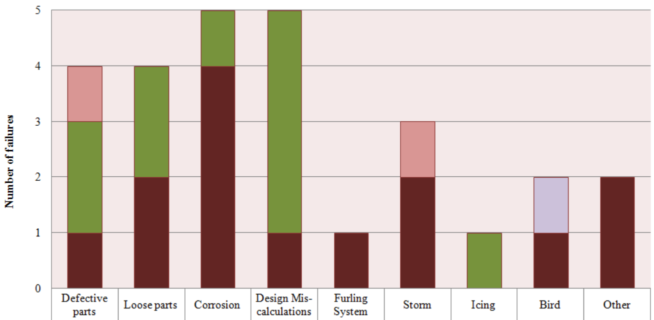
In conclusion, an 850W ferrite AFPM generator is manufactured locally (designed for a 2.4m rotor diameter) and its performance is validated and compared experimentally with an equivalent AFPM generator manufactured with neodymium magnets.

II. Corrosion in Locally Manufactured Small Wind Turbines

Corrosion of the AFPM generator rotor disks is one the most common failures of locally manufactured small wind turbines. This can consist either of corrosion in the back iron of the rotor disk, if it has not been galvanized or powder coated, or corrosion on the neodymium magnet itself, as seen in Fig. 1. In both cases the probability of corrosion is reduced with the use of vinyl ester resins for encapsulating the magnets of the rotor disks.

(a) (b)

Fig. 1. Two cases of corrosion in locally manufactured SWTs (a) corrosion of the back iron disk, (b) corrosion of a NFeB magnet



	Defective parts	Loose parts	Corrosion	Design Mis-calculations	Furling System	Storm	Icing	Bird	Other
5th year								1	
3rd year	1					1			
2nd year	2	2	1	4			1		
1st year	1	2	4	1	1	2		1	2

Fig. 2. The number of failures that occurred in the first five years of operation of 11 locally manufactured small wind turbines, and the cause of the failure.

In the user survey [21] conducted by the Rural Electrification Research Group (RurERG) of the NTUA on maintenance aspects of locally manufactured small wind turbines, 19% of failures in the first five years of operation were caused by corrosion. If extreme environmental conditions such as storms are not considered in the causes of failure, then the percentage of failures due to corrosion rises to 27% (Fig.2). These failures result in loss of production and shutdown of the small wind turbine, thus increasing the amount of time that the renewable energy system is not producing energy, which is a crucial factor for remote battery based off-grid systems.

In response to the findings of the survey, the design of AFPM generators with the use of ferrite magnets was investigated. These magnets are known to have very high resistance to corrosion since they already consist of iron oxides (MO×6(Fe2O3)). Furthermore, ferrite magnets have low and stable prices in the global market, are easily produced in many parts of the world and are made from cheap and accessible materials.

III. AFPM Generator Design

The design process for AFPM generators in direct battery applications has been previously analyzed in [22]-[24]. Initially, the cut-in rotational speed n of the rotor is calculated in (1). Indicative values used are a high value of tip speed ratio λ=8.75, since the generator has not started charging the battery yet and is spinning freely and a cut-in wind speed v_w (m/s) of 3m/s. The radius of the rotor R_{turb} (m) defines the length of the blades to be used with the AFPM generator.

$$n = \frac{60 v_w \lambda}{2\pi R_{turb}} \quad (1)$$

The electrical power output of the generator at rated conditions P_{nom} (W) can be calculated in (2). The rated wind speed is considered to be 10m/s; the aerodynamic coefficient c_p for locally manufactured small wind turbines has been measured to be 0.38 at 10m/s [25]; the efficiency η of the generator at rated power is estimated at 0.8; and ρ is the air density in kgr/m^3.

$$P_{nom} = \frac{1}{2} c_p \eta \rho \pi R_{turb}{}^2 v_w{}^3 \quad (2)$$

The induced EMF voltage E_f (V) during cut-in conditions can be calculated in (3), when the generator is not yet under load, but connected to the battery bank through an uncontrolled diode bridge rectifier. The appropriate battery voltage V_{batt} (V) of the system is required and that can either be 12, 24 or 48VDC.

