20th International Conference on Renewable Energies and Power Quality (ICREPQ'22)
Vigo (Spain), 27th to 29th July 2022
Renewable Energy and Power Quality Journal (RE&PQJ)
ISSN 2172-038 X, Volume No.20, September 2022

Low-cost variable-speed wind turbines design by recycling small electrical machines. Arrangement of permanent magnets in the rotor.

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Abstract. This paper describes the design of low-cost variable-speed wind turbines by recycling small electrical machines. In this way, electrical machines such as automobile claw-pole alternators, induction motors for domestic applications, or simply electric motors for some industrial applications are studied, considering their reuse as permanent magnet synchronous generators (PMSG) in small wind turbines or hydro-power turbines. The main purpose is the integration of hybrid energy conversion systems (wind and hydraulic turbines) in small stand-alone microgrids within the rural environment. Likewise, in order to optimize the design, the arrangement of the permanent magnets in the rotor is analyzed. The analysis has been carried out using the FluxMotor simulation software, which is based on the 2D finite element method. At the same time, the FEM software provides a lot of information about the optimization of the electrical machine and its multiple design options and topologies. Suggested designs have similar performance as well as a similar size and weight. The purpose has been to explore different topologies and select the most efficient designs. In this way, it is shown that it is possible to reuse an electrical generator easily, without losing much of the general performance.

Keywords. low-cost wind-turbine, harvesting energy, reuse and recycling of electrical machines, automobile claw-pole alternator, retrofitted to permanent magnet synchronous generators, variable speed generators, small FEM-3D (Finite Element Method), stand-alone microgrid.

1. Introduction

In the last decade, small wind power systems are very attractive to support the energy demand of rural areas, in stand-alone installations, or in developing countries where the infrastructure of electrical microgrids is very limited. Likewise, energy harvesting (wind, photovoltaic, thermal, etc.) has emerged as an innovative alternative to keep small stationary hardware platforms running for several years without supervision. Some examples may be: weather stations, flow measurement equipment in irrigation canals, telecommunications facilities, etc.

Several authors have made comparisons on the efficiency of small wind turbines and different experimental models in low wind speed conditions. Thus, Wirtayasa *et al.* [1], [2] describe the design of a small 1kW/300rpm axial-flux permanent magnet generator (AFPMG) intended for mini-hydro-power plants. The numerical method (FEM-2D software) was used to validate the flux density value in the air gap and the dimensions of the magnetic circuit. Similarly, Latoufis *et al.* [3], [4] propose the open-access design and manufacture of small wind turbines. Thus, local manufacturers can redesign small wind turbines for power supply in remote rural areas according to available materials. The purpose is rural electrification in developing countries.

Low-cost renewable energy technologies can make small-scale electricity production much more accessible to less advanced rural communities. The development of the hybrid electric vehicle has caused some authors [5], [6] to consider it important to raise aspects related to reuse and recycling in the electric machine design for traction applications. From that perspective, these electrical traction elements can be easily reused in the development of small permanent-magnet synchronous generators. Thus, Ani *et al.* [7] or Artal-Sevil *et al.* [8], analyze the reuse of a claw-pole automotive alternator to build a small wind turbine. Likewise, the different parameters necessary for the design of the wind turbine and its detailed calculation procedure are described. In both cases the results shown are satisfactory. Similarly, Omri *et al.* [9] present a 3D model based on a magnetic equivalent circuit (MEC) applied to different topologies of claw-pole synchronous machines. The proposed modelling approach takes into consideration the variation of the rotor position, that is, MEC dependent on the rotor position.

The alternator-based turbine system is therefore a low-cost solution aimed at making wind power available in more deprived areas, where the current cost of the technology is still prohibitive. Thus, Melcescu *et al.* [10], Lundmark *et al.* [11], and Devornique *et al.* [12] apply numerical analysis by finite element method (3D-FEM) for the design and development of a hybrid claw-pole synchronous generator. The output voltage is easily regulated with minimum power, through the current in the field coil. The claw-pole machine is widely used in the automobile industry due to its robustness and low cost compared to other electrical machines.

