Optimal adaptation of the wind rotor to the permanent magnets synchronous generator of a small passive wind turbine

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***Abstract*— This work deals with the problem of optimal design of a fully passive small wind turbine chain whose main components are the wind rotor and the generator. This involves optimizing the synchronous generator with permanent magnets, and secondly ensuring mutual adaptation between the wind rotor and the optimized generator, so that the assembly is more attractive and more sensitive to the conversion of wind energy. Thus, we are interested in maximizing the electromagnetic torque of the machine while minimizing the total cost of the active part of the machine. Then we adapted the characteristics of the wind rotor to those of the optimized generator. The originality of this work was to find, for a given performance generator, the radius of the sail according to the wind potential of the location. A bi-objective optimization based on the genetic algorithm allowed us to obtain good results. The analysis of these results shows that for an optimized generator there is a radius of the wing adapted to a given wind speed.**

Keywords— Optimal adaptation, Passive wind turbine, Permanent magnet, Synchronous generator.

I. Introduction

The energy needs of today's world are growing steadily because of overpopulation all over the planet. Also, the increase of the pollution which entails the increasing industrialization of the majority of the countries, constrains the development of clean and harmless renewable energies [1].

Thus, the efforts are oriented much more towards the development of the production of solar and wind energy either locally or for large scale production. Due to the abundance of these resources (sun and wind) and their ecological character (no emissions of greenhouse gases and waste), they are considered as the energies of the future. In this context, our work focuses on the wind energy sector and the tools for its exploitation and development.

Wind turbines convert the kinetic energy of the wind into mechanical energy, and then into electricity. The blades of the wind rotor capture some of the energy contained in the wind and transfer it to the hub which is fixed on the shaft of the wind turbine. The latter then transmits the mechanical energy to the electrical generator which transforms the latter into electrical energy. Therefore, the generator and the wind rotor are revealed as the main elements of a wind chain whose researchers and industrialists are exploring solutions to optimize their performances while taking into account the cost of manufacturing.

When designing an electrical drive, it is interesting to apply optimization methods to determine the optimal values of the dimensioning variables according to the constraints of the specifications [2]. Thus, our work focuses on maximizing the electromagnetic torque that contributes to the improvement of the output power while minimizing the total cost of the active part of the generator on the one hand, and to ensure a mutual adaptation between the rotor wind turbine and the optimized generator on the other hand. The main objective is to find the sail characteristics according to the wind profile for a given performance generator. For that, a multi-objective optimization approach is used, of type NSGA II genetic algorithm.

II. Méthodologie

A. *Passive wind string*

The small-power passive wind chain that is the focus of our work is composed of a three-blade direct-drive turbine driving a Buried Permanent Magnets Synchronous Generator (BPMSG). The three-phase generator current is rectified by a diode bridge that delivers directly to a 48 V TBT battery bus as shown in Fig. 1 [3].

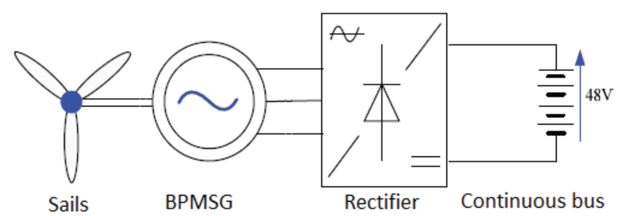

Fig. 1. Global architecture of the passive wind chain

For this architecture, the wind energy captured by the turbine is maximized through a "natural adaptation of impedance" of the entire wing-generator-bridge of battery-bus diodes. Unlike conventional active systems that adapt with MPPT (Maximal Power Point Tracking) type control. Mutual adaptation of the sizing of elements in the system is very important to maintain energy efficiency despite wind changes.

Thus, in the absence of power electronics and control by MPPT, the device is effective only if the adaptation of the components is optimal. We assume that the parameters of the turbine are manipulable. The diode rectifier is a "passive" element that has few or no parameters to size. In addition, if the battery bus is fixed at 48 V, that is to say the standard value of the storage systems inserted in the autonomous or island devices, then the device that remains to be optimized to improve the recovered power. is circumscribed around the generator of the wind energy conversion chain. As the problem is defined, it will only be necessary to adapt the

