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Development of a small wind turbine for stand-alone system in rural environment. Reuse and recycling of electric motors.

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Abstract. This paper studies the feasibility of using small electrical machines (e.g. automotive alternator, induction motors of domestic applications or electrical motors of some industrial application) as low cost generators for small wind turbine or small hydro power; its transformation in generators is not difficult. The objective is to provide a comparison among permanent magnet synchronous generator PMSG with different topologies (rotor configurations). The analysis was performed using FEMM-2D simulation software, which is based on finite element method. Small wind and hydro power systems are very attractive to support the energy demand for rural areas or developing countries where the electrical microgrid infrastructure is limited. Claw-pole automotive alternators can provide low cost alternative to permanent magnet synchronous generators for small wind and hydro turbines applications. The objective is the integration of hybrid energy conversion systems in microgrids and the development of small stand-alone systems in rural environment.

Keywords

Small wind turbine, Microgrids, Permanent magnet synchronous generator, Harvesting Energy, Variable speed generators, Wind and Hydro power systems, Claw-pole automotive alternator, FEM-2D (Finite Element Method).

1. Introduction

A major reason for the low penetration of small wind and hydro turbines in the market is the high cost of current systems. Fractional horsepower electrical motors can be found in any home appliances, as washing machines, refrigerators, dryers, etc.; its transformation in generators is not difficult [1]. The generator is a main element of small wind turbines and it has the function of converting the mechanical energy from the turbine into electrical energy. The generators used in the market can be classified in two types: Electrically Excited Synchronous Generator (EESG) and Permanent Magnet Synchronous Generator (PMSG). Small wind and hydro power systems are very attractive to support the energy demand for rural areas or developing countries where the electrical microgrid infrastructure is limited. Thus the integration of small stand-alone systems in rural environments is possible. Energy harvesting from renewable and alternative resources through recycled electrical machines is currently a research topic [2].

Some authors, Alatalo M. et al [3], have considered recycling aspects on the design of electrical machines that are introduced in the new electric and hybrid vehicles. While Jagau H. et al [4] present a design approach for a sustainable wind energy capture and storage system; it proposes a low cost electricity generation and storage solution for the electrification of rural areas through a sustainable topology. Bumby J.R. et al [5] describe the model, design and development of an axial-flux permanent magnet generator for use in small-scale wind and water turbines. On the other hand, Milivojevic N. et al [6] present current state of small wind turbine technology and also propose a different approach to the design procedure for a wind turbine generator system. Melcescu L. et al. [7] present the numerical results of a permanent magnet claw poles wind generator (3D-model) developed by FEM.

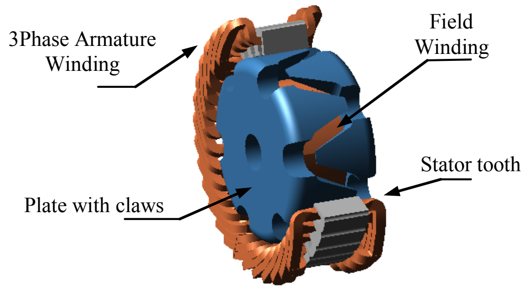


Fig. 1. Typical claw-pole automotive alternator.

Other authors as Arumugam D. et al [8] and Ofordile S. et al [9] have evaluated the feasibility of using claw pole automotive alternator as a generator for small wind turbine. The energy yield from the automotive alternator system is comparable with many commercially available systems. While Lundmark S.T. and Alatalo M. [10] or Durairaju K. [11] have modelled and simulated using the finite element method (ANSYS FEM-3D) the behavior of a typical claw-pole automotive alternator. Thus the performance and effectiveness of an alternator has been studied in these documents.

A small electrical alternator of a car, truck or crawler is the simplest example of a device which can be easily reused to generate electrical energy, without any change, see Fig. 1. The goal of the electric machines designer is to achieve high efficiency, torque density and long lifetime. Claw-pole automotive alternators can provide low cost alternative to permanent magnet synchronous generators for small wind and hydro turbines applications [12]. Stator has laminated core with copper wires inserted in slots. The fields windings in the rotor are made of fine wire and enclose the rotor claws made of solid iron. Power is transferred to the DC excitation field winding on the rotor via copper slip-rings and carbon brushes.