Fig. 1. Prototype of a small vertical axis wind turbine with 600W/24V power approx.

In recent years, researchers have proposed different configurations for synchronous machines that can be easily recycled. Advances in electrical machine design have provided manufacturers with some opportunities to save energy, reduce costs, and use less rare-earth magnets. Thus, some studies [13], [14] have shown that synchronous reluctance motor (SynRM) designs can be reused in small stand-alone generation applications mainly due to their mechanical robustness, low cost, and low maintenance requirements.

Other authors [15], [16] have described different design approaches for a sustainable wind energy harvesting and storage system. The purpose is the development of a small-scale stand-alone wind power system for power generation in rural and remote areas. Meanwhile, in [17] a novel methodology for the optimization of a water-pumping system or a power supply system to telecommunications equipment is presented. Likewise, Li *et al.* [18] describe the recycling process associated with electrical machines and the retrofitting of asynchronous motors to permanent magnet generators under circular economy conditions. Thus, the squirrel-cage rotor is replaced by a permanent magnet rotor, developing the magneto-thermal analysis through the finite element method.

Today, permanent magnet synchronous motors are the dominant technologies in many traction applications. Its high efficiency and high torque density make this technology very popular among electrical machine manufacturers. The decreasing cost of SmCo and NdFeB permanent magnets and their availability in the market has caused permanent magnet synchronous generators to be widely used in small applications. On the other hand, Zhao *et al.* [19] and Bhagubai *et al.* [20] propose the optimal design of a permanent magnet synchronous generator rotor. In this way a Halbach PM rotor topology is analyzed. This research mainly includes the analytical model, optimization design, coupled field model, parameter identification, etc. Some advantages such as their small size, lightweight, easy maintenance, high efficiency, reliability, and no moving contacts, make these small permanent magnet generators the choice for vertical and horizontal-axis wind turbines intended for power supply in stand-alone installations or rural areas.

The objective of this paper is to evaluate the feasibility of reusing small electrical machines as a generator for small wind turbines. Comparing their energy performance-based on the permanent magnet arrangement in the rotor. The output performance of the wind turbine is determined by measuring tests within FEM simulation. Concepts for optimizing the generator and achieving a good match between turbine and alternator characteristics are also presented.

This paper is organized as follows. Section I presents a brief introduction and state-of-the-art associated with the study addressed. Section II presents the analysis and estimation of a small wind turbine. Section III describes the magnetic model of various topologies of permanent magnet synchronous generators. Section IV shows and discusses the simulation results. Finally, conclusions and some brief considerations are summarized in Section V.

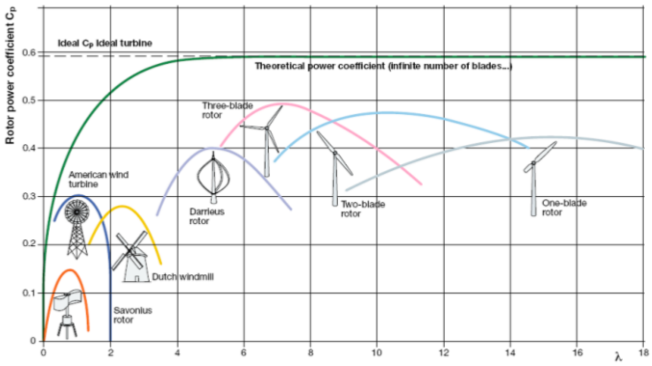


Fig. 2. Average wind turbine power coefficient (c_P) vs. tip speed ratio curves for different blade types [21].

