Comparison of Coreless and Soft Magnetic Composite Core Axial Flux Permanent Magnet Generators for Locally Manufactured Pico-Hydro Plants

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***Abstract* — Locally manufactured pico-hydro plants are typically used in off-grid battery based renewable energy systems and frequently utilize coreless axial flux permanent magnet generators (AFPMG) due to their simple manufacturing process. In this paper the use of iron-cored AFPMGs is investigated with the aim of reducing the permanent magnet material of the machine while minimize its cost and mass. The use of Soft Magnetic Composite (SMC) materials such as iron powder is investigated, which can provide a cost effective and simple manufacturing approach for the stator core. Two different AFPMG topologies are investigated, namely a double-rotor single-stator and a single-rotor single-stator machine topology, in order to maximize the generator efficiency and use effectively the available permanent magnet material, while allowing for simple air gap regulation of the pico-hydro plant. The Particle Swarm Optimization (PSO) is applied to the two AFPMG topologies for air-cored and iron-cored stators, in order to specify the optimum permanent magnet dimensions which maximize efficiency and minimize cost and mass, while the final designs are verified and fine-tuned with Finite Element Analysis (FEA) simulations. Finally, prototypes of the different AFPMG configurations are manufactured and tested, both on a generator test-bench and as part of a pico-hydro plant, directly driven by a locally manufactured Turgo turbine.**

***Index Terms*—Hydroelectric power generation, Picohydro power, Permanent magnet machines, Soft magnetic materials, Neodymium, Battery management systems, Particle swarm optimization, Finite element analysis, Manufacturing processes**

I. INTRODUCTION

The local manufacturing of small scale renewable energy technologies can significantly increase energy access and reduce initial costs for rural communities. Specifically the use of locally available materials, tools and manufacturing techniques can reduce maintenance costs [1] by providing appropriate training to the user community.

A current technology with such characteristics is that of locally manufactured small wind turbines (LMSWTs) [2]-[5]. Widespread design manuals [6] have provided a reference for energy practitioners worldwide on how to manufacture small wind turbines for the electrification of rural communities in developing countries, while global practitioners' networks, such as the Wind Empowerment Association [7] have emerged out of the process.

Using a similar manufacturing process, locally manufactured pico-hydro plants (LMPHPs) have provided a low cost and robust renewable energy source for off-grid battery based systems. LMPHPs are battery charging variable speed machines which consist of a Turgo or Pelton plastic spoon turbine [8] and of an axial flux permanent magnet generator (AFPMG). The use of AFPMGs is typical for pico-hydroelectric applications [9]-[11], mostly due to simple manufacturing techniques required for constructing the stator and the rotor of the machine and lower cost of materials when compared to radial flux machines [12].

The AFPMGs used in locally manufactured renewable energy applications are usually coreless and consist of a double-rotor single-stator topology. Although in LMSWTs it is not advised to use an iron core in the stator winding [13] (due to high cogging toque in low wind speeds and over speed issues due to a high stator inductance in high wind speeds) in LMPHPs, which operate in a more stable environment and most frequently at rated conditions, an iron cored AFPMG is preferable due to the reduction in magnetic material requirements. In order to reduce the manufacturing complexity and costs of laminated steel cores, Soft Magnetic Composite (SMC) materials such as iron powder have been used extensively for the fabrication of AFPMGs [14]-[18]. In addition to the introduction of an iron core, alternative AFPMG topologies can be used for LMPHPs such as the single-rotor single-stator topology, which allows for fast air gap regulation in variable flow conditions, in order to operate the turbine at maximum efficiency.

In this paper various AFPMG topologies are be studied for their appropriateness in LMPHPs, such as the double-stator single-rotor and the single-stator single-rotor topologies, with the use coreless and SMC cored windings. Initially, the properties of the SMC core to be used in the LMPHP are studied and its magnetization curve is investigated. The design of SMC cored AFPMGs is developed further using an analytical model and simplified magnetic equivalent circuits (MEC). The design of coreless and SMC cored AFPMGs is optimized with the use of the Particle Swarm Optimization (PSO) in order to optimize the generators for cost, efficiency and mass, along with the use of a Finite Element Analysis (FEA) for validation of the magnetic field properties and for conducting the preliminary AFPMG design. Once the optimal magnet dimensions have been found for different machine topologies, a coreless and a SMC cored AFPMG are manufactured locally and tested in the lab, both on a generator test-bench and as part of a PHP, directly driven by a locally manufactured Turgo turbine.

