ENERGY OPTIMIZATION OF A WIND SYSTEM WITH SMALL POWER BY FUZZY MPPT ALGORITHM

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ABSTRACT
This work is devoted to the energy optimization of a wind power system based on synchronous permanent magnet machine. A strategy MPPT (Maximum Power Point Tracking) with fuzzy logic is used in order to obtain a maximum energetic output at each speed of wind. The control of the generator is based on a vector control with structure PWM. A speed regulation whose reference is defined according to fuzzy algorithm MPPT is added with this structure. A sample of the wind measured on real site (Antsiranana Madagascar), during a given time is used for simulation. The obtained results show the effectiveness of the adopted strategy. Indeed, one could collect 97% of the maximum energy which can be extracted from the profile of the considered wind. The energy gain obtained by the MPPT device is 13% compared to the operation with velocity of constant reference.

Keywords: energy optimization, wind power system, MPPT, fuzzy logic, synchronous permanent magnet machine, vector control.

1. INTRODUCTION
Renewable energies systems or RES, (hydraulic, solar, wind, geothermic…) constitute only 20% of electrical production in the world. Excluding the hydroelectric one, this rate falls to 2% (B. Multon *and al* 2004; C. Alonso 2010).
At the horizon of 2020, the European Economic Community has triple objectives to increase the share of the renewable energies to a total value of 20%, to decrease pollution of 20% and to save 20% of energy. In Madagascar, the use of these RES is now necessary to resolve pollution problems and to bring economic solutions taking into account problems of fuels whose coasts do not cease increasing.
Currently, wind power systems take more and more place in the production of electricity. Parallel to the system with great power, those with small one begin to increase for isolated site. This case is well adapted for more countries like Madagascar. It is the reason which justifies the choice of this technology for the present paper.
More chains of wind power production use synchronous permanent magnet machine. In order to maximize the efficiency of the aero generator, various solutions are examined.
For the wind turbine, a characteristic, the power coefficient according to the reduced speed, Cp (λ), which depends on the parameters of construction, makes it possible to obtain the curve of power. This one requires an adaptation of the mechanical load in order to ensure a good efficiency: it is the maximization of the power or MPPT.
The generator is connected electrically to a static inverter. This converter can have a structure which depends on the strategies of research of the maximum point of power. Two families of these strategies exist for this purpose (Mirecki 2005):

1. An indirect control of the wind power using a chain of conversion containing bridge of diodes and a chopper. This structure requires the knowledge of the Cp (λ)
2. A speed or torque control starting from the structure of rectifier MLI and a mechanical sensor (velocity and position). In this way, various strategies for optimal point of power are proposed, specially the one that the characteristic Cp (λ) is not needed.

In this paper, it is assumed that the characteristic Cp (λ) is unknown. An algorithm, based on fuzzy logic, is used to control the machine in order to extract the maximum of the wind.

2. WIND GENERATOR MODELLING
The wind generator includes the turbine with variable speed which is coupled directly with a synchronous permanent magnet connected to a continuous bus by a converter MLI. The system is represented in figure 1.

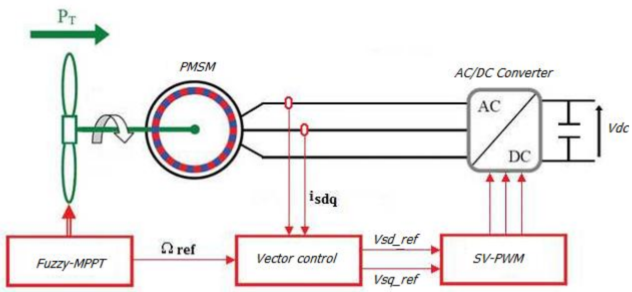

Figure 1: Structure of the wind generator

2.1. Mechanical equations

The differential equation which characterizes the mechanical behaviour of the unit harnesses – generator is given by (Cardenas and Dobson 1996; Gerqud 2002):

$$(J_T + J_m)\frac{d\Omega}{dt} = C_{eol} - C_{em} - (f_m - f_t).\Omega \qquad (1)$$

Where J_T et J_m are respectively the inertia of the harnesses and the generator, f_m friction coefficient of the machine, f_t friction coefficient of the pales and C_{eol}, the static torque given by the wind generator.

The torque given by the wind generator is:

$$C_{eol} = \frac{C_p(\lambda).\rho.R^2.H.V_v^2}{\lambda} \qquad (2)$$

Where ρ is the density of the air, V_v the wind speed, R radius of the aerofoil and H its height.

2.2. Synchrounous machine modelling

The modelling of the PMSM is already the subject of many works. A model in the Park reference is used in this work.

The stator dq-winding Voltages can be expressed as follows (Sturtzer and E. Smichel 2000; Abdessemed and M. Kadjoudj 1997):

$$V_{sd} = R_s.i_{sd} + L_s\frac{di_{sd}}{dt} - L_s.\omega.i_{sq} \qquad (3)$$

$$V_{sq} = R_s.i_{sq} + L_s\frac{di_{sq}}{dt} + L_s.\omega.i_{sd} + K_A.\omega \qquad (4)$$

Where, i_{sd}, i_{sq} are the stator currents, V_{sd} and V_{sq}, the stator voltages, R_s and L_s denote respectively stator and inductance cyclic stator, p and ω are the number of pair of poles and the speed of the equivalent dq-windings (in electrical rad/s) in order to keep the d-axis always aligned with the stator magnetic axis (Kimbark 1995), K_A is a coefficient characterizing the machine(maximum flux megnet).

The speed ω is related to the actual rotor speed Ω as:

$$\omega = p.\Omega \qquad (5)$$

In the normal speed range below the rated speed, the reference for the d-winding current is kept zero (ids = 0). The electromagnetic torque can be expressed as follows:

$$C_{em} = p.K_A.i_{sq} \qquad (6)$$

The simulation block diagram for the PMSM is shown in Figure 2.

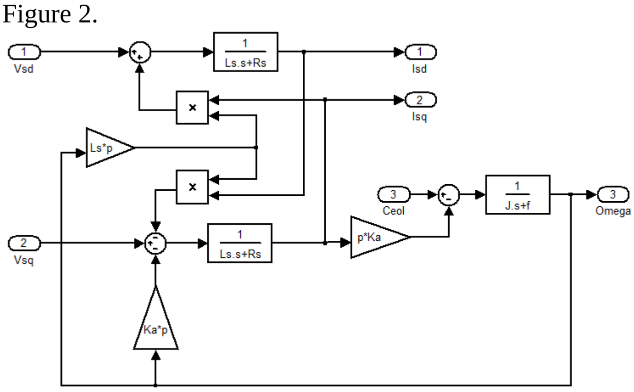

Figure 2: PMSM block diagram

2.3. Model of the rectifier with MLI

For the study of system generator-rectifier MLI, ideals switches are used for the rectifier one models the rectifier. The function of the switches is to establish a connection between alternate side and continuous bus. The states of these switches are defined like follow (A.S. Toledo 2000; Abdessemed 2011):

$$S = \begin{cases} +1 \Rightarrow \bar{S} = -1 \\ -1 \Rightarrow \bar{S} = +1 \end{cases} \qquad (7)$$

The coupling equation between of the alternative and continuous sides is given by (Belakehal and *al* 2010):

$$C\frac{dU_{dc}}{dt} = S_a i_a + S_b i_b + S_c i_c - i_L \qquad (8)$$

3. ENERGY OPTIMIZATION OF WIND SYSTEM

3.1. Power maximization method

The characteristic of the optimum capacity of a wind system is strongly nonlinear and has a shape like a bell. For each speed of wind, it is necessary that the system finds the power maximum which is equivalent to the optimal speed revolutions so corresponds to a defined load torque. The diagram of the Figure 2 gives an example of characteristic curves of a wind generator in the power-rotation speed plan.

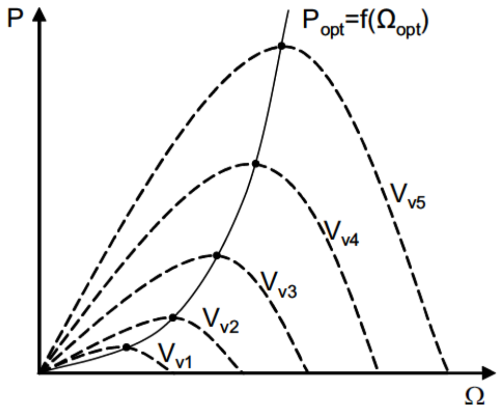

Figure 3: Characteristics in power-speed plan

The whole of the tops of these curves, which are the required optimal points, defines a curve (cubic form) known as of optimum power. Ideally, this curve must be followed constantly during the operation of the wind system.

If the knowledge of these characteristics is missing, rules of behavior to ensure the convergence to the optimal point are relatively simple to establish. These rules depend on the variations of power ΔP and speed ΔΩ.

Example:

IF ΔP > 0 AND ΔΩ > 0 THEN ΔΩref > 0

From the existence of these linguistic rules, the use of a MPPT device based on fuzzy set can be applied

3.2. The MPPT with Fuzzy Logic

The MPPT device based on measurement of electrical power (ΔP) in the DC bus and speed rotation (ΔΩ) variations gives the reference speed $\Delta\Omega_{ref}$ according the equations:

$$\Delta P = P_k - P_{k-1} \qquad (9)$$

$$\Delta\Omega = \Omega_k - \Omega_{k-1} \qquad (10)$$

$$\Omega_{ref} = \Omega_{k-1} + \Delta\Omega_{ref_k} \qquad (11)$$

Figure 3 gives an application of a research in (P- Ω) plane.

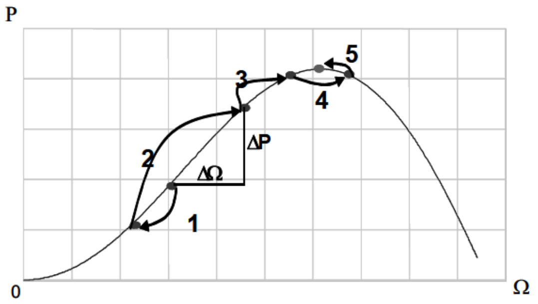

Figure 4: Principle of the MPPT operation at constant wind speed

Example:

IF (ΔP > 0 AND ΔΩ> 0) THEN ΔΩref > 0

IF (ΔP <0 AND ΔΩ > 0) THEN ΔΩref < 0

So, the change of ΔP resulting from the variation of the speed is either in the positive direction or in the negative direction. The value of ΔP can also be small or on the contrary large. From this judgement, the set point speed is increased or decreased in a small or respectively large way in the direction which makes it possible to increase the power. This command allows the research of the optimum point.

If the wind speed is not constant, the research of the maximum point of power is carried out in the way presented on Figure 5: it is noted that the same type of rules like with constant wind speed can be applied.

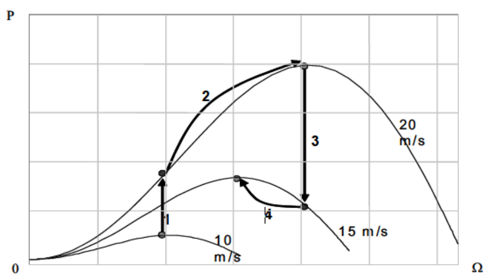

Figure 5: Principle of the MPPT at changing wind speed.

Control by fuzzy logic does not require the system modelling. However, a global knowledge of its behaviour, in closed loop for example, is needed. This knowledge must be transcribed to a form of rules.

The common scheme uses fuzzy logic method is shown in Figure 6:

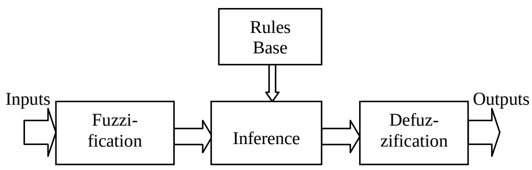

Figure 6: Basic scheme of fuzzy logic

In this case, ΔP and ΔΩ are the inputs and $\Delta\Omega_{ref}$ is the output. The membership functions of the inputs are chosen as triangular and trapezoidal and a singleton one is used for the output. The expression of the rule is then as follows:

$$\text{(If } x_1 \text{ is A) AND (} x_2 \text{ is B) THEN } S_k = C_k \qquad (16)$$

Here, C_k is a constant.

Figure 7 shows the inputs membership functions and Figure 8 gives the output membership one.

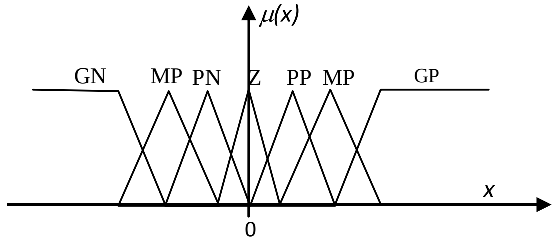

Figure 7: Inputs membership functions

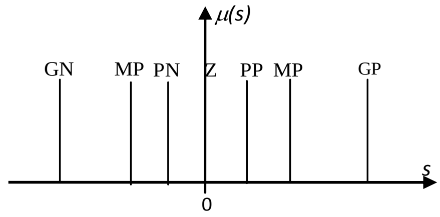

Figure 8: Output membership function

Table 1 resumes the rules base with a number of membership functions N = 7.

Table 1: Rules base

ΔP / $\Delta\Omega_{(k-1)}$	GN	MN	PN	ZE	PP	MP	GP
GN	GP	GP	MP	ZE	MN	GN	GN
MN	GP	MP	PP	ZE	PN	MN	GN
PN	MP	PP	PP	ZE	PN	PN	MN
ZE	GN	MN	PN	ZE	PP	MP	GP
PP	MN	PN	PN	ZE	PP	PP	MP
MP	GN	MN	PN	ZE	PP	MP	GP
GP	GN	GN	MN	ZE	MP	GP	GP

1. If a great increase speed involves a great increase in the power, the speed must be strongly increased.
2. If a great increase speed involves a great reduction in the power, the speed must be strongly decreased strongly to obtain a fast increase in the power.
3. If a great increase speed involves a weak increase in the power (near the optimal speed), the speed needs to be fairly increased.
4. If a null speed variation involves an increase in the power, one deduces that the wind speed is increased, it is thus necessary to increase the speed to approach the new optimal point.
5. If a null speed involves a reduction in the power, it means that the wind speed is decreased, it is thus necessary to decrease speed to approach the new optimal speed.

The central line (*ΔΩ[k-1]=ZE*) means that a variation of the power is due to a modification of the wind speed rather than to the variation of machine speed Ω. It breaks the horizontal axial symmetry of the Table 1.

In this paper, the Sugeno's methods are chosen: a singleton is used as the membership function of the rule consequent combined by max-min method for the rule evaluation. The Sugeno defuzzification is then weighted average method:

$$s = \sum \frac{\mu(s_k).s_k}{\mu(s_k)} \qquad (12)$$

4. SIMULATION RESULTS

The method consists in measuring, with a sampling time T_{MPPT}, the speed Ω, the voltage *Uc* and the current *Ic* on the continuous side and to calculate the power *P*. The power and speed variations are then deduced. Figure 9 shows the method.

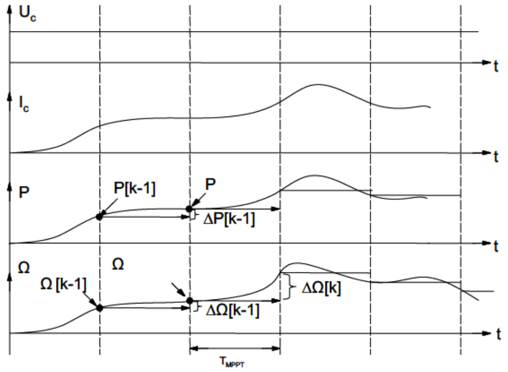

Figure 9 : Sampled inputs for the algorithm.

It may be highlighted here that measuring or calculating the power side receptor (for example battery) permits to obtain an optimization for the global system. Figure 10 shows the complete system.

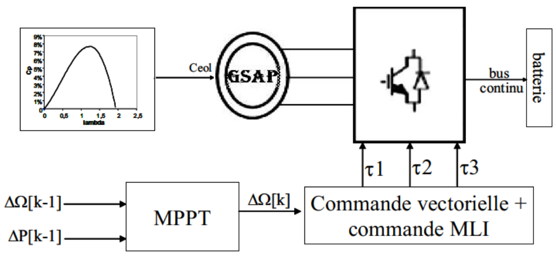

Figure 10: Complete scheme for the fuzzy -MPPT

Figure 11 gives a sample of wind speed measured on real site and used for the simulation.

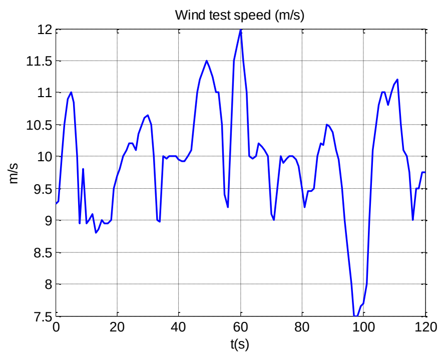

Figure 11 : Sample of the wind speed

Following figures resume the simulation results.

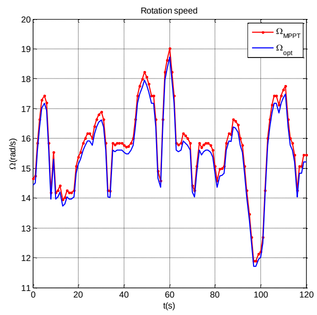

Figure 12: Speed obtained with MPPT and with λ_{opt}

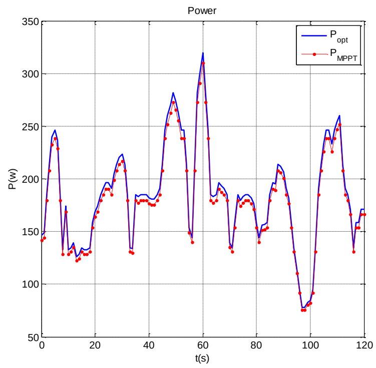

Figure 13: Power curves

The wind turbine speed determines the operation point compared to the point of maximum power. The difference between speed resulting from the MPPT and optimal speed results then in a loss into power presented on Figure13. The optimal power curve is calculated using the expression (17) and the maximized power curve corresponds at the speed resulting from the MPPT shown on Figure 12.

$$P_{opt} = \frac{1}{2} C_p^{opt} . \rho . S . V_v^3 \qquad (17)$$

Figures 13 and 14 give respectively the efficiency calculated according to the equation (18) and energies, calculated according to the equation (19).

$$\eta = \frac{P_{MPPT}}{P_{opt}} \qquad (18)$$

$$E = \int_{t0}^{t1} P(V_v) dt \qquad (19)$$

$$\Delta E = E(t_1) - E(t_0) \qquad (20)$$

$$\varepsilon_E^{\%} = \frac{\Delta E_{opt} - \Delta E_{MPPT}}{\Delta E_{opt}} 100 \qquad (21)$$

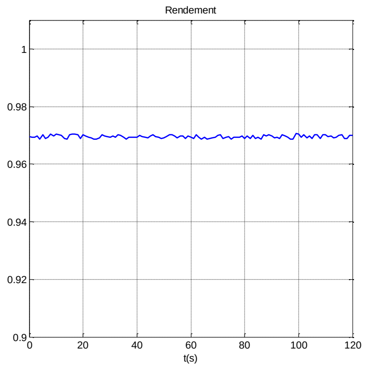

Figure 14: Effiency behaviour

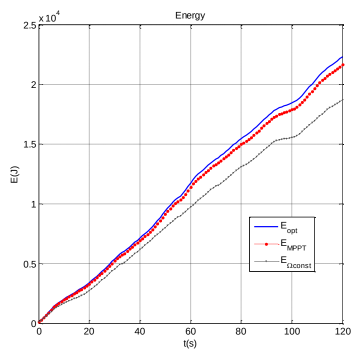

Figure 15: Energies obtained by different methods

According to the energy curves (see Figure15), it can be noted a profit approximately 13% on the energy recovered with MPPT method compared to the equivalent system operating with constant speed.
The representation of the energy "collected" by the system is a relevant criterion of appreciation of the energy effectiveness. The variation calculated according to the equation (16), between optimal energy resulting from optimal power P_{opt} and the obtained using MPPT method one gives a quantification of the energy quality taken on a given lapse of time. Here, this variation is 3,15%.
All these simulation results show the reliability of the adopted energy strategy optimization. It should be noted that the power is measured on electrical side.

5. CONCLUSION

An optimization method of energetic efficiency of a wind system based on a synchronous permanent magnet machine provided with a MLI rectifier converter is implemented in this article.The objective is to maximize the power collected for each wind speed.
The optimization approach adopted in this work makes it possible to move the operation point of the wind system by adjusting its speed at any wind speed, so that the collected power is always maximum.
The proposal offers a very interesting alternative compared to the traditional methods, which require the knowledge of the curve characteristic of the windmilln turbine.
The comparison between the energetic efficiency obtained by fuzzy MPPT with the one by constant speed makes it possible to validate the method. Indeed the average value of the output obtained MPPT, during the time of test is approximately 97%.
However, it may be noted that the algorithm is not able to distinguish if the power variation is due to the wind speed variation or to the variation of Ω.

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