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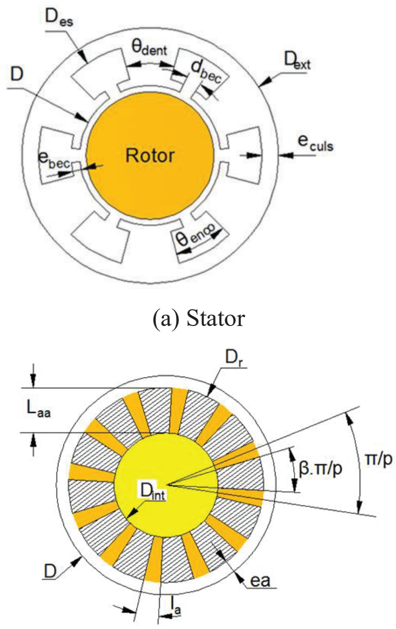
parameters of the turbine to the generator to capture the maximum wind energy.

B. Modeling the BPMSG

Our study focuses on the structure of permanent magnet synchronous machine with flux concentration. The principle of this structure is to increase the magnetic induction in the gap compared to the residual induction of the magnets. The geometrical parameters of the two essential parts (the stator and the rotor) are grouped together in Fig. 2.



(a) Stator

(b) Rotor

Fig. 2. Stator and rotor of the BPMSG

The geometrical parameters of the BPMSG are defined in Table I.

Table I: Geometrical dimensions of the BPMSG

Designations	Symbols
Bore diameter of air-gap	D
Diameter of the bottom of notches	D_{es}
External diameter of the stator	D_{ext}
Peripheral diameter of the rotor	D_r
Internal diameter of the rotor	D_{int}
Width of the magnets	l_a
Radial length of the magnets	L_{aa}
Thickness of the air-gap	ea
0ening step of the poles	β
Angular width of a tooth	θ_{dent}
Angular width of a notch	θ_{enco}
Thickness of the nozzle	e_{bec}
Distance between two nozzles	d_{bec}
Active length of the machine	L

Analytical expression of electromagnetic torque

An electric machine transforms mechanical energy into electrical energy and vice versa. The torque in a machine is proportional to the rotor volume and also to the value of the current [4]. In the general case, one must take into account the saliency of the machine, with inductances of axis d and axis q. It is known that the variation of inductance has an influence on the electromagnetic torque of the machine with the existence of the reluctance torque by the saliency. Then, a torque expression that applies to all conventional synchronous machines or inverted saliency when operating linearly with sinusoidal currents is given by [2]:

$$C_{em} = m.p\left[\varphi_v I_s \cos\psi - \frac{1}{2}(L_d - L_q)\, I_s^2 \sin 2\psi\right] \qquad (1)$$

Where m is the phase number, p is the number of pole pairs, Φ_v is the effective value of the no-load flux in the air gap, I_s is the effective value of the phase current and ψ is the wedging angle between the vectors of the current I_s and the magnetomotive force E.

In the case of synchronous machines with permanent magnets, where $L_d < L_q$, the reluctance torque can be added to the synchronous torque to increase the value of the resulting torque if the sign of $\sin 2\psi$ is positive.

Expression of the cost of the active part of the machine

The masses of the different parts of the machine are decisive parameters because they proportionally define the manufacturing cost of the machine. They are simply expressed as a function of the volume of the active part considered and the density of the material used [5].

- ***Stator mass***

The stator consists of a stack of ferromagnetic sheets constituting the thickness of the cylinder head e_{culs} and the teeth.

The cylinder head is likened to a hollow cylinder of inside diameters D_{es} and outside D_{ext}. As a result, the volume of the stator yoke V_{cs} is given by:

$$V_{cs} = \pi L e_{culs}(D_{es} + e_{culs}) \qquad (2)$$

The teeth are straight, that is to say that the width of a tooth remains constant over its entire height (excluding isthmus). The tooth is then defined by its angular width outside the isthmus θ_{dent} and its height h_d. The tooth root or the isthmus is defined by its angular expansion θ_{ep}, its width at the center of the bloom h_2 and its width at the notch opening $h_2 + h_3$. The angular expansion of the tooth root is given by:

$$\theta_{ep} = \frac{2\pi}{N_{enco}} - \frac{2b_2}{D} \qquad (3)$$

The volume of the feet of teeth is :

$$V_{pdent} = N_{enco} D L \theta_{ep}\left(\frac{2h_2 + h_3}{4}\right) \qquad (4)$$

The volume of the teeth off isthmus is given by:

$$V_{hdent} = \frac{\pi L}{2}\left[D\left(h_d - (h_2 + h_3)\right) + h_d^2 - (h_2 + h_3)^2\right] \qquad (5)$$

The total volume of the stator is equal to:

$$V_{stator} = V_{cs} + V_{pdent} + V_{hdent} \qquad (6)$$

The mass of the stator steel is then

$$M_{stator} = \rho_{acier} V_{stator} \quad (7)$$

- ***Copper mass***

We evaluate the length of a turn to calculate the winding mass. Each turn can be broken down into two parts: two active conductors in the notches and two outer connections to the notches that form the coil heads.