2. Analysis of a small wind turbine

The energy harvested by a wind turbine depends on the wind speed and the wind distribution curve at the site, while the wind variation in most areas can be described by the Weibull distribution. Due to this, the maximum power P_{WT} that can be extracted by a wind turbine is expressed as a function of wind speed as,

$$P_{WT} = \frac{1}{2}\rho_{air} c_P(\lambda, \theta)\pi R^2 v_{air}^3 \quad (1)$$

where ρ_{air} is the mass density of air (ρ_{air} = 1,225kg/m^3), R is the wind turbine rotor radius, v_{air} is the wind speed and c_P (λ, θ) is the power coefficient also called aerodynamic efficiency. This coefficient c_P can be obtained with the diagram shown in Fig. 2, being function of the relationship between the tip speed λ (standard speed divided by the wind speed) and the pitch angle θ [21]. Similarly, the maximum theoretical power that can be extracted from the wind is determined by Betz's law and is equivalent to 59.3% of the total wind power.

The power extracted from the wind P_{WT} can be calculated as (1). However, the electrical power P_E obtained is reduced by the generator efficiency η_{PMSG}, gearbox efficiency η_{GB}, and power electronics efficiency (inverter-rectifier) η_{PE}.

$$P_E = P_{WT}\eta_{PMSG}\eta_{GB}\eta_{PE} \quad (2)$$

Figure 2 represents the aerodynamic characteristic of each type of turbine (Savonius, Darrieus, Three-blade, American wind turbine, etc.). These curves usually have a parabolic shape. Therefore, there is a maximum output power for variable wind speeds that is at the "top" of the curve. Tip speed ratio λ at which the turbine is operating can be expressed as,

$$\lambda = \frac{\omega_m R}{v_{air}} \quad (3)$$

where ω_m is the mechanical angular velocity (rad/s). Thus, the maximum power point tracking (MPPT) algorithms are used to maintain the operating point at its highest value. This is achieved by controlling the rotational speed of the turbine rotor.

3. Magnetic models

The starting point (base case) is a permanent magnet synchronous machine (PMSM), whose main dimensions are given in Table 1. A simplified diagram of the electrical machine is shown in Fig. 3. Simulations have been conducted using Altair FluxMotor software (2D-finite element method modelling).

Table I. Main dimensions of the base case PMSM.

TOPOLOGY	Stator outer diameter	270 mm
	Stator inner diameter	176 mm
	Stator length	250 mm
	Number of slots	36
	Air gap	2 mm
	Rotor outer diameter	172 mm
	Rotor inner diameter	60 mm
	Length	250 mm
	Pole pairs	5
MAGNET (base case)	Magnet height	6 mm
	Magnet angle	30°
SLOT	Slot height (HS)	27 mm
	Slot width (WS2)	12 mm
	Intermediary height of the slot (H1)	0.7 mm
	Intermediary width of the slot (WS1)	8.5 mm
	Height of slot opening (HO)	0.5 mm
	Width of slot opening (WO)	4 mm
	Length of 45° chamfer	30 mm
WINDING	One layer. Fractional pitch	
	Wye connection	
	Number of turns per coil	
	Number of wires in hand	40
	Wire diameter	15

On the one hand, four rotor configurations have been tested, named "outer ring PMs", "inner ring PMs", "layer PMs", and "V-block PMs" (see Fig. 4). The PMs volume and the magnetomotive force (it is proportional to the PMs magnetization length) have been kept constant in all the simulations, in order to study the rotor topology effects on the machine performance. Table 2 indicates the geometric parameters used in each case study.

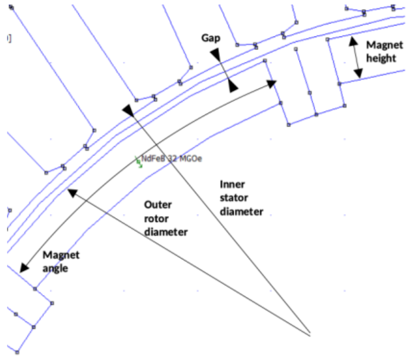


Fig. 3. Stator and rotor dimensions of the base case.

Table II. PM dimensions and volume per pole.