$$E_{fcutin} = \frac{V_{batt}}{1.35\sqrt{3}} \quad (3)$$

The magnet's dimensions w_m, l_a and h_m, among other variables mentioned below, are given (in m) as inputs to the process, and some of them will later be optimized using the PSO algorithm. Other inputs are: the number of magnet poles p used in the AFPM generator, which when increased, the nominal frequency f_{nom} (Hz) and the efficiency η of the generator at rated conditions are also increased; the mechanical clearance g between the stator and the rotor which is usually kept at 3mm in order to avoid friction in the future; and the thickness of the stator t_w (m). The maximum magnetic flux Φ_{max} (Wb) per pole can be calculated in (4) and by calculating the magnetic flux density B_{mg} (T) on the magnet's surface in (5) in (6) [24]. The value of B_{mg} is also verified using FEA software, as described later.

$$\Phi_{max} = B_{mg} w_m l_a \quad (4)$$

$$B_{mg} = \frac{B_r}{1 + \mu_{rrec} \frac{(g + 0.5t_w)}{h_m} k_{sat}} 0.5 \quad (5)$$

$$\mu_{rrec} = \frac{1}{\mu_0} \frac{B_r}{H_c} \quad (6)$$

In (5) and (6) μ_0 is the vacuum permeability (Wb/(A·m)), μ_{rrec} is the recoil permeability, B_r is the remanent magnetic flux density (T), H_c is the coercive field strength (A/m) and k_{sat} is a saturation factor.

The number of turns per coil N_c is calculated in (7) for the cut-in EMF voltage E_f and rotational speed n, the number of coils per phase q, the number of poles p, and k_w a winding coefficient equal to 0.95 [23].

$$N_c = \frac{E_f \sqrt{2}}{q 2\pi k_w \Phi_{\max} n \frac{p}{120}} \quad (7)$$

The coil leg width w_c is calculated in (8) by first calculating the nominal AC current I_{ac} in (9) [22]. The coil fill factor k_f is considered to be 0.55 and ρ_{cu} is the electrical resistivity of copper (Ωm). The heat coefficient c_q is set to 0.3W/cm^2, which corresponds to a current density J close to 6A/mm^2. This is has been proven to be adequate for AFPM generators in small wind turbines without a casing and with natural air flow cooling.

$$w_c = \frac{I_{ac} N_c}{\sqrt{\frac{2c_q k_f t_w}{\rho_{cu}}}} \quad (8)$$

$$I_{ac} = \frac{P_{nom}}{3E_{fnom} \eta} \quad (9)$$

The conductor cross-sectional area s_c in the coils is calculated in (10) and the inner diameter R_{in} in (11) [22]. The outer diameter of the rotor disks can then be calculated by adding the effective length of the generator, which is equal to l_a the magnet's radial length.

$$s_c = \frac{k_f w_c t_w}{N_c} \quad (10)$$

$$R_{in} = \frac{6qw_c + 3qw_m}{2\pi} \quad (11)$$

While designing for different magnetic materials, the magnet thickness h_m needs to be considered. Ferrite magnets are significantly weaker than neodymium magnets, and thus it is necessary to increase the magnet thickness in order to achieve maximum energy in the magnetic field without reducing the air gap.