The different elements of a conventional claw-pole automotive alternator are shown in figure 2. The stator consists of standard 3 phase winding and rotor consists of a field winding claw-pole arrangement. A field regulator controller will adjust the field current to maintain the terminal voltage at regulation voltage.

Fig. 2. Different elements of an automotive alternator.

2. Permanent Magnets.

Most of the low-speed wind turbines are small permanent magnet generators. These devices have the advantages of high efficiency and reliability since there is not need external excitation and conductor losses are removed from the rotor. The permanent magnets currently used in the construction of electric machines can be divided into three groups, according to chemical composition and material properties: alnico, ceramic and rare earth.

Neodymium iron boron (Nd2Fe14B) is a type of rare earth magnetic material; it is the most advanced commercialized permanent magnet material available today. This material has similar properties as the samarium cobalt SmCo5 except that it is more easily oxidized and generally doesn't have the same temperature resistance. However, NdFeB magnets have the highest energy products approaching 52MGOe and are mechanically stronger than SmCo5 magnets. Although this material is more costly by weight than ceramic or ferrite (iron oxide with BaC03 or SrC03) and alnico (alloy of aluminium, nickel and cobalt), but produces the highest amount of flux per unit of volume or mass; making it very economical for many applications. A comparative analysis is performed in order to find the most efficient solution in terms of price-performance ratio.

TABLE I
SELECTED MATERIAL MAGNETIC PROPERTIES.

Type magnet	Maximum Energy Bhmax (MGOe)	Residual Flux Density Br(G)	Coercive Force Hc(Koe)	Working Temperature ºC
Ceramic	3,4	3950	2400	400
Alnico	3,9	10900	620	540
$SmCo_5$	20	9000	8000	260
Sm_2Co_{17}	28	10500	9500	350
$Nd_2Fe_{14}B$	33	11500	10700	180

Table I shows the most significant properties of different commercial magnets. The material data have been extracted from the sales catalogue of Advanced Magnetic Materials. Beneficial characteristics of NdFeB magnets include their very high energy product, very high coercive force, and moderate temperature stability. Drawbacks include lower mechanical strength and low corrosion resistance when not properly coated or plated. This type of permanent magnet can be magnetized in a variety of directions.

3. Simulation of a Permanent Magnet Synchronous Generator using FEM-2D.

In this section the modeling and simulation of a permanent magnet synchronous generator (PMSG) is performed using the finite element method (FEM) through the FEMM-2D software. Development begins with a stator belonging to a three-phase asynchronous machine, in an effort to simulate and convert small electric motors in low-power wind and hydro generators; for example the conversion of a car alternator or the washing machine motor, see Fig. 3. These devices have a power less than 1kW.

The stator of the electric motor, is composed of 36 slots (stator slot number Z = 36). The coils for each phase are predefined by the manufacturer, see Fig. 5. Other parameters of the model are: depth d = 250mm, rotor diameter $Ø_r$ = 174mm, air gap thickness δ = 2mm, poles number 2p = 10. In order to compare different topologies, also it has been considered a maximum volume of permanent magnet (NdFeB material) vol_{pm} = 675cm^3. The aim is to simplify the design, minimizing the number of variables to study in the problem. Thus it has been limited his study to a comparison of results among different geometries in the rotor magnets. Magnetic non-linearity has been considered through respective *B = f(H)* dependence. Figure 4 shows the silicon steel curve used for the numerical analysis in FEMM-2D software.