Ring PMs (outer and inner)	TM (mm)	6
	C (deg)	30
	PMs volume per pole (cm^3)	65.18
Layer PMs	TM1 (mm)	6
	WM1 (mm)	15
	TM2 (mm)	6
	WM2 (mm)	6
	PMs volume per pole (cm^3)	63.00
V-block PMs	TM (mm)	6
	WM (mm)	22
	PMs volume per pole (cm^3)	66.00

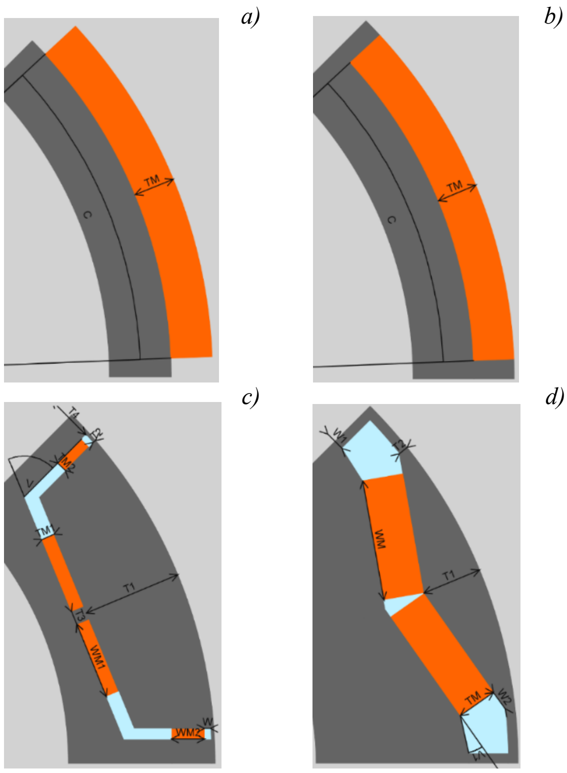


Fig. 4. Different arrangements of the PMs in the rotor of the synchronous generator. a) Outer ring PMs, b) Inner ring PMs, c) Layer PMs, d) V-block PMs.

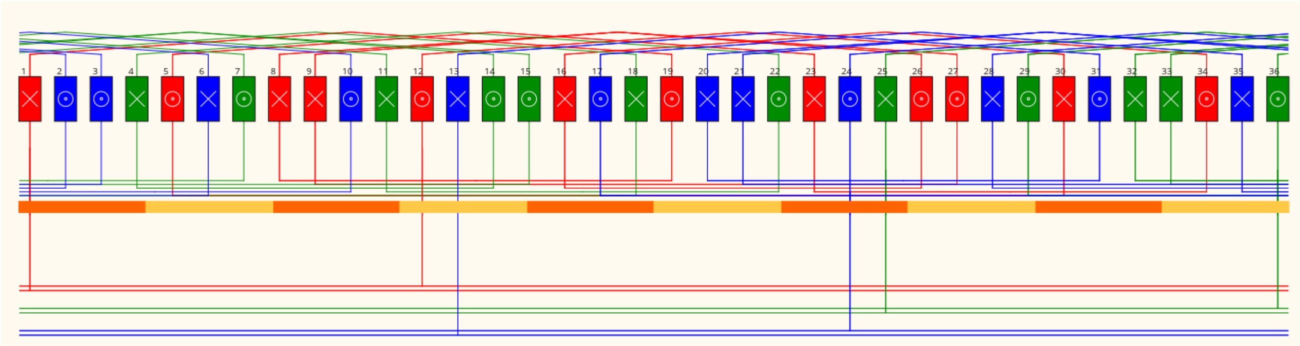


Fig. 5. Winding layout. Winding view including phase connections.

On the other hand, the stator (slots and winding) is the same in the four PMSM models, with a three-phase, fractional-pitch winding. The winding connections are shown in Fig. 5. In this picture, each colour represents one coil turn (there are 40 turns per phase, series-connected) and the circles correspond to each of the wires in parallel (15 wires per turn). Meanwhile, the filling of each stator slot is shown in Fig. 6.