IV. Design Optimization and Simulation of AFPM Generators Using Different Magnetic Materials

The particle swarm optimization (PSO), a stochastic global optimization method, is deployed as it has been extensively applied to generator design with satisfactory results [19] [26]. Apart from fast convergence, another advantage of the PSO is its simplicity. Only two vectors are associated for each particle of the swarm, namely its position and velocity. The current position of a particle is a candidate solution, and the next candidate position/solution is determined by the velocity of the particle based on its own experience and on the experience of the whole swarm. After each iteration the velocity v_n and position x_n vectors of all particles are updated according to (12) and (13) respectively.

$$v_n = wv_n + c_1 rand()(p_{best,n} - x_n) + c_2 rand()(g_{best,n} - x_n) \quad (12)$$

$$x_n = x_n + \Delta t \cdot v_n \quad (13)$$

In (12) and (13) w is the inertia constant, c_1 the particle's self-acceleration constant, c_2 the particle's social acceleration constant, *rand()* is a function generating random numbers between 0 and 1, Δ_t is the time step, and $p_{best,n}$ and $g_{best,n}$ are the particle's personal best solution and the swarm's global best solution, according to the fitness function described in (14). Appropriate calibration of w, c_1 and c_2 is required in order to achieve fast convergence. In this analysis the values of w=0.5, c_1=0.1 and c_2 =0.9 have been used with satisfactory results.

The analytical design methodology described in the previous chapter was developed in MATLAB along with the PSO algorithm. Two different magnetic materials were optimized; a grade N40 NdFeB magnet and a C8 Ferrite magnet for a set of four different rotor diameters, spanning from 2.4m to 4.2m.

The design variables of the optimization were chosen to be the magnet width w_m and the magnet length l_a and their values were taken from a solution space ranging from 20mm to 90mm, which was considered to include the optimal solutions after some trial designs. The magnet thickness was kept constant at 10mm for the NdFeB magnets and at 20mm for the Ferrite magnet. The number of poles was increased for the ferrite AFPM generators in order to produce comparable performance characteristics to neodymium generators. The objective function (fitness) (14) was minimized, by trying to reduce the total cost of the generator *GenCost* while increasing the efficiency η at rated power. A weighted coefficient k_{eff} was introduced in order to vary the importance of the efficiency variable in the optimization.

$$F = GenCost - \eta \cdot k_{eff} \quad (14)$$

Furthermore, some construction constraints were introduced which resulted in the rejection of designs that would not comply. In (15) the coil leg width is restricted by the stator thickness due to limitations in manufacturing.

$$\frac{t_w}{w_c} \leq 0.35 \quad (15)$$

Once the optimization results were obtained, the optimal generators were simulated with the 2D finite element analysis software FEMM, in order to verify their performance and fine tune the designs (Fig. 3). A 2D FEA only considers the active length of the machines and does not take into account the magnetic field near the end windings, as would be the case for a 3D FEA. Nevertheless, the 2D analysis has been found to predict experimental results with an accuracy of 3-4% [27], for double rotor single stator coreless AFPM generators, which is considered sufficient for the current study.

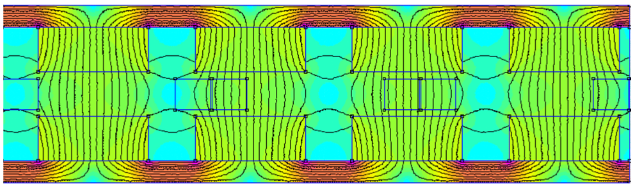


Fig. 3. A Ferrite magnet AFPM generator simulated with the 2D FEA software, FEMM.

A. *Optimal magnet dimensions for each rotor radius*

The optimal magnet dimensions for the two magnetic materials and for the four different blade rotor radii are shown in Table I. As expected, more magnetic material is required to produce the same performance characteristics in ferrite generator designs, which translates to a larger surface area of magnets and more poles. This in turn increases the outer diameter of the generator back iron disks.

TABLE I
OPTIMAL FERRITE AND NEODYMIUM MAGNETS PER BLADE ROTOR RADIUS

	Ferrite C8		***NdFeB N40***	
R_{turb}*(m)*	w_m*(mm)*	l_a*(mm)*	w_m*(mm)*	l_a*(mm)*
1.2	49	45	34	36
1.5	60	52	39	43
1.8	55	57	36	44
2.1	63	66	39	52

In Table II, the AFPM generator designs that use the optimal Ferrite C8 and the optimal Neodymium N40 magnets are compared in terms of rated efficiency, cost and mass, for the whole range of radii.