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II. PICO-HYDRO PLANT DESIGN FOR LOCAL MANUFACTURING

Pico-hydro plants are part of the smallest category of hydroelectric power generation, which refers to schemes with rated power of less than 5 kW. Such systems usually supply remote and off-grid areas and provide electricity for rural communities and small scale industries. Typically they are 'run-of-river' schemes, meaning that they neither require the construction of a dam nor do they stop the river flow, but instead they divert part of the flow into a channel or pipe and then through the turbine. Such systems constitute one of the most cost-effective renewable energy solutions due to their small initial capital requirements and mainly due to their continuous operation, producing rated power 24 hours per day and 7 days per week.

Major components of a pico-hydroelectric are the intake, the forebay tank, the penstock pipe which feeds the hydro turbine with water through the nozzles and supplies the required mechanical power to the generator of the PHP [19]. LMPHPs typically consist of a Turgo or a Pelton turbine, the choice of which depends on the head and flow requirements of the application. The turbine consists of plastic spoons which are locally manufactured with the use of 3D printers or injection molding techniques. The casing of the turbine is manufactured out on stainless steel and provides the required angle for the water jet to hit the spoons. Several nozzles can be accommodated with Turgo turbines, typically two or four, depending on the available flow. A shaft connects the AFPMG with the turbine through a flange. The AFPMG is manufactured using simple tools and techniques and is mounted on a steel frame on top of the casing (Fig.2).

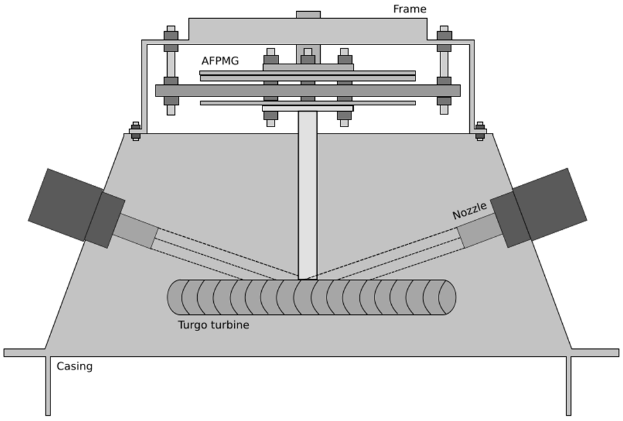

Fig. 2. A LMPHP consisting of an AFPMG and supporting frame, a plastic Turgo turbine and casing, a direct drive shaft and multiple nozzles.

Essential to the design is the choice and sizing of the turbine runner. The most suitable type of turbine for the specific application is chosen, depending on the head, the flow, the rated speed of the generator and the need for a satisfactory efficiency factor under conditions of partial flow. Further calculations include the number and size of the turbine spoons, from which result the turbine diameter and its speed, and calculations of the nozzle number and diameter.

In this paper, frequently encountered values of net head H_{net} and flow Q will be considered, namely those of 10m and 5l/sec, which in turn will need to produce 350W of electrical power at 750 RPM. For this application, a Turgo turbine is chosen, equipped with 20 spoons at a PCD of 17.37cm, fed by two nozzles of diameter 15.1mm each. Provided that the maximum efficiencies of the Turgo turbine and the AFPMG are in the range of magnitudes of 0.78 και 0.85 respectively, a 350W output will be achieved by the PHP.

III. SOFT MAGNETIC COMPOSITE CORES

Stator cores of AFPMGs are usually manufactured with laminated steel or with soft magnetic composite materials. Soft magnetic powder composites have the advantage of simplifying the manufacturing process and reducing the cost of AFPMGs and can achieve a significant tradeoff among permeability, losses and saturation levels when compared to laminated iron cores [15]. SMC materials are produced from high purity and compressibility iron powders, the particles of which are coated with insulating materials which produce high electrical resistivity. The coated powder is then compressed with resin to form a solid magnetic core and then heat-treated to anneal and cure the bonds.

The local manufacturing of a SMC core can prove to be demanding especially in terms of the powder metallurgy process for compressing the material. For the scope of this study, the SMC material Somaloy 1000 3P was used, considering its widespread use in electromagnetic applications, yet the compression phase was not included in the manufacturing of the AFPMG stator cores, in order to comply with the simple manufacturing requirements of locally manufactured renewable energy technologies. The Somaloy iron powder was mixed during the casting of the stators with vinyl ester resin, in a 7:1 mass ratio (Fig.3).