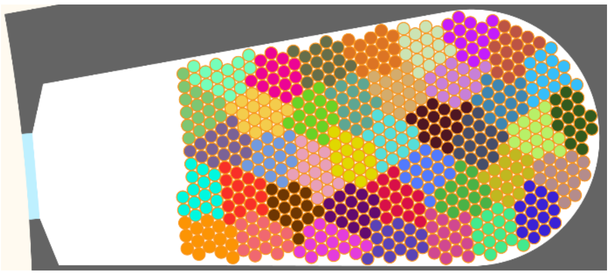


Fig. 6. Slot filling view. Each colour represents one coil turn and the circles correspond to each of the wires in parallel.

Considering the initial data of the three-phase squirrel-cage induction motor, the arrangement of permanent magnets in the rotor is analyzed in order to reuse the new electrical machine as a synchronous generator. The stator is made of Si M-27 steel (non-linear), with 0.635 mm sheet thickness and 0.98 stacking factor. NdFeB 32 MGOe magnets have been used in the rotor. These magnets have a high coercivity and high remanence. An example of the analyzed magnetic equivalent model with a V-block PM arrangement on the rotor is shown in Fig. 7. While Table 3 shows the unit reluctance of each of the magnet arrangements in the generator rotor. In all the cases analyzed, the reluctance (pu) of the magnetic circuit is similar. In Fig. 4 it is possible to observe the geometry of the rotor in each case.

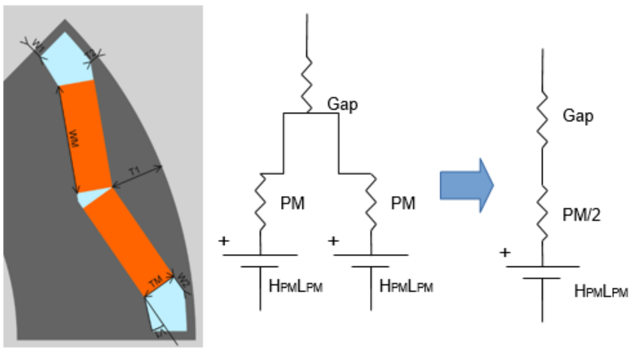


Fig. 7. Magnetic equivalent model with V-block PMs arrangement on the rotor.

Table III. PMs reluctance (pu) in each assumption.

Arrangement of the rotor	PMs Reluctance (pu)
Outer ring PMs	1
Inner ring PMs	1
Layer PMs	1.11
V-block PMs	1.06

4. Simulation Results

Through the simulation of the different cases (FluxMotor software), it has been possible to obtain a comparison between the PM arrangements in the rotor. The proposed generators have been tested under MTPA command in the whole operation range. Table 4 shows the main specifications of the PMSM generators.

Table IV. Main generator specifications.

Rated speed (rpm)	83
Maximum speed (rpm)	166
Line current, RMS (A)	16
Maximum line-line voltage, RMS (V)	390

The cogging torque and torque-speed curves for each analyzed permanent magnet synchronous generator are shown in Figs. 8 and 9. As result, it is observed that the V-block PMs rotor arrangement has lower cogging torque and lower average torque. While the outer or inner ring PMs rotor arrangement have higher cogging torque and higher average torque.

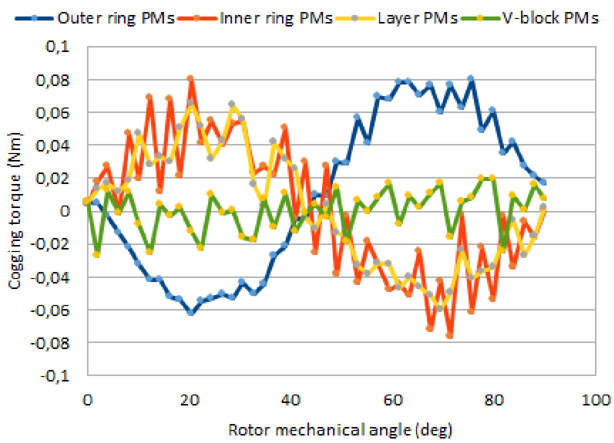


Fig. 8. Cogging torque in each case studied.