TABLE II
GENERATOR DESIGNS USING THE OPTIMAL MAGNETS FOR EACH MATERIAL PER ROTOR RADIUS

Optimal	***NdFeB N40***	*Efficiency*	*Cost (€)*	*Mass(Kg)*
	1.2m	0.881	280	12.9
	1.5m	0.879	391	22.4
	1.8m	0.879	495	30.4
	2.1m	0.875	633	42.6
	Ferrite C8	*Efficiency*	*Cost (€)*	*Mass(Kg)*
	1.2m	0.846	256	23.6
	1.5m	0.859	375	38.3
	1.8m	0.859	478	51.9
	2.1m	0.863	626	70.2

The ferrite generators operate with similar rated efficiencies as the neodymium generators, which was the initial goal of the design process. The cost of the ferrite and the neodymium generators is similar (a 4% average reduction of cost for the ferrite generators) since expensive neodymium magnetic material is exchanged with cheaper materials, such as ferrite and copper for the coils, but these materials are used in greater mass, which counter balances the overall cost. The mass of the ferrite generators is significantly larger than that of the neodymium ones by an average of 1.7 times, which will pose a problem if larger small wind turbines are designed. Yet for the rotor diameters addressed in this paper, each rotor disk remains under 30kg, which is the safe lifting weight for construction work. Nevertheless, increasing the weight of the small wind turbine increases the structural tower requirements during installation and this needs to be considered further.

B. *Universal magnet dimensions for each magnetic material*

Acquiring the appropriate size and type 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 issue has been overcome with the use of the same magnet dimensions for a range of AFPM generator designs that can be used with a range of rotor blades, such as the ones described in this paper. This allows for specific magnet dimensions to become widely available in the market, which in time even reduces their price due to mass production, allowing the local manufacturer to place smaller orders at local suppliers of magnets. For these reasons, a “universal” magnet is designed, which is a magnet that can be used effectively in the whole range of rotor radii under investigation. The universal magnet dimensions are calculated for each magnetic material and shown in Table III.

TABLE III
UNIVERSAL MAGNET DIMENSIONS

Magnetic material	***NdFeB N40***	***Ferrite C8***
w_m*(mm)*	39	55
l_a*(mm)*	49	62
h_m*(mm)*	10	20

The results of using the universal magnet dimension for both magnetic materials and all radii are shown in Table IV. The universal magnets can be compared with the optimal designs of section A, per rotor radius. It can be concluded that the exchange of the universal magnets with the optimal magnets for each magnetic material and for the whole range of rotor radii is possible, with a small increase in the cost of the generator by an average of 10%.

TABLE IV
GENERATOR DESIGNS USING THE UNIVERSAL MAGNETS FOR EACH MATERIAL PER ROTOR RADIUS

Universal	***NdFeB N40***	*Efficiency*	*Cost (€)*	*Mass(Kg)*
	1.2m	0.907	347	12.4
	1.5m	0.891	408	21.2
	1.8m	0.896	527	28.3
	2.1m	0.868	628	44.5
	Ferrite C8	*Efficiency*	*Cost (€)*	*Mass(Kg)*
	1.2m	0.860	310	24.9
	1.5m	0.865	381	36.6
	1.8m	0.865	483	50.2
	2.1m	0.845	610	72.9

C. *Comparison of Commercial and Universal magnets*

After conducting a market research with magnet suppliers on currently available Ferrite and Neodymium magnet sizes, it was concluded that some magnet sizes appeared to be common among suppliers, for various reasons. These were considered to be widely available “commercial” magnets that a local manufacturer could currently buy and use, at an affordable price. The commercial magnet dimensions for NdFeB N40 are L46xW30xT10mm and for Ferrite C8 L50xW50xT20mm.