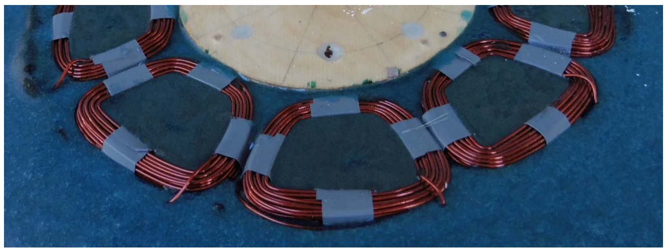

Fig. 3. The soft magnetic composite material mixed with vinylester resin and poured into the stator's condetrated windings.

For conducting both analytical modelling and FEA for the SMC cored AFPMGs considered in this paper, the experimental investigation of the magnetic properties of the locally manufactured SMC cores was considered necessary and was conducted using a SQUID magnetometer. The magnetization curve of a 12gr irregular SMC core specimen can be seen in Fig.4. This magnetization curve will provide the magnetic properties of the SMC core that will be used in the FEA of later sections of the paper. In addition, an estimation of the permeability value μ_{core} of the SMC core can be attained for different ranges of operation in a magnetic field.

IV. IRON-CORED AFPM GENERATOR DESIGN

The design process for coreless AFPMGs in direct battery applications has been previously analyzed in [20]-[22]. In this section the design of iron-cored AFPMGs is developed, using an analytical model with a simplified 2D (MEC), an approach which has been used extensively in AFPM generator analysis [23]-[24]. The MEC of the two machine topologies considered in this paper, namely the double-rotor single-stator and the single-rotor single-stator topologies can be seen in Fig.5 and Fig.6 respectively

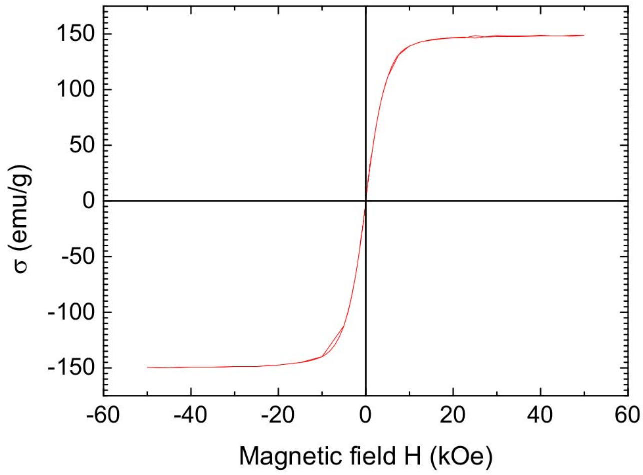

Fig. 4. The magnetic field strength H against magnetization σ for the specimen under test (1 Oe = $10^3/4\pi$ A/m and 1 emu/g = 1 Am^2/kg).

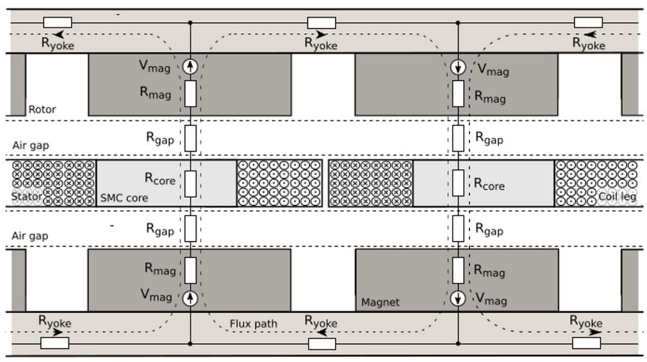

Fig. 5. The simplified Magnetic Equivalent Circuit for a double-rotor single-stator AFPMG topology.

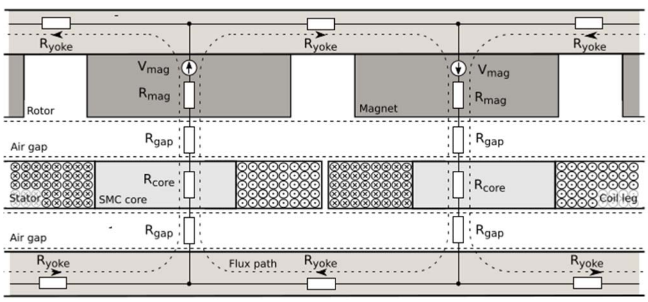

Fig. 6. The simplified Magnetic Equivalent Circuit for a single-rotor single-stator AFPMG topology.