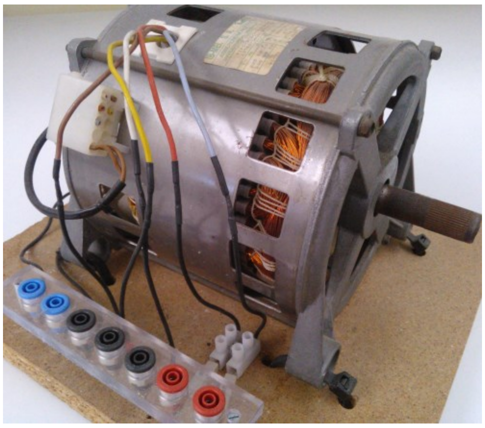


Fig. 3. Example of recycled electric machine.

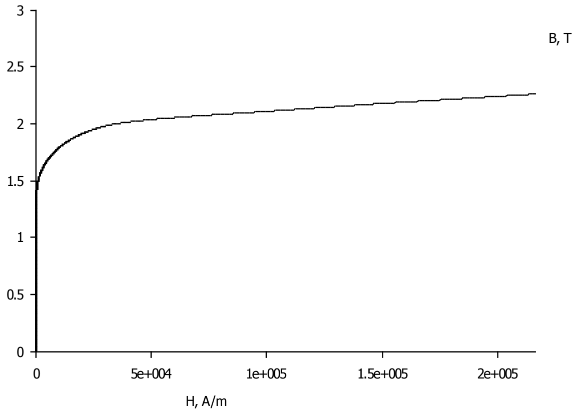


Fig. 4. *B = f(H)* curve type *Si M27-steel*. FEMM-2D software Graphic.

The data described here show different possibilities and rotor geometries. Also indicate that through the simulation of different cases (FEMM-2D) it has been possible to develop a comparison among the different rotor types. Parameters to consider were: induction waveform in the air gap, flux per pole, flux linkage or voltage obtained in the coil. Stator geometry in the PMSG is shown in figure 5. The stator is constituted by the stack of silicon steel laminations type *Si M27-steel*. Indicate that all laminated sheets are joined by a small external welding wire, without addition of material, which prevents sliding between them (this mechanical phenomenon is not modeled).

TABLE II

FEMM-2D SIMULATION PARAMETERS

Parameters Setting		View Setting	
Frequency	50Hz	Coordinates	Cartesian
Depth	250mm	Length Units	mm
Precision	1e-08	Grid Size	0,25
Problem type	Planar	Edit Action	Node
AC Solver	Newton	Pixels/Units	100

The simulation parameters used by the FEMM-2D software are shown in Table II. The model has four through holes (*430 stainless steel)* for the subsequent incorporation of screws and caps, see fig. 5. The inner diameter of the stator is $Ø_{int\_stator}$ = 178mm where the slots Z = 36 are uniformly distributed; slot area A_{slot} = 280mm^2. The conductor used was copper with a maximum current density of J = 4,9A/mm^2; placing N_{c1} = 40 turns per slot (N_{c1} number of effective turns per slot). The winding factor and fill coefficient also have been considered. These parameters are coefficients and ratios to introduce in each stator slot. The slot fill factor is assumed to *f* = 0,65. This parameter is calculated as the cross-sectional area of all conductors (number of turns) divided by the slot area.

The distribution of the coils corresponds to a symmetrical three-phase winding, in one layer and with the parameter "q" fractional (number of slots per pole and per phase). All slots are wound with 6 coils per phase, 36 slots and 5 pairs of poles to (1+1/5) slots per pole and phase. The direction of current flow through the coils, it is marked with +/- sign in the model, see Fig. 5. As is recycled machine designed to operate as a generator, the electrical circuit in the different phases corresponds to a wye connection (with accessible neutral).

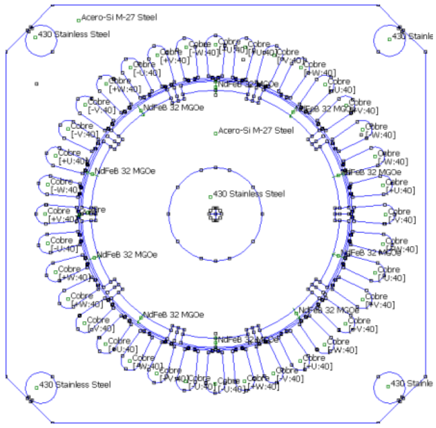


Fig. 5. Rotor geometry with magnets located outside of the rotor. PMSG radial flow. The picture shows the materials used in each area of the simulation. FEMM-2D image.