The results of using the commercial magnet dimension for both magnetic materials and all radii are shown in Table V. It was observed that the universal magnets achieve higher efficiency and lower mass (at an average increase of 8% in cost) especially as the blade rotor radius increases. Specifically, for the ferrite generator with R_{turb}=2.1m, the currently available L50xW50xT20mm commercial magnet would be inappropriate, as it results in a generator whose individual parts are over 30kg. Similarly, for NdFeB N40, it was observed that the universal magnet results in more appropriate designs than the current L46xW30xT10mm commercial magnet, especially for the larger rotor blade radius of 2.1m.

TABLE V
GENERATOR DESIGNS USING THE COMMERCIAL MAGNETS FOR EACH MATERIAL PER ROTOR RADIUS

	NdFeB N40	*Efficiency*	*Cost (€)*	*Mass(Kg)*
Commercial	1.2m	0.887	295	12.5
	1.5m	0.850	383	25.2
	1.8m	0.861	484	32.8
	2.1m	0.803	641	58
	Ferrite C8	*Efficiency*	*Cost (€)*	*Mass(Kg)*
	1.2m	0.852	267	23.4
	1.5m	0.843	363	39.3
	1.8m	0.839	468	55.6
	2.1m	0.794	652	89.2

It can be concluded that the universal magnet is more appropriate for all designs, yet if necessary the commercially available magnet size can be used, except for the case of the small wind turbine with blade radius of R_{turb}=2.1m.

V. EXPERIMENTAL COMPARISON OF NEODYMIUM AND FERRITE AFPM GENERATORS

An 850W ferrite generator was constructed locally for a rotor with diameter 2.4m (R_{turb}=1.2 m). The commercial C8 ferrite magnet was used, with dimensions L50xW50xT20mm, as it was the most readily available magnet in the market, whose dimensions were close to the optimal Ferrite C8 magnet configuration for this rotor radius. The steps taken in the construction process and the experimental setup are depicted in Fig. 4. Air ducts were laser cut on the back iron disks for better cooling [28] and weight reduction. A neodymium AFPM generator, which has been designed with the use of the commercial L46xW30xT10mm magnet for a 2.4m diameter rotor [4], was manufactured locally in the NTUA and was used in the comparative laboratory bench tests. The basic characteristics of the two generators being tested are presented in Table VI.

The generators 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 state of charge of the battery bank was kept constant at 65% and at a voltage of 49VDC throughout the experiments. The phase resistance and inductance of the stator of each generator were measured at room temperature, and were found to be 0.66Ω/2.19mH and 0.92Ω/2.65mH, for the neodymium and ferrite generators respectively. The higher resistance and inductance of the ferrite generator stator was expected, because of the larger amount of coils per phase than the neodymium stator.

TABLE VI
BASIC CHARACTERISTICS OF THE NEODYMIUM AND FERRITE GENERATORS

Magnetic Material	***NdFeB N40***	***Ferrite C8***
Rated Power	840 W	840 W
Number of poles	12	16
Number of coils	9	12
Magnet dimensions	30x46x10mm	50x50x20mm
Design cut-in	215 RPM	215 RPM
Battery Voltage	48 V	48 V
Total Mass	12.5 kg	25.8 kg
Total Volume	3.9 dm^3	10.7 dm^3
Total Cost	328 €	219 €
Magnets' cost	240 €	99 €

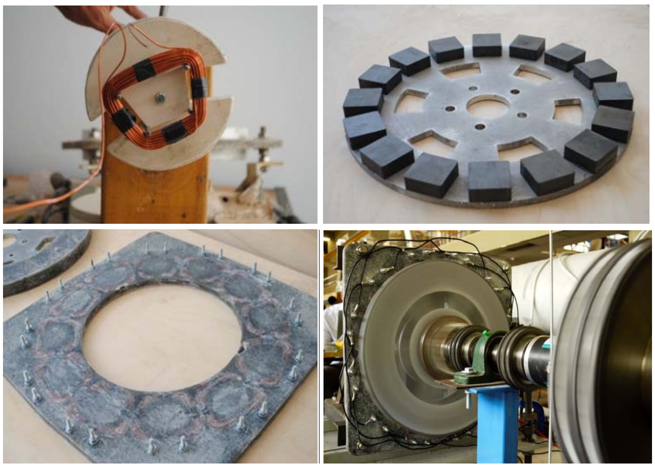


Fig. 4. Steps of the construction process such as coil winding, the magnet rotor disk, the stator cast in resin and the assembled ferrite magnet generator on the laboratory test bench.