The magnetic flux density in the air gap B_{mg} (T) can be found on the basis of Kirchhoff's magnetic voltage law when applied to the above MEC. For the double-rotor single-stator machine topology, B_{mg} is given by (1) while for the single-rotor single-stator machine topology B_{mg} is given by (2).

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

$$B_{mg} = \frac{B_r}{1+\frac{\mu_{rrec}}{h_m}(2g+t_w k_{sat})} \quad (2)$$

$$\mu_{rrec} = \frac{B_r}{\mu_0 H_c} \quad (3)$$

$$k_{sat} = \frac{\mu_0}{\mu_{core}} \quad (4)$$

In both (1) and (2) 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 μ_{core} is the permeability of the SMC core, while w_m, l_a and h_m are the magnet's width, radial length and axial thickness respectively, g is the mechanical clearance between the stator and the rotor and t_w is the thickness of the stator.

The maximum magnetic flux Φ_{max} (Wb) per pole is calculated using (5) while using the calculated magnetic flux density B_{mg} (T) on the magnet's surface using (1) or (2) depending on the machine topology. The value of B_{mg} is verified using a FEA in later sections of the paper.

$$\Phi_{max} = B_{mg} w_m l_a \quad (5)$$

Using the above results, the number of turns per coil N_c for different machine topologies is calculated in (6) for the rated 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 [22] for double layer concentrated windings.

$$N_c = \frac{E_f\sqrt{2}}{q 2\pi k_w \Phi_{max} n \frac{p}{120}} \quad (6)$$

V. Design Optimization and Simulation of Coreless and SMC Core AFPMG

The Particle Swarm Optimization (PSO), a stochastic global optimization method used frequently for multi-criteria optimizations in electrical machines [25]-[27], was coupled with a 2D electromagnetic FEA, in order to optimize different design topologies for cost, efficiency and mass, while minimizing the permanent magnet material.

Appropriate calibration of various PSO constants was conducted in order to achieve fast convergence, such as the particle self-acceleration constant (c_1=0.3), the particle social acceleration constant (c_2 =0.7) and the inertia constant (w=0.7). Four AFPMG design variables were optimized, namely the magnet length l_a, the magnet width w_m, the magnet thickness h_r and the stator thickness tw, while taking values from an appropriate solution space. The number of poles varied from 8 to 12, and the magnet grades varied between N40 and N42 for Neodymium block magnets.

The objective function displayed in (7) was used for minimizing the total cost *GenCost* and mass *GenMass* of the generator while increasing the efficiency η at rated power. Different weight coefficients were introduced in order to vary the significance of the previously mentioned performance criteria, specifically k_m, k_c and k_e. Particular focus was given to the generator efficiency η at rated power and to the overall cost, by adjusting accordingly the relevant weight coefficients k_e and k_c. Finally, penalty functions $P(x)$ were assigned to candidate designs with overheating stators.

$$F = (1-\eta)\cdot k_e + GenMass \cdot k_m + GenCost \cdot k_c + P(x) \quad (7)$$

Candidate designs were simulated using a 2D magnetostatic FEA (Fig. 7) for the validation of the flux density in the generator air gap. The 2D FEA used has been previously validated in [28] against experimental results, with an accuracy of 3%.

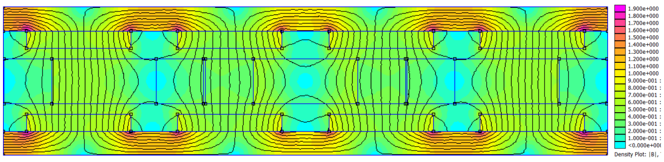

Fig. 7. A double-rotor single-stator SMC core AFPMG simulated with the 2D FEA software Finite Element Method Magnetics (FEMM).

A. Optimal magnet dimensions and AFPMG topologies

The optimal rotor desing and magnet dimensions for four different AFPMG topologies used in LMPHP were optimizaed, namely the SMC cored and coreless double-rotor single-stator and single-rotor sinlge-stator topologies. Improved perfomace characteristics were obseved for the SMC cored double-rotor single-stator and for the coreless single-rotor sinlge-stator topologies, the optimization results for which are shown in Tables I and II.

TABLE I
OPTIMAL ROTOR DESING AND MAGNET DIMENSIONS FOR EACH AFPM MACHINE TOPOLOGY

Optimal	*SMC Cored Double-Rotor Single-Stator*				
	Grade	*No Poles*	*l_a (mm)*	*w_m (mm)*	*h_m (mm)*
	N42	12	31	28	5
	Coreless Sinlge-Rotor Single-Stator				
	Grade	*No Poles*	*l_a (mm)*	*w_m (mm)*	*h_m (mm)*
	N40	8	38	44	10

TABLE II
GENERATOR PERFORMANCE USING THE OPTIMAL MAGNETS FOR EACH AFPM MACHINE TOPOLOGY

Optimal	*SMC Cored Double-Rotor Single-Stator*			
	Power (W)	*Efficiency*	*Cost (€)*	*Mass (kg)*
	342	0.87	147	6.1
	Coreless Sinlge-Rotor Single-Stator			
	Power (W)	*Efficiency*	*Cost (€)*	*Mass (kg)*
	328	0.81	273	10.9

The SMC cored double-rotor single-stator AFPMG topology displays superior performance than the coreless single-rotor single-stator AFPMG topology, due to a reduction in the use of magnetic materials. Both in terms of efficiency but also in terms of cost, the SMC cored double-rotor single-stator AFPMG displays a significant improvement, that of 7.5% in efficiency and of 46% in a reduction of cost. Increased efficiency and lower cost is a crucial aspect of LMPHP. On the other hand the single-rotor single-stator topology allows for simple air gap regulation without dismantling the AFPMG, which allows the user to easily adjust the PHP performance to seasonal variations of water flow. For the above reasons both machine topologies are considered candidates for optimized LMPHP, both in terms of performance but also in terms of simple maintenance and use.

B. Comparison of Commercial and Optimal magnets

A market research was conducted for available Neodymium magnet sizes, and specific sets of dimensions appeared more frequently among suppliers. These were considered to be “commercial” magnets which could be easily sourced by a local manufacturer and could be bought and used in small quantities and at an affordable price. The commercial magnet dimensions that are close to the optimal magnet dimension of the previous section are for NdFeB N40 46x30x10mm (L/W/T) and for NdFeB N42 30x30x5mm (L/W/T).

TABLE III
GENERATOR PERFORMANCE USING THE COMMERCIAL MAGNETS FOR EACH AFPM MACHINE TOPOLOGY

Commercial	*SMC Cored Double-Rotor Single-Stator*			
	Power (W)	*Efficiency*	*Cost (€)*	*Mass (kg)*
	321	0.87	155	6.8
	Coreless Sinlge-Rotor Single-Stator			
	Power (W)	*Efficiency*	*Cost (€)*	*Mass (kg)*
	318	0.79	246	10.7

From Tables II and III, it can be concluded that the optimal magnet dimensions display better performance characteristics for all designs, as would be expected, yet if necessary the “commercial” magnet sizes can also be used with minor increases in the total cost of the AFPMG or a small reduction in the overall efficiency.

VI. EXPERIMENTAL COMPARISON OF CORELESS AND SMC CORED AFPM GENERATORS

Two LMPHPs were manufactured locally at the NTUA workshops with the participation of students, and were then used in the comparative laboratory bench and hydraulic tests (Fig.8). Specifically, the optimized designs of the previous section were fabricated with the use of commercial magnet sizes producing two 400W LMPHPs, one using an SMC cored double-rotor single-stator AFPMG and the other a coreless single-rotor single-stator AFPMG. The basic characteristics of the two AFPMGs under test are presented in Table IV.

During the bench tests, the AFPMGs were rotated at different revolutions per minute (RPM) using a DC motor drive and suppling power either to a battery bank or to a resistive variable load, through an uncontrolled diode bridge rectifier. Electrical power characteristics were measured both on the AC and on the DC side of the system and the mechanical torque was measured on the generator shaft. The operation of the AFPMGs was coherent with the FEA conducted in the optimizations of the previous section, with a maximum error of 3%, while the efficiency vs current graphs can be seen in Fig.9. The efficiency of the SMC cored AFPMG is significantly improved over its coreless counterpart, not only as a maximum value but also for a wider range of operating currents.