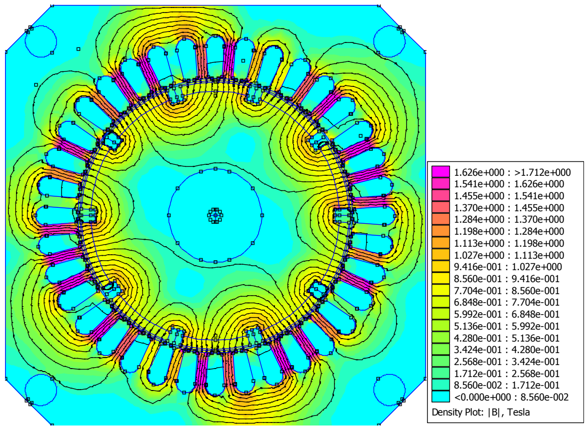
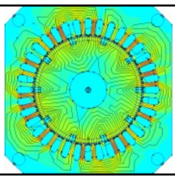
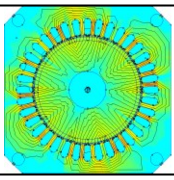
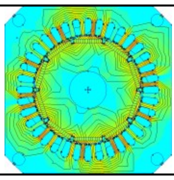
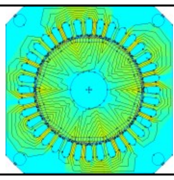
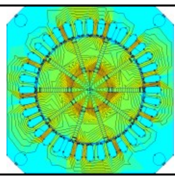
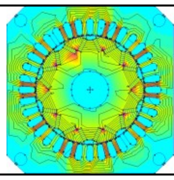


Fig. 6. Magnetic Flux Density (Field Density T). The minimum value corresponds to 2,01e-004T and the maximum value corresponds to 1,712T. FEMM-2D image.

The external dimensions of the rotor and its geometry change slightly depending on the location of the permanent magnets and their superficial distribution. At all times maintaining an air gap δ = 2mm. The rotor is constructed as a result of the stacking of silicon steel sheets, type *Si M27-steel*. While the generator shaft is composed of *430 stainless steel* material, with a diameter $Ø_{shaft}$ = 60mm; in order to provide the rotational torque required by wind or water turbine coupled. As already mentioned in previous sections, the number of pole pairs taken as a reference, corresponds to p = 5. The magnets are formed by *NdFeB*, such magnets have high coercivity and high remanence. A higher value of coercivity is more

TABLE III

COMPARISON AMONG DIFFERENT PMSG MODELS FEMM-2D.

FEMM-2D PMSG Models	External PM Rotor	Internal PM Rotor	Polar Expansions Rotor	Polygonal PM Rotor	Concentred Flux Rotor	V-Centred Flux Rotor
						