In the absence of inclination of the notches, the length of the active part is equal to the length of the sheet package. The volume of copper occupying the notches is:

$$V_{cu\_enco} = \pi L h_d K_R \left(h_d + \frac{D}{4}\right) \quad (8)$$

With K_R defining the filling coefficient of the notches.

The volume of the reel heads is calculated from their length and is expressed by:

$$V_{cu\_tête} = \pi L_{tête} h_d \frac{D_{es}\theta_{enco}}{2} N_{enco} K_R \quad (9)$$

Where N_{enco} represents the number of slots in the stator.

Finally the total volume of copper in the machine is given by:

$$V_{cuivre} = V_{cu\_enco} + V_{cu\_tête} \quad (10)$$

The total mass of copper is then:

$$M_{cuivre} = \rho_{cuivre} V_{cuivre} \quad (11)$$

Where ρ_{cuivre} refers to the density of copper.

- **Rotor mass**

Compared to the electromagnetic operation of the machine, the rotor does not need to be a full cylinder. It should just be of sufficient thickness to ensure the looping of the field lines without exceeding a given level of induction in the material.

As shown in figure 1, the flux-concentration buried magnet rotor has a relatively complex geometry. The ferromagnetic part is a cylinder head of external diameter D_r and inner diameter D_{int} and thickness e_{culr}. This is equal to the length of the magnets.

Taking into account these considerations, the volume of the rotor yoke is given by:

$$V_{cr} = \frac{\pi L}{4}(D_r^2 - D_{int}^2) \quad (12)$$

All the magnets have a parallelepipedal shape of radial length L_{aa}, peripheral thickness l_a and axial length L. The volume of the magnets is deduced therefore by the relation:

$$V_{aim} = 2p l_a L L_{aa} \quad (13)$$

The tree volume is given by:

$$V_{arb} = \frac{\pi L D_{int}^2}{4} \quad (14)$$

The total rotor volume is then:

$$V_{rotor} = V_{cr} - V_{aim} + V_{arb} \quad (15)$$

The mass of the rotor steel is given by:

$$M_{rotor} = \rho_{acier}(V_{cr} - V_{aim} + V_{arb}) \quad (16)$$

The mass of permanent magnets is given by:

$$M_{aim} = \rho_{aim} V_{aim} \quad (17)$$

The total mass of the steel is:

$$M_{acier} = M_{stator} + M_{rotor} \quad (18)$$

The total mass of the generator is deduced by the relation:

$$M_g = M_{acier} + M_{cuivre} + M_{aim} \quad (19)$$

Finally, the active cost of the generator is given by :

$$C_{actif} = P_{acier} M_{acier} + P_{cuivre} M_{cuivre} + \rho_{aim} M_{aim} \quad (20)$$

The densities and prices of the materials used are summarized in Table II.

Table II: Density and Cost of Materials [6]

Materials		Density (kg. m^{-3})	Cost (euro / kg)
Steel		$\rho_{acier} = 7850$	$P_{acier} = 10$
Copper		$\rho_{cuivre} = 8920$	$P_{cuivre} = 6$
Permanent magnets	**NdFeB**	$\rho_{aim} = 7500$	$P_{aim} = 150$
	Ferrite	$\rho_{aim} = 5000$	$P_{aim} = 5$