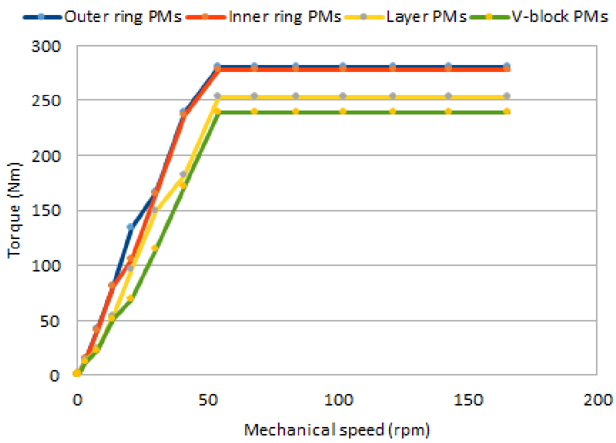


Fig. 9. Torque-speed curves in each case studied.

The measurement devices and equipment used to check the behavior of the developed system are shown in Fig. 10. In this case, a DC motor has been used to simulate the rotation of the wind turbine blades at variable speeds. In this way, it is easy to simulate different wind speeds in the laboratory, it is only necessary to change the supply voltage supplied to the DC motor. In the real case, the frequency provided by the generator will depend on the speed of the small wind turbine or the hydro turbine, depending on the case applied (variable speed generation).

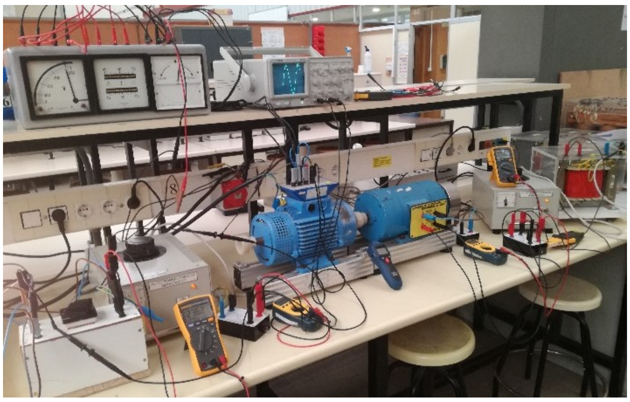


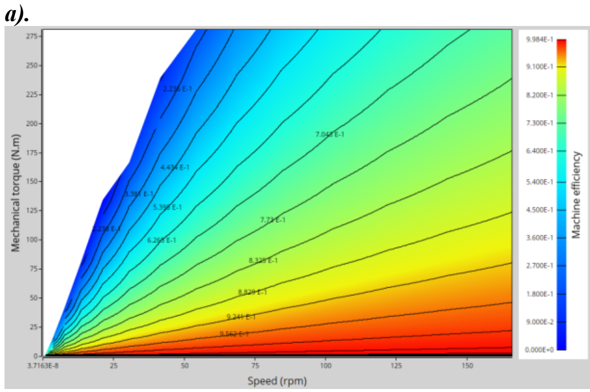
Fig. 10. Test-bench used to check the behavior of the developed prototype.

Likewise, in Fig. 11 the machine efficiency map in each PM arrangement studied is presented. Thus, the efficiency of the recycled motors at different speeds and torques can be calculated through these diagrams. In this way, it is possible to locate the most suitable point of the generator's working region. The estimation of losses in the magnetic core and permanent magnets are traditionally carried out from time-dependent FEM simulations [16] for a certain rotation speed to include the effect of harmonics.