Element number	415831	261003	256243	287450	325524	415131
Nodes number	208048	130637	128246	143876	162926	207724
Flux density Upper bound	1,712T	2,684T	2,861T	3,737T	2,736T	2,763T
Flux density Lower bound	2,01e-004T	1,952e-004T	1,521e-004T	1,672e-004T	2,596e-004T	1,456e-004T
Torque from Stress Tensor about (0,0)	290,031Nm	315,776Nm	303,247Nm	297,034Nm	205,126Nm	102,779Nm
Normal flux Airgap	-1,002e-015Wb	4,931e-016Wb	-5,011e-016Wb	9,107e-018Wb	-2,133e-016Wb	-3,599e-017Wb
Magnitude of flux density $\|B\|_{max}$ airgap	1,02896T	1,06315T	1,34171T	1,1872T	1,2245T	1,4791T
Average B.n Airgap	-7,3414e-015T	3,6120e-015T	-3,6453e-015T	6,6711e-017T	-1,563e-015T	-2,621e-016T
MMF drop along contour	-1,75881 Amp-turns	-2,77282 Amp-turns	2,02465 Amp-turns	3,12316 Amp-turns	-1,89457 Amp-turns	-1,40147 Amp-turns
Average H.t Airgap	-3,22082A/m	5,07773A/m	3,68906A/m	5,71929A/m	-3,46943A/m	2,67786A/m
Force in x-direction	3,0422N	40,886N	-4,94022N	31,8511N	9,98401N	5,71728N
Force in y-direction	-6,3649N	-10,556N	8,93748N	4,28554N	2,49453N	10,4364N
Airgap block cross-section area	0,001975m^2	0,001207m^2	0,001159m^2	0,001318m^2	0,001516m^2	0,001965m^2
Rotor block cross-section area	0,016992m^2	0,017762m^2	0,017692m^2	0,017549m^2	0,017167m^2	0,016962m^2
Magnetic Field Energy airgap cross-section	55,657Joules	58,941Joules	41,902Joules	60,087Joules	41,954Joules	52,173Joules
Permanent magnet block volume	650,02cm^3	649,98cm^3	677,55cm^3	675,00cm^3	675,00cm^3	660,00cm^3

difficult to demagnetize the magnet for shares in external magnetic fields or temperature changes. A higher value is higher remanence magnetic flux can create the magnet. These types of magnets have a maximum operating temperature of 150/200ºC. In the selected case they have a maximum magnetic energy $(BH)_{max}$ = 32MGOe. Similarly it must be indicated that their relative cost is usually high.

A. An example of analysis: Permanent magnets located outside the rotor.

In this case the magnets have a geometry equivalent to a truncated circular sector, located outside the rotor (see Fig. 5). The direction shown by the green arrows indicate their polarity (north or south). As shown in the figure, the air gap $\delta \neq$ constant, there is a small gap between the permanent magnets that form the slotted rotor (air). These slots are designed to increase the overall reluctance in order to reduce the leakage flux generated by the permanent magnets. In this model, the mesh has a total number of 208048 nodes and 415831 elements (see external PM rotor FEMM-2D model in Table III).

Figure 6 shows the set of the field lines between the stator and rotor in the generator proposed (magnets on the outer surface of the rotor). In addition, the magnetic flux density value (flow density) at each point, in color map format, is also indicated.

Similarly Fig. 7 shows the magnetic flux density waveform obtained in the air gap *B.n normal Flux density*; where it can be seen the number of poles located in the rotor (2p = 10) represented by the protuberances of the wave. The induction waveform contains different peaks that represent the step between different slots (36 stator slots); due to the variation of the reluctance in the system. To determine the torque on the shaft in the model proposed (external PM rotor), a circle is performed on the inside of the air gap $\delta = 2$mm; by computing the line integral over this closed path, the Internal

Electromagnetic torque is obtained (*Torque from Stress Tensor*). The FEMM-2D software provides the following result: Torque from Stress Tensor about (0,0) T = +290,03Nm, see Table III.

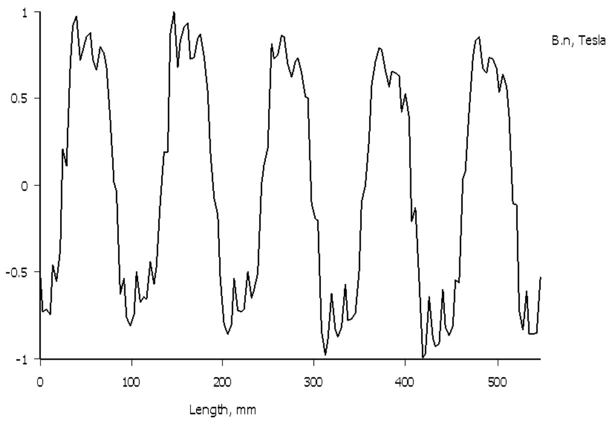


Fig. 7. Induction waveform in the air gap (B.n Normal Flux Density). FEMM-2D software Graphic.

TABLE IV
DATA PROVIDED BY FEMM-2D SOFTWARE FOR U, V AND W COILS.