C. *Model of the wind turbine*

Wind energy conversion systems convert the kinetic energy of the wind into mechanical energy through the wind turbine and into electrical energy via a generator. The energy dE of an air column of length dl, of section S, of density ρ animated with a velocity V_v can be written [7,8]:

$$dE = \frac{1}{2}\rho\, S\, dl\, V_v^2 \quad (21)$$

Assuming that $dl = V_v\, dt$, we draw the expression of the power P of the mass of air passing through the section S and moving at the speed V_v:

$$P = \frac{dE}{dt} = \frac{1}{2}\rho\, S\, V_v^3 \quad (22)$$

In reality, the power recovered by a wind turbine is only a percentage of this power. Thus, the reduced speed coefficient λ is a specific factor of the wind turbines, it is defined as the ratio of the tangential speed at the end of the blades ΩR_v on the instantaneous wind speed V_v:

$$\lambda = \frac{\Omega\, R_v}{V_v} \quad (23)$$

As we have emphasized above, it is not possible to fully capture the power P supplied by the air mass, this would imply a zero wind speed after the sensor member. The power factor is defined as follows:

$$C_p = \frac{P_{éol}}{P} = \frac{P_{éol}}{\frac{1}{2}\rho\, S\, V_v^3} \quad (24)$$

With

$P_{éol}$: the power captured by the wind turbine in (W);

S: the area swept by the wind turbine in (m^2);

ρ: the density of the air in ($kg.m^3$), the value of which depends on the height where the turbine is installed.

Thus, the wind power is determined analytically by the following formula:

$$P_{éol} = \frac{1}{2}\,\rho\, C_p\, S\, V_v^3 \quad (25)$$

The torque coefficient is very useful in order to calculate the value of the torques produced for different operating points, in particular at a zero speed of rotation. Indeed, at startup, there is a torque on the shaft due to the force of the wind on the blades while the power is zero, which corresponds to a value of C_p zero. The expression of the wind torque is given by:

$$C_{éol} = \frac{1}{2}\,\rho\,\pi\, C_T\, R_v^3\, V_v^2 \quad (26)$$

With $C_T = \frac{C_p}{\lambda}$, the coefficient of the couple.

D. *Mechanical coupling model between the turbine and the generator*

The structural and dynamic properties of the transmission chain are to be considered in the design phase because they significantly affect the quality of the electrical energy generated, at least in an intermediate harmonic frequency range. However, the mechanical representation of the whole wind chain is very complex. The mechanical elements of the aerogenerator and the forces experienced or transmitted through these elements are numerous. It is therefore necessary to make a choice of elements and magnitudes related to these elements that one wishes to integrate into the model.

In this study, we adopted a simplified model, which characterizes the mechanical behavior of the chain as a whole as shown in Fig. 3 [7].

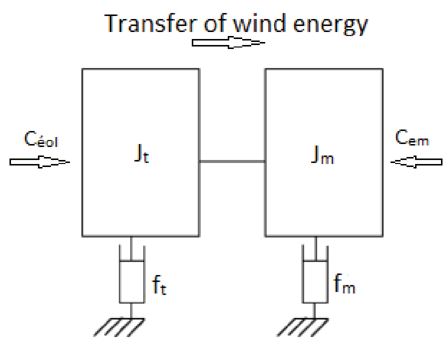


Fig. 3. Mechanical coupling between the turbine and the generator

The differential equation that characterizes the mechanical behavior of the turbine and generator set is given by [7, 9, 10]:

$$(J_t + J_m)\frac{d\Omega}{dt} = C_{éol} - C_{em} - (f_t + f_m)\Omega \quad (27)$$

Where J_m is the inertia of the machine, f_m the coefficient of friction of the machine, J_t the inertia of the turbine, f_t the coefficient of friction of the blades, Ω the speed of rotation of the turbine and $C_{éol}$ the static torque supplied by wind.

We only have the mechanical parameters of the machine and the inertia of the wing. That's why in our application, it is only considered the coefficient of friction associated with the generator (that of the wing is not taken into account).

$$\begin{cases} J_t + J_m = J_t \\ f_t + f_m = f_m \end{cases} \quad (28)$$

As a result, the model that characterizes the mechanical behavior of the wind chain is given by the following differential equation:

$$C_{éol} = J_t\frac{d\Omega}{dt} + C_{em} + f_m\Omega \quad (29)$$

In this study, we are interested only in the "initial established regime", that is to say that the performances of the system are calculated in regime starting from an initial speed of rotation equal to the speed of rotation given as a result of the wind profile.

Finally, the mechanical equation of the wind chain in static mode (neglecting the effect of inertia) can be put in the form:

$$C_{éol} = C_{em} + f_m\Omega \quad (30)$$

Thus, for a given optimized torque generator, the radius of the wing as a function of the wind speed can be in the form:

$$R_v = \left(\frac{2(C_{em} + f_m\Omega)}{C_T\rho\pi V_v^2}\right)^{\frac{1}{3}} \quad (31)$$

E. *Formulation of the BPMSG optimization problem*

In an optimization problem, three notions must be defined. These are the input parameters comprising the various input parameters that are set during the optimization process, the optimization variables that are chosen according to their influence on the objective function and the optimization constraints.