TABLE IV
BASIC CHARACTERISTICS OF THE TWO AFPMG TOPOLOGIES

AFPMG Type	***SMC D-R S-S***	***Air S-R S-S***
Rated power	400 W	370W
Rated speed	750 RPM	750 RPM
Rated current	4.65 A	3.75 A
Battery voltage	48 V	48 V
Rotor outer diameter	22 cm	25 cm
Effective length inner Ø	15.8 cm	18.6 cm
Thickness of rotor discs	10 mm	6 mm
Number of poles	12	8
NdFeB magnet grade	N42	N40
Magnet dimensions	30x30x5mm	46x30x10mm
Magnet to pole ratio *ai*	0.60	0.54
Coil leg width	11 mm	28 mm
Stator axial length	13 mm	13 mm
Number of turns	67	146
Copper diameter	1.25 mm	1.32 mm

Fig. 8. The LMPHP tested in the hydraulics laboratory of the NTUA, a double-rotor single-stator AFPMG on the DC motor test bench and a locally manufactured 3D printed Turgo turbine.

The two LMPHPs were then installed in the applied hydraulics laboratory of the NTUA and were directly driven by a 3D printed locally manufactured plastic spoon Turgo turbine, driven with a closed loop pumping system at a net head of 10m and at a flow rate of 5l/sec (Fig.8). The LMPHPs were directly connected to a battery bank and were driven at rated conditions. The operation characteristics and the overall efficiency of the PHPs can be seen in Table V. It is observed that the operation of the SMC cored AFPMG increases the overall water-to-wire efficiency $Eff_{w\text{-}el}$ of the PHP system by 7%, from a value of 0.71 produced when the coreless AFPMG is used to a value of 0.78 when using the SMC cored AFPMG.

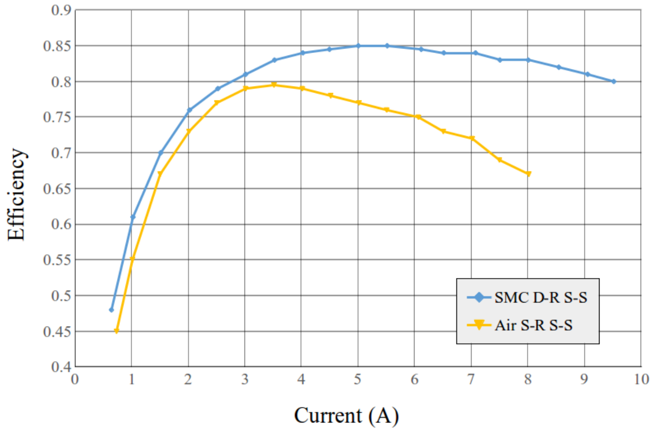

Fig. 9. The efficiency of the two AFPMG types under test over a range of curents.

TABLE V
LMPHP OPERATION AND EFFICIENCY AT RATED CONDITIONS

SMC Cored Double-Rotor Single-Stator					
RPM	V_{ac} *(V)*	I_{ac} *(A)*	P_{elec} *(W)*	P_{water} *(W)*	$Eff_{w\text{-}el}$
742	28.6	4.65	399	515	0.78
Coreless Sinlge-Rotor Single-Stator					
RPM	V_{ac} *(V)*	I_{ac} *(A)*	P_{elec} *(W)*	P_{water} *(W)*	$Eff_{w\text{-}el}$
753	32.9	3.78	372	524	0.71

VII. CONCLUSIONS

This paper focuses on the use of SMC materials for iron-cored AFPMGs used in LMPHPs, in comparison with coreless AFPMGs, with the aim of reducing the permanent magnet material, while maximizing efficiency and minimizing cost and mass. The use of the SMC material Somaloy is investigated experimentally using a SQUID magnetometer, while fabrication of the core is achieved using simple techniques. Two different AFPMG topologies are investigated, namely a double-rotor single-stator and a single-rotor single-stator machine topology with the use of SMC cored and coreless windings. The design of SMC cored AFPMGs is developed further using an analytical model and simplified MECs. The PSO is used in order to optimize the design of coreless and SMC cored AFPMGs for cost, efficiency and mass, along with the use of a FEA. Once the optimal magnet dimensions have been found for different machine topologies, a coreless and a SMC cored AFPMG are manufactured locally and tested in the laboratory, both on a generator test-bench and as part of a PHP, directly driven by a locally manufactured Turgo turbine. Both in terms of genrator efficiency but also in terms of cost, the SMC cored double-rotor single-stator AFPMG displays significant advantages over the coreless single-rotor single-stator AFPMG, with a reduction in the overall generator cost of 46%. In addition, the operation of the SMC cored AFPMG increases the overall water-to-wire efficiency of the locally manufactured pico-hydroelectric system by 7%. It is concluded that the use of SMC cored AFPMGs can significantly improve the performance and the reduce generator costs of LMPHPs.

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