	+U Coil	+V Coil	+W Coil
Total Current	22,50A	-11,25A	-11,25A
Voltage Drop	118,543V	-59,271V	-59,271V
Flux Linkage	-0,0681Wb	0,8121Wb	-0,6539Wb
Flux/Current	-0,00302H	-0,07219H	0,05813H
Voltage/Current	5,2685Ω	5,2685Ω	5,2685Ω
Power	2667,22W	666,80W	666,80W

Through analysis of the data provided by the FEMM-2D software it is possible to know the value of the most characteristic parameters in different phases, such as voltage and current induced. Table IV represents an example of the results provided by FEMM-2D software; the values correspond to the three coils referred +U, +V and +W.

B. Comparison PMSG Models.

Table III shows the results provided by the FEMM-2D software for each type of basic configuration of the rotor. In all cases, the objective has been to keep constant the permanent magnet volume $vol_{pm} = 675cm^3$. Thus it has been possible to compare parameters such as: element number, equation number, flux density, rotor cross-section, torque and force, air gap, etc.

Figures 8 and 9 show the induction waveform in the air gap (*B.n Normal Flux Density*), for each model studied. Geometric models as V-Centred Flux Rotor and Polar Expansions Rotor provide an induction waveform in the air gap of greater magnitude (keeping constant the volume of material NdFeB), see Table III. Data Magnitude of flux density $|B|_{max}$ air gap: Polar Expansions Rotor: $|B|_{max} = 1{,}34T$; V-Centred Flux Rotor $|B|_{max} = 1{,}48T$.

C. Brief Comments.

This paper has presented a three-phase asynchronous motor and its transformation to a small permanent magnets synchronous generator. The purpose is to develop a low cost generator for small wind turbine or small hydro power. Different rotor geometries have also been raised and studied: constant and variable air gap, rotor models with polar expansions and concentrated flow, etc. Geometry, section and location of permanent magnets on the rotor have also varied between the different PMSG models in the FEMM-2D simulations.

The simulation models have been developed in 2D Planar geometry (frequency 0Hz, static problem) with a precision 1,0 e-008 and depth of 250mm; allowing easily modify the parameters in the different models of electric generators raised. The purpose was to obtain some results and characteristics of the permanent magnet synchronous generators without the need for their physical construction. FEMM-2D v4.2 ×64bit is the finite element software used. OctaveFEMM v1.2 User's Manual has been used for data management. This program is free software and was developed by David Meeker.

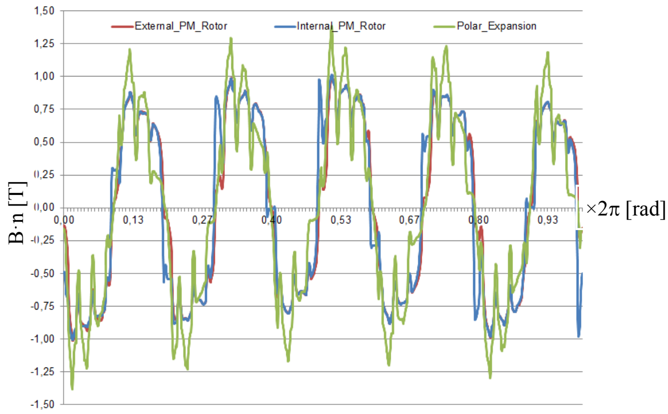


Fig. 8. Induction waveform in the airgap, B.n Normal Flux Density. Models: External PM Rotor, Internal PM Rotor and Polar Expansions Rotor. FEMM-2D software Data.