The lists of optimization variables are given in Table III.

Table III: BPMSG Optimization Variables

Variables	Names	Bounds	
l_a	Width of magnets (mm)	3	10
L_{aa}	Radial length of magnets (mm)	30	100
D	Bore diameter (mm)	200	600
L	Active machine length (mm)	150	350
θ_{dent}	Angular width of the teeth (rad)	$\pi/10$	$\pi/30$
e_a	Thickness of the gap (mm)	1	3
p	Number of pole pairs	3	10
N_{ce}	Number of conductors per slot	4	10
N_{enco}	Number of notches	10	30

In addition, the BPMSG must be sized to maximize its performance while reducing the cost of manufacturing. It is therefore to maximize the electromagnetic torque and minimize the total cost of the active part of the machine. For this optimization, two feasibility constraints are explored:

• The first equality constraint expresses the correctness of the dimensions inside the stator. The bore diameter D must correspond to that of the inside diameter, the radial length of magnets L_{aa} and the thickness of the air gap e_a.

The second inequality constraint makes it possible to have the angular width of a tooth smaller than that of a stator slot. This contributes to the minimization of the mass of the load.

Thus, one can write the problem of optimal design of the BPMSG in the form of a problem of multicriteria optimization and under constraints:

$$\begin{cases} minimize(C_{em}^{-1}, C_{actif}) \\ D - 2(L_{aa} + e_a) = 0{,}03 \\ \dfrac{\pi}{N_{enco}} - \theta_{enco} \leq 0 \end{cases} \quad (17)$$

III. Results and Discussion

We chose to apply the NSGA II genetic algorithm for solving the optimization problem. It offers a good compromise between exploitation and exploration of the research space and is implemented in the Matlab environment.

The parameters of the genetic algorithm have been set empirically. Thus, the starting population is composed of 160 individuals, the probability of crossing and that of mutation are fixed respectively at 0.6 and 0.05. We also set 400 as the maximum number of objective function ratings as the stopping criterion.

Fig. 4 to 7 illustrate the Pareto fronts of the optimal solutions obtained respectively for Ferrite and NdFeB magnets and for different phase currents in the case of a two-criteria optimization; the opposite of the electromagnetic torque on one side, and the total cost of the active parts of the BPMSG on the other.

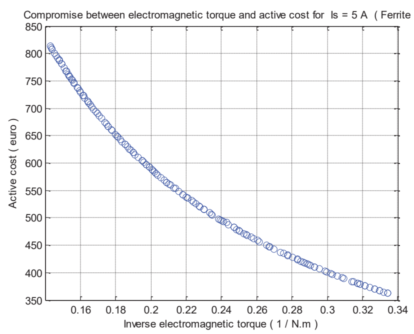


Fig. 4. Compromise between electromagnetic torque and active cost for $I_s = 5\ A$ (Ferrite).

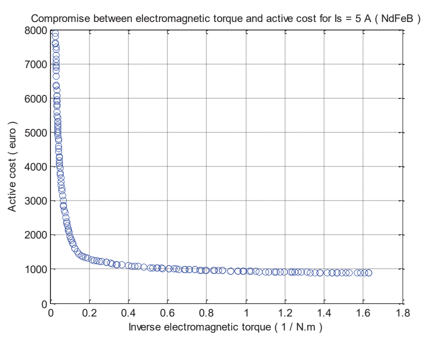


Fig. 5. Compromise between electromagnetic torque and active cost $I_s = 5\ A$ (NdFeB).

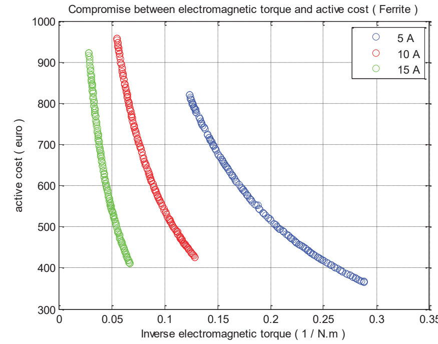


Fig. 6. Compromise between electromagnetic torque and active cost parameterized by the phase current (Ferrite).

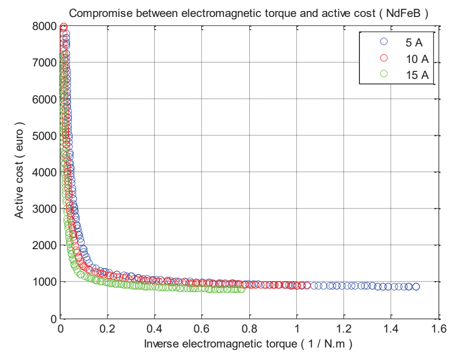


Fig. 7. Compromise between electromagnetic torque and active cost parameterized by the phase current (NdFeB).

It is interesting to observe the optimization results by varying the type of magnet. Each point of the curves of Fig. 4 to 7 represents an optimized solution with well-defined geometrical and electrical magnitudes. The knowledge of these optimization variables makes it possible to analytically deduce the performance parameters of the equivalent electric circuit of the machine.

These Pareto curves make it possible to determine the best compromise between the electromagnetic torque and the active cost. They also allow the designer to choose the best solution, which is in most cases in the bend of the curve.

It is easily noted that the electromagnetic torque increases with the phase current while the active cost of the generator decreases. Ferrite is the type of magnet best suited to the structure of the generator chosen for our study. It has a higher performance / cost ratio compared to the expensive NdFeB magnet.

In addition, the principle of the structure of the BPMSG which is the object of our work is to increase the magnetic induction in the air gap, sometimes doubling the magnetization remanent magnets, so the risk of magnetic saturation is very high for NdFeB. On the other hand, Ferrite, by its weak residual induction, is revealed as a better candidate for the GSAPE with concentration of flux.

For an optimized BPMSG configuration, the characteristics of the wind turbine can be adapted according to the wind profile. This is simply to find the radius of the sail as a function of the wind speed as shown in Fig. 8 and 9.

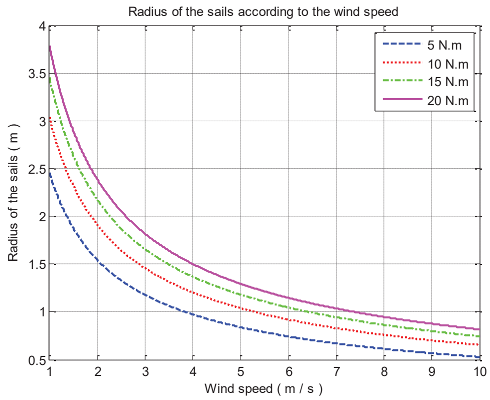


Fig. 8. Radius of the wing as a function of the wind speed parameterized by the electromagnetic torque.

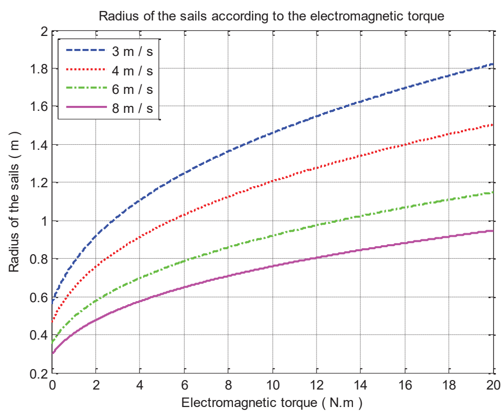


Fig. 9. Radius of the wing as a function of the electromagnetic torque parameterized by the wind speed.

For the curves of Fig. 8 and 9, it can be noted that the radius of the wing decreases with the wind potential that is to say the wind speed but increases with the electromagnetic torque of the generator. Note also that, for a given wind speed, the radius of the wing increases with the speed of rotation of the turbine. But when the speed of rotation is fixed, the radius varies in the opposite direction of the variation of the speed of the wind.

IV. Conclusion

This article is mainly based on the optimization of flux concentration BPMSG. The objective is to find a better technico-economic performance i.e. a good electromagnetic torque for an affordable manufacturing cost. From the Pareto fronts obtained for the two types of magnet (Ferrite and NdFeB), we find better compromises between the electromagnetic torque and the cost. The results obtained with Ferrite have a good energy and economic performance. For the same torque, the ferrite provides a satisfactory cost compared to the NdFeB magnet which gives a very high cost.

Then, the choice of an optimal solution makes it possible to adapt the radius of the wind turbine to the optimized generator taking into account the wind potential (wind speed) of the location of the wind turbine.

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