Fuzzy optimization strategy of the maximum power point tracking for a variable wind speed system

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ABSTRACT

Wind power systems are gaining more and more interests; in order to diminish dependence on fossil fuels. In this paper, we present a variable speed-wind energy global system based on a synchronous generator with permanent magnetic (PMSG). The major goal of this study is to track the maximum power that is present in the turbine. An examination of control methods to extract the MPPT point, from a wind energy conversion system (WECS) under variable speed situations is presented. An intelligent controller based on the fuzzy logic control (FLC) is proposed for regulating permanent magnetic synchronous generator (PMSG) output power, in order to improve tracking performance. The principle of this maximum power point tracking (MPPT) algorithm consists in looking for an optimal operating relation of the maximum power, then tracking this last. We simulated our system with MATLAB-Simulink software. The found results will be debated to elucidate performance of the global system.

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1. INTRODUCTION

Wind turbines are one of the imperative services for generating renewable and clean energy; various motivations make this energy competitive. Wind energy has become competitive because it is clean and renewable, in addition industrialized costs are more and more minimized [1]. In recent years, wind energy is quickly growing and is regularly used for power generation. By 2020, wind power satisfies around 12% of the energy demand in the world. Variable speed wind turbines (VSWT) topologies cover different generators and converter structures, based on cost, productivity, energy catching throughout the year. Production systems based on VSWT with permanent magnetic synchronous generator (PMSG) are considered as promising and practical technologies in the wind generation industry, and thus allows high efficiency. We can also get rid of the gearbox, because the wind speed is very small. This peculiarity of this system is very important, the presence of a gearbox can make the system more critical, and this disadvantage can be minimized in a wind turbine, with a doubly fed induction generator (DFIG) thanks to the use of electronic converters [2].

In recent wind power plants, new combinations of maximum power point tracking (MPPT) control have emerged, with the aim of extracting maximum energy for varying wind speeds. Several MPPT methods are used in wind turbines to adjust generation system to ideal speed. We will quote hill climbing search (HCS), constant tip speed ratio (TSR), power signal feedback (PSF), optimum torque (OT), perturb and observe (P&O), and techniques based on artificial intelligence [3]. For each technique, we find advantages and handicaps for driving MPPT patterns. The TSR is very good except that a trustworthy anemometer is needed to evaluate the sale speed, [4]. For other techniques mentioned, the PSF and OT require knowledge of all parameters, to have extreme power curve. In P&O technique, and to design algorithms, we do not need to know specifications of the turbine or sensors, which improve system dependability, but this technique has a slower response and oscillates around the MPPT point [5]; in addition, this technique does not respond effectively to quick variations of the wind speed, and then system performances will be affected.

To overcome all these drawbacks, new techniques have emerged; do to progresses in computing such as artificial intelligence, which is more and more used following great performance offered by this approach. Fuzzy logic control (FLC) is a concrete example for MPPT applications because this technique gives more flexibility. The big advantage of FLC is to adjust very quickly, and without knowing any estimated controller parameters [6]–[8]; this interest is very beneficial, when we are in front variable wind profile. Several authors have started research on the fuzzy control of power systems based on wind energy. In the reference [9], a suggested WECS residing of PMSG is plugged to an uncontrolled rectifier, the boost converter has a duty cycle, which reflects the FLC output; by adjusting this duty cycle, we can is extract a maximum power. While in study [10], the FLC controller is directly applied to regulate the PMSG output power, which is connected to a direct current (DC) load.

This work is ordered as the description of wind energy conversion system (WECS) modeling covering wind turbine and PMSG models in section 2. After this (section 3), we debate a computational technique that depend on the FLC strategy; we have to design an MPPT controller from a PMSG connected to the grid by a three-level NPC inverter. The WECS efficiency is shown after simulation results (section 4) under MATLAB/Simulink software. Finally, the conclusion is debated at the last section 5.

2. MODELLING OF WECS

2.1 WIND turbine modelling

A wind turbine converts aerodynamic to electrical energy. Mechanical power is thus obtained once the aerodynamic power has been transformed. Mathematical expression of kinetic energy, is given by (1) [11]:

$$E_c = \frac{1}{2} m v^2 \tag{1}$$

where, $m = \rho . v . S . \Delta t$; *m:* air mass (Kg); ρ: air density (Kg/m^3); *S:* surface wich is swept by blades (m^2)*;* R: blade radius (m); wind speed (m/s).

In practical application, wind speeds behind (v_a) and in front (v_b), must be considered. The theoretical power (P_T) and the maximum extracted power (P_{Ext}), are related by the following system [4]–[8]:

$$\begin{cases} P_T = \frac{1}{2} \rho \pi R^2 v_b^3 \\ P_{Ext} = \frac{1}{2} \rho \pi R^2 \left(\frac{v_a + v_b}{2} \right) (v_b^2 - v_a^2) \end{cases} \tag{2}$$

The aerodynamic power is established by (3):

$$P = \frac{1}{2} \rho \pi R^2 v^3 C_p(\lambda, \beta) \tag{3}$$

with C_p : power coefficient; β: blade pitch angle (deg)*;* λ: tip speed ratio (TSR).

Several numerical approximations have been developed [12] to determine an expression of the coefficient C_p:

$$\begin{cases} C_p(\lambda, \beta) = c_1 * \left(\frac{c_2}{\lambda_i} - (c_3 * \beta) - c_4 \right) * e^{-\frac{c_5}{\lambda_i}} + (c_6 * \lambda) \\ \frac{1}{\lambda_i} = \left(\frac{1}{\lambda + 0.08 * \beta} \right) - \left(\frac{0.035}{\beta^3 + 1} \right) \end{cases} \tag{4}$$

The six constants have for values: $c_1 = 0.5176$; $c_2 = 116$; $c_3 = 0.4$; $c_4 = 5$; $c_5 = 21$; $c_6 = 0.0068$. In practice, we cannot convert more than 59% of kinetic into mechanical energy [13]. In the literature, this restrictionhas the name of the Betz limit. The theoretical maximum value of $C_p(\lambda, \beta)$ is:

$$C_{p.max} = {}^{16}/_{27} \approx 0.593c$$

λ (TSR) is given by the following relation:

$$\lambda = \frac{R.\Omega_{Turb}}{v} \quad (5)$$

Ω_{Turb} is the mechanic turbine speed (rad/s).

Generally, turbines with small power have fixed blades; we considered that the setting angle β is set to (β=0). A simplified model can be found, if only the electrical characteristics of the system are taken into account:

$$J_T \frac{d\Omega_{mec}}{dt} = T_{Turb} - T_{em} - C_f \Omega_{Turb} \quad (6)$$

where, J_T: total inertia (kg/m^2); T_{Turb} and T_{em}: aerodynamic and lectromagnetic torque; C_f: viscous friction coefficient.

2.2. PMSG modeling

The PMSG is one of the most used generators in wind power. Three phases are formed through the three-stator windings [14]. By neglecting the zero-sequence component of the flux, we will only be interested in the fundamental harmonic. We thus obtain a simplified Park model. The electromagnetic model of PMSG can be written under the following system of equations [15], [16]:

$$\begin{cases} V_d = -R_s I_d - L_d \frac{dI_d}{dt} + \omega L_q I_q \\ V_q = -R_s I_q - L_q \frac{dI_q}{dt} - \omega L_d I_d + \omega \Phi_f \\ \frac{dI_d}{dt} = -\frac{R_s}{L_d} I_d + \omega \frac{L_q}{L_d} I_q - \frac{1}{L_d} V_d \\ \frac{dI_q}{dt} = -\frac{R_s}{L_q} I_q - \omega \left(\frac{L_d}{L_q} I_d + \frac{1}{L_q} \Phi_f \right) + \frac{1}{L_q} V_q \end{cases} \quad (7)$$

After this, we can easily define the electromagnetic torque value [17]:

$$T_{em} = \frac{3}{2} \left[\left(L_d - L_q \right) I_d I_q + I_q \Phi_f \right] \quad (8)$$

where, R_s : is the stator winding resistance; L_d; L_q: direct and quadrature inductances of the stator winding; V_d: direct voltage of the stator space phasors; V_q: quadrate voltage; I_d: direct stator current; I_q: Quadrate stator current; Φ_f: permanent flux; ω*:* angular frequency of the generator; p: poles number.

2.3. Control strategy of the WECS

In Figure 1 and in the WECS diagram, the rectifier task is to transform the AC into a DC signal. After this, a boost converter is connected in order to generate maximum electrical energy. The generated voltage is boosted up, and again this increased voltage is applied to a DC/AC inverter.

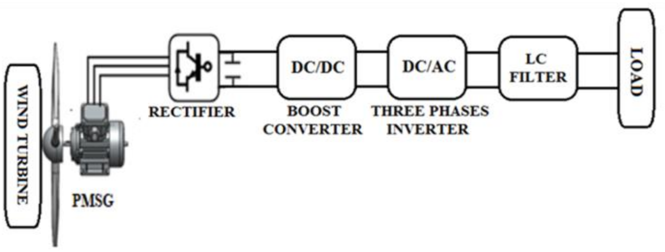

Figure 1. Design of WECS based on PMSG

2.4. Modelling of boost converter

Four main elements, which are the diode, the capacitor, the inductor, and the electronic switching device, ensure the transfer of energy in a step-up converter [18]. Schematics of all componentss are given in

Figure 2. The switching on and off-time period controls the average output voltage. The constant K is defined as the switching duty cycle. The boost converter job is separated into two separate modes [19]:
- Mode 1: begins when transistor SW=1 (switch on) at $t = 0$. I_L increases and runs through L and SW as shown in Figure 3 mode 1.
- Mode 2: When SW=0, I_L current flows directly to reach the load. The coil current begins to decrease and vanishes in the next cycle. The load thus consumes the energy stored in the coil as shown in Figure 3 mode 2.

In our global system (WECS), the boost converter is employed to track the maximum wind power, where an MPPT controller is used. The control method based on MPPT allows having a maximum power for a strong and fast variation of the wind speed. We judge the importance of this WECS system compared to the extraction precision of the maximum power by the MPPT controller. The PMSG based MPPT control mainly focuses on converting variable to fixed voltage and frequency.

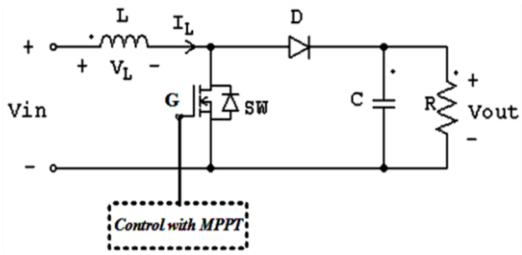

Figure 2. Boost converter diagram

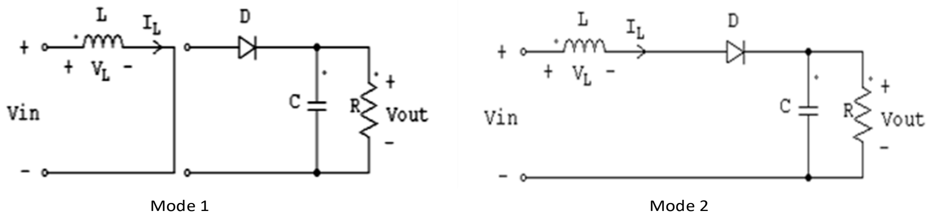

Figure 3. Designs of modes 1 and 2

2.5. Inverter modelling

A three-phase, three level inverter [20], [21] is used to generate AC load voltage; V_{c1} and V_{c2} are voltage supplies for the inverter; they have same values as shown in Figure 4. Two middle diodes allow the output voltage to reach zero. It is very important to prevent short circuits of conduction voltage sources, and then the inverter must be operated in its commendable mode.

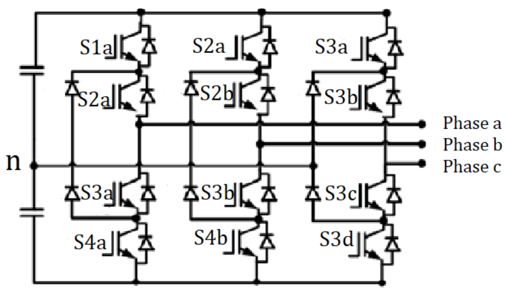

Figure 4. Inverter configuration

3. FUZZY LOGIC CONTROL STRATEGY

Lofti Zadeh is the forerunner of artificial intelligence [22]–[24]; in 1965, he published an article on fuzzy set theory, which contributed to the artificial intelligence development. Fuzzy logic has indeed led to several methods such as machine learning, or the notion of neural network and is widely used in various fields of computing. After this, scientific works led to the concept of "non-classical" logic, called fuzzy logic, on the one hand, and to the concept of neural networks, suitable for modeling and nonlinear controlling process, on the other hand, found applications in automation. This opened up new perspectives in process control. A fuzzy controller strategy has commonly three stages: i) fuzzification: converting the input variable from the real value to the fuzzy value, ii) setting fuzzy logic rules "if ...then", and iii) defuzzification: transform the fuzzy output value to its actual, in order to examine the object.

3.1. Fuzzy system input-output variables

The MPPT-FLC integrated in our system admits two input variables: i) $E_v(k)$, is the voltage error between moments k and k-1 and ii) $E_p(k)$, is the power error between moments k and k-1.

$$\begin{cases} E_v(k) = V_d(k) - V_d(k-1) \\ E_p(k) = P(k) - P(k-1) \end{cases} \tag{9}$$

The duty cycle reflects the FLC output. The maximum power can be reached if this duty cycle is adjusted; all these parameters are visible in Figure 5.

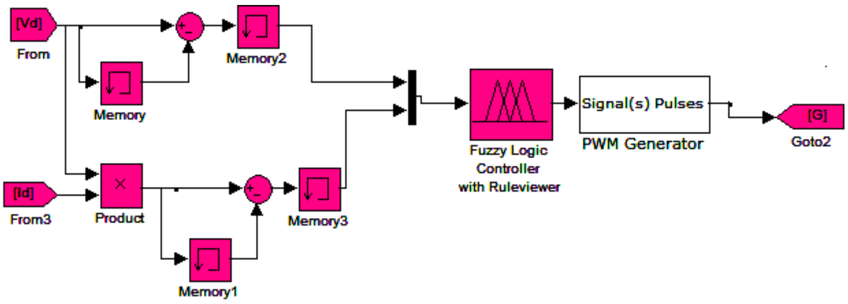

Figure 5. FLC-MPPT controller model

3.2. Membership functions

Using Mamdani's technique, membership functions and analogous limits are given for both input/output linguistic variables. To give more precision to our fuzzy strategy, we chose five linguistic variables: i) input variable $E_v(k)$: {big negative (BN), negative (N), small negative (SN), zero (Z), small positive (SP), positive (P), and big positive (BP)}; ii) input variable $E_p(k)$: {negative (N), zero (Z), and positive (P)}; and iii) output variable G: {very negative (VN), negative (N), small negative (SN), zero (Z), small positive (SP), positive (P), and very positive (VP)}.

Figures 6, 7 and 8 respectively, show Input/output variables of the FLC. After fuzzification process, adefuzzification is executed. Fuzzified values are converted into defuzzified values; this action gives final output values. The combination of different linguistic input variables engenders 21 possible solutions of the duty cycle. Inference rules are presented in Table 1. The numerical result provided by the inference block is exposed in the Figure 9. As an example, for the case of a BP voltage error (3.3) and a power error PO (0.264) we will have as duty cycle VP (D = 4.34).

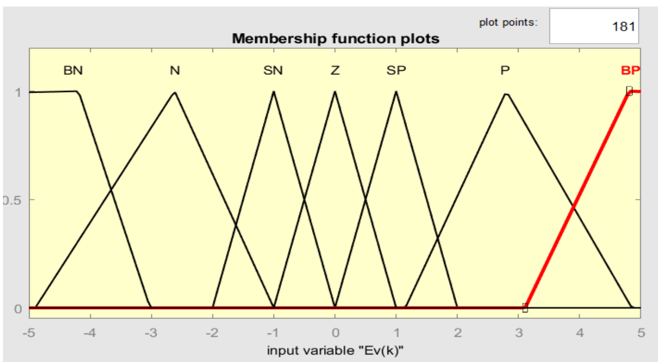

Figure 6. Membership functions for the input variable $E_v(k)$

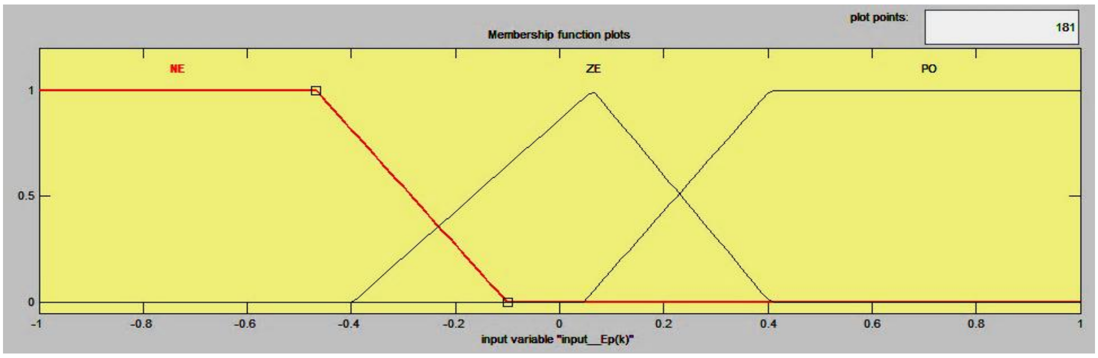

Figure 7. Membership functions for the input variable $E_p(k)$

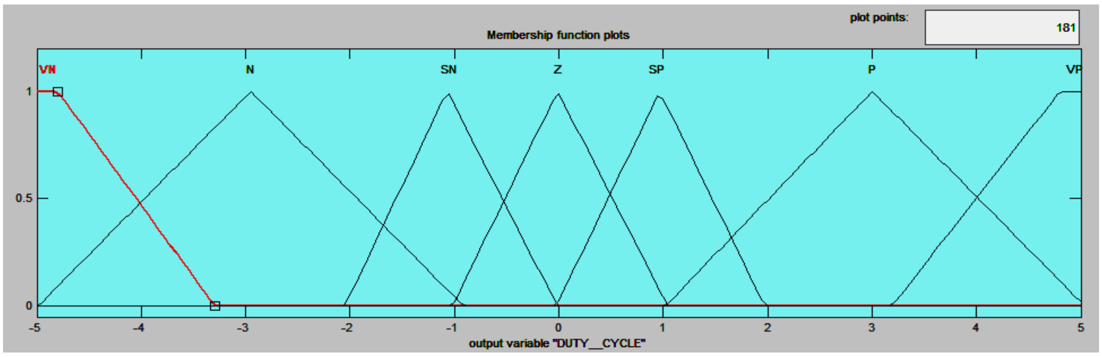

Figure 8. Membership functions for the output variable G

Table 1. Inference rules of the FLC

Output variable Duty_cycle		Input variable $E_V(k)$						
		BN	N	SN	Z	SP	P	BP
Input Variable $E_p(k)$	N	VP	SN	N	Z	SP	P	VP
	Z	VP	SN	SN	Z	SP	VP	VP
	P	VP	VN	VN	Z	P	VP	VP

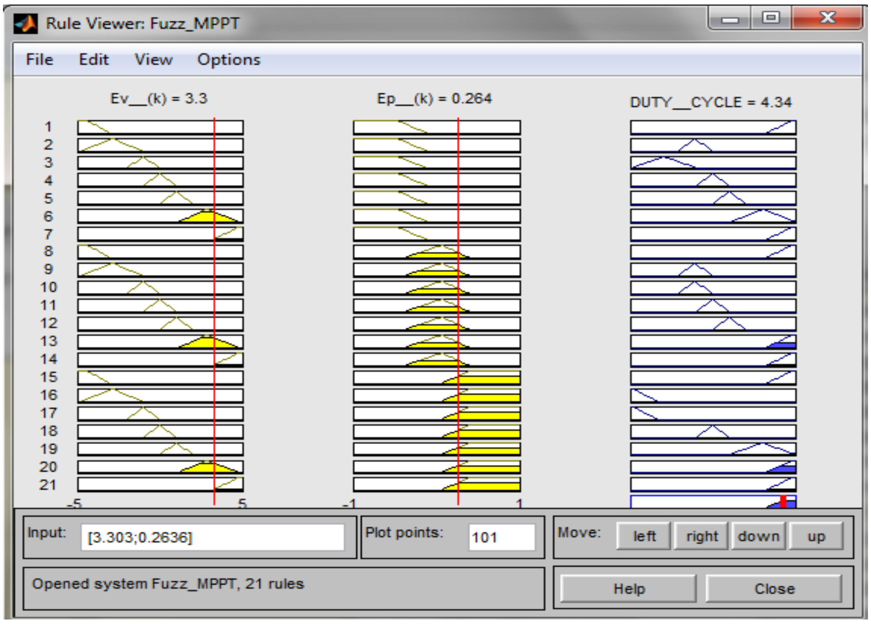

Figure 9. Inference block with numericalresults

4. SIMULATION RESULTS

For testing the efficiency of our control method and to validate global results; a full diagram shown in Figures 10 and 11 is executed in MATLAB/Simulink software system. A variable wind speed profile shown in Figure 12 is applied to the system. it is given by (10) [25].

$$v(t) = 8 + \sin(0{,}3047.t) + 4\sin(0{,}8665.t) + 2\sin(3{,}2930.t) + \sin(9{,}6645.t) \tag{10}$$

The FLC Control system implemented to the WECS is executed to track the MPPT point. Thus, Figure 13 shows the voltage variation in the output of boost converter, this last is directly connected to the inverter. We find the following figures which respectively show voltage, current and active power waveforms of the PMSG as shown in Figures 14, 15 and 16. The PMSG power curve progresses at a pace similar to the wind profile applied to the system.

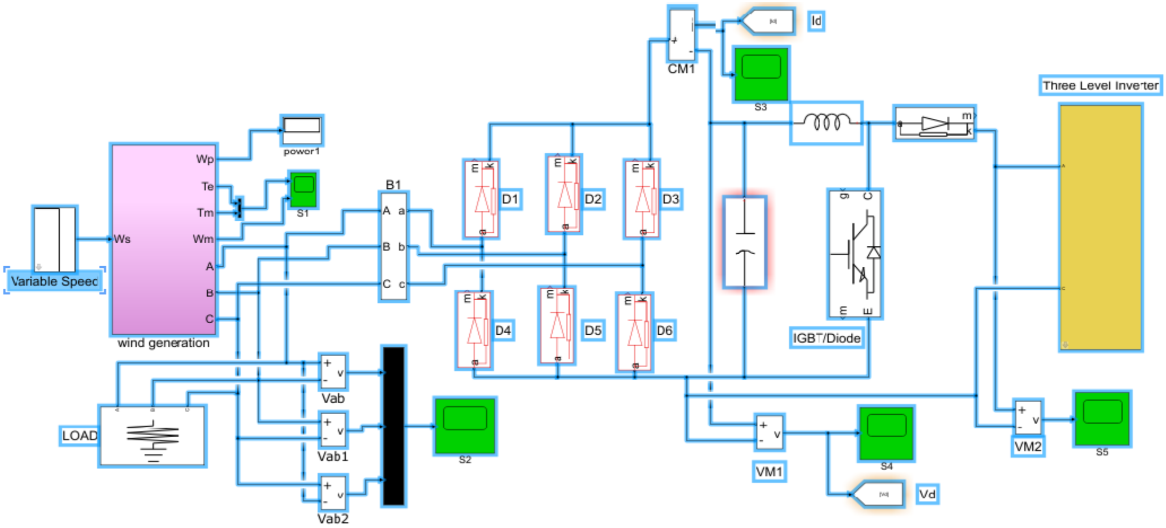

Figure 10. Global full diagram of WECS