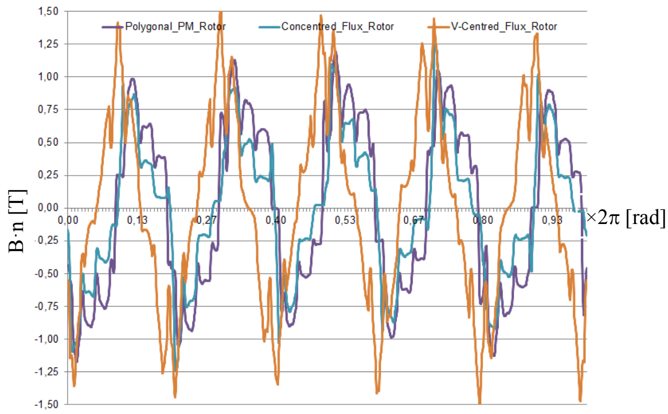


Fig. 9. Induction waveform in the airgap, B.n Normal Flux Density. Models: Polygonal PM Rotor, Concentred Flux Rotor and V-Centred Flux Rotor. FEMM-2D software Data.

Table III shows that models based on polar expansions $\delta \neq cte$ (Polar Expansions Rotor and V-Centred Flux Rotor) have a better performance. Induction waveform obtained in the air gap in the different cases can be approximated as a sine wave (although with a high degree of deformation and hence a high harmonic content). Thus a complete periodic waveform is obtained every 1/5 turn (2p = 10). The frequency depends on the speed of the wind or hydro turbine, according to the case applied (variable speed generation).

For practical purposes, the generation to variable speed has not major problems (sinusoidal or square waveform of variable frequency). AC/DC converter (rectifier) transforms the waveform of variable frequency in a DC bus. A DC/DC Boost converter increases the voltage in the original bus. Subsequently a DC/AC converter provides a sinusoidal phase voltage and frequency equivalent ($V_{AC}|_{rms} = 230V$, $f = 50Hz$). The objective is the integration of hybrid energy conversion systems in microgrids and the development of small stand-alone systems in rural environment. Conventional PMSG-based wind generation system is shown in Fig. 10.

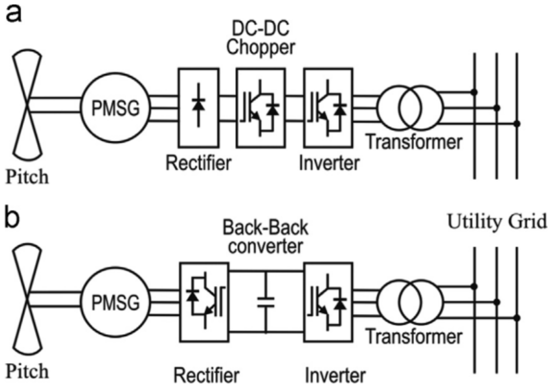


Fig. 10. PMSG-based wind generation system: (a) diode front end system, (b) full rated back-to-back converter system.

The estimated cost for the transformation of the electric motor to the generator (the stator windings do not have to be modified) depends on the level of machining required by the rotor. The cost of the permanent magnets to assemble in the rotor is approximately 385€ in each of the options (depends on the manufacturer). The initial volume of magnets has been considered as a constant parameter in the model, since design optimization is sought. While the machining cost the rotor increases considerably depending on the complexity of the selected design; being external & internal PM rotor model the most economical options.

4. Conclusion

This paper studies the feasibility of using small electrical machines (e.g. automotive alternator, induction motors of domestic applications or electrical motors of some industrial application) as low cost generator for small wind turbine or small hydro power. The objective is the integration of hybrid energy conversion systems and development of small microgrids. The analysis was performed using FEMM-2D simulation software, which is based on finite element method. Also it has been shown a comparison among different topologies of permanent magnet synchronous generator PMSG. Although complex and sometimes time consuming, numerical analysis has a great value as it can provide information prior to building the machine. Moreover, it allows access to local and instantaneous values (such as magnetic flux density, local force density, induced flux in a coil side, etc.), which are sometimes difficult to obtain by experimental testing.

The use of permanent magnets based NdFeB is the best solution for low-speed PMSGs, both in terms of weight and size in the design of the generator prototype. Although the main disadvantage of permanent magnet synchronous generators is the high cost of magnets and the demagnetization risk at high temperature. The permanent magnet alternator-based turbine system is therefore a low cost solution designed to ensure that wind energy is available in areas where the current cost of the technology is prohibitive.

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