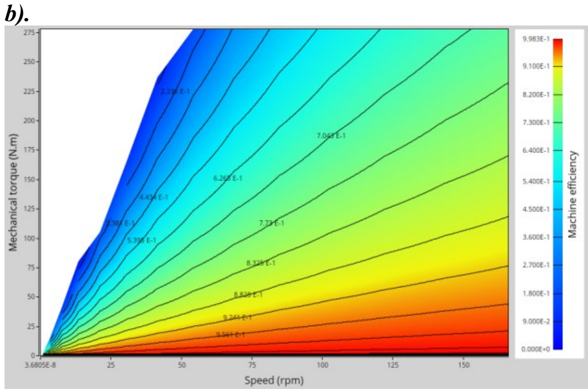
5. Conclusion

This paper has described the reuse and recycling of small electrical machines, such as automobile claw-pole alternators, induction motors for domestic applications, or simply electric motors for some industrial applications. These devices can be used as low-cost electrical generators for the design and development of small wind turbines or small hydro-power turbines. The main objective has been the integration of hybrid-power conversion systems (wind and hydro-turbines) in small microgrids, as well as the development of autonomous off-grid systems in rural areas.

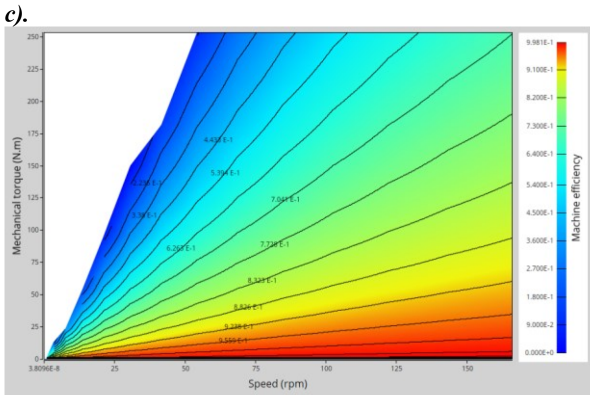
a).



b).



c).



d).

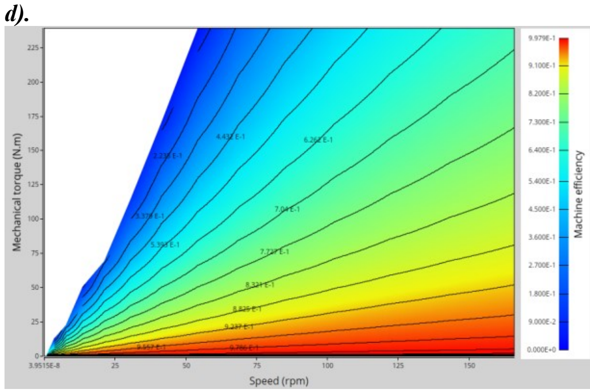


Fig. 11. Efficiency map for each permanent magnet arrangement: a) outer ring, b) inner ring, c) layer, d) V-block.

The reuse and transformation of these electrical machines as permanent magnet generators and their application in autonomous systems can be proposed both for remote areas and in agricultural and livestock environments. In this document, the costs derived from the transformation to a permanent magnet synchronous generator have not been considered. It should be noted that, for more complex topologies, the cost of permanent magnets (€1.85/cm^3

approx. NdFeB) or the cost associated with rotor machining, can exceed the cost of a small electrical machine. The numerical analysis (2D-FEM) has allowed us to validate the design process and the analytical results. The different models have been developed using the FluxMotor software. Numerical software provides a lot of information about the many electrical machine design options and their optimization. FluxMotor has turned out to be a good tool specialized in the design of electrical machines. In this way, it has allowed us to explore different topologies and select the most efficient designs. A wind turbine based on reusing a claw-pole alternator or retrofitting to a permanent magnet synchronous generator (PMSG) can be a low-cost solution designed to ensure that wind power is available in less advanced areas where the current cost of the technology is still prohibitive.

Acknowledgement

The authors would like to thank the support of Government of Aragon and the European Union project T28_20R, "building Aragon from Europe". This research work has been supported by the State Research Agency (AEI) of the Spanish Ministry of Science under grant PID2019-104711RB-I00 and has also been supported in part by the Spanish Ministry of Universities under Grant FPU20/03436.

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