The generators were rotated at different revolutions per minute (RPM) and all currents and voltages were measured, both on the AC and on the DC side of the system, while also measuring the mechanical torque on the generator shaft.

The power curves of the two generators are plotted along with the mechanical power curve of the 2.4m diameter rotor at 9m/s, as derived from wind tunnel tests on rotors with similar airfoil designs [25], Fig. 5. Due to the differences in stator resistance and inductance, the two generators produce the same amount of power but at different RPM, causing the ferrite generator to operate at higher λ when connected to the rotor blades. As the c_p vs λ curve of the 2.4m rotor reaches a plateau, this does not significantly affect power production in high wind speeds such as 9m/s, although it might increase the noise production of the rotor and also increase the leading edge erosion of the blades. If better power matching between the rotor and the generator were required, the air gap of the

Neodymium and Ferrite axial flux generators could be regulated in order to operate at higher or lower RPM respectively. In addition, the power transmission cable resistance, connecting the generator to the battery, could be altered to assist in this regulation.

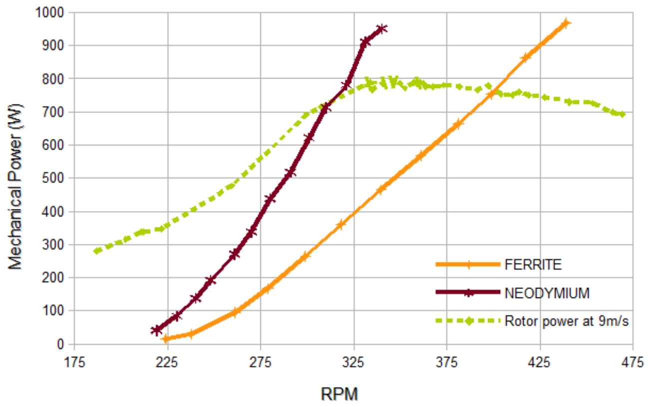


Fig. 5. The mechanical power curves of the neodymium and ferrite AFPM generators and the 1.2m rotor at 9m/s, when connected to a 48VDC battery bank with an 80m 3x4mm^2 power transmision cable.

The efficiency of the two generators was measured (Fig. 6) for the complete range of operational RPM of the wind energy system. The two generators operate with similar efficiencies throughout their power range, with the ferrite generator being just as efficient, according to the initial design approach. It can be noted that the Ferrite generator is slightly more efficient in the lower power range of 50-250W, which correspond to lower wind speeds such as 4-7m/s, which are typically more frequent in small wind turbine installation sites. This will potentially allow for an increase in the annual energy production of the Ferrite generator small wind turbine, although further research is needed in this direction.

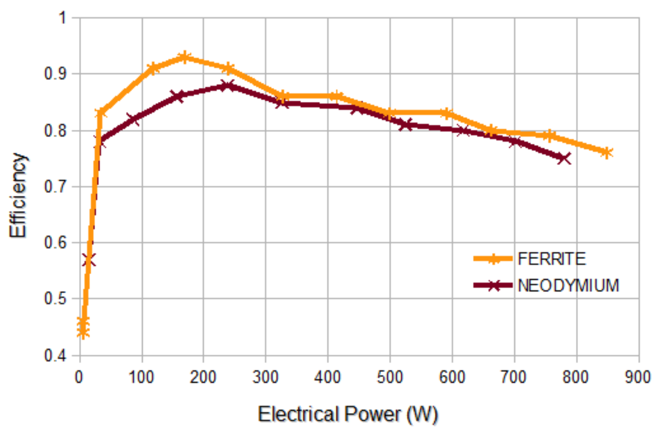


Fig. 6. The generators' efficiency against their produced electric power.

VI. Conclusions

This paper focuses on material issues, such as the corrosion of permanent magnets, which have arisen in the application of small scale wind energy systems. Significant reasons have been presented for replacing neodymium magnets with hard ferrites in AFPM generators for locally manufactured small wind turbines. Appropriate designs using ferrite magnetic materials have been proposed for turbine rotor diameters of 2.4 to 4.2m, with comparable performance to their neodymium counterparts and with similar costs, but with more mass and volume. With the goal of assisting small wind turbine manufactures in better addressing design and materials issues, the universal magnet design presented in this paper aims at improving availability and reducing costs for permanent magnets, while preserving the AFPM generator's performance. Experimental results presented in this paper show that Ferrite and Neodymium AFPM generators for small wind applications, in the 0.8-3kW range, can have similar performance. Finally, it is noted that in order to ensure the optimal operation of the wind energy system the designer would need to take into account the power matching factors of the generator and the rotor blades, due to the increased internal resistance of Ferrite AFPM generators.

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VIII. Biographies

Kostas Latoufis received the MEng degree in Electrical and Electronic Engineering from the Imperial College London (UK) in 2000. Since 2004, he has been working as a researcher in the Electric Power Division of the National Technical University of Athens (NTUA) in the area of Distributed Energy Resources, and is currently a PhD student in the Fluids Division of the NTUA School of Mechanical Engineering. His research interests include off-grid renewable energy systems, axial flux permanent magnet generators, locally manufactured small wind turbines, rural electrification development projects, small wind turbine blade design and science, technology and society (STS) studies. He is a member of the IEEE, of the City and Guilds of London Institute, of the Royal College of Science Association, of the technical chamber of Greece (TEE) and a member of the Executive Board of the Wind Empowerment Association, an association for the development of locally built small wind turbines for sustainable rural electrification.

Katerina Troullaki received the Diploma in Electrical and Computer Engineering from the National Technical University of Athens, with a specialization in Renewable Energy. Her main area of interest is distributed renewable energy production for rural electrification. Currently she is working as a developer and entity tester for 4G mobile network entities in the Athens R&D center of Nokia Networks.

Thomas Pazios received the Diploma in Electrical and Computer Engineering from the National Technical University of Athens (NTUA) in 2012. Since then, he has been working as a researcher in the Electric Power Division of the NTUA, and specifically in the SmartRUE research group, in the area of Renewable and Distributed Energy Resources. Currently he is a PhD student at the Electric Power Division of the NTUA and works as a research assistant at the Hellenic Electricity Distribution Network Operator (HEDNO). His research interests include microgrids, SCADA, smart meters, small wind turbines and rural electrification. He is a member of the technical chamber of Greece (TEE).

Nikos Hatziargyriou (S'80-M'82-SM'90-F'09) was born in Athens in 1954. He received the Diploma in Electrical and Mechanical Engineering from NTUA (National Technical University of Athens) and the MSC and PhD degrees in Electrical Power Engineering from UMIST, Manchester, in 1979 and 1982, respectively. From 1984 he is with the Power Division of the School of Electrical and Computer Engineering of NTUA, where he is full professor, since 1995. From February 2007 until September 2012 he was Deputy CEO of PPC (Public Power Corporation), responsible for the Transmission and Distribution Divisions, island DNO and the Center of Testing, Research and Prototyping. He is a member of the CIGRE, Chair of Study Committee C6 "Distribution Systems and Dispersed Generation" and convener or member of several Working Groups and Task Forces, a Fellow Member of the Institute of Electrical and Electronics Engineers (IEEE), member of the Power Engineering and Computer Societies, immediate past chair of the Power System Dynamic Performance Committee and member of several subcommittees and working groups of IEEE, and a member of the Energy Committee of the Athens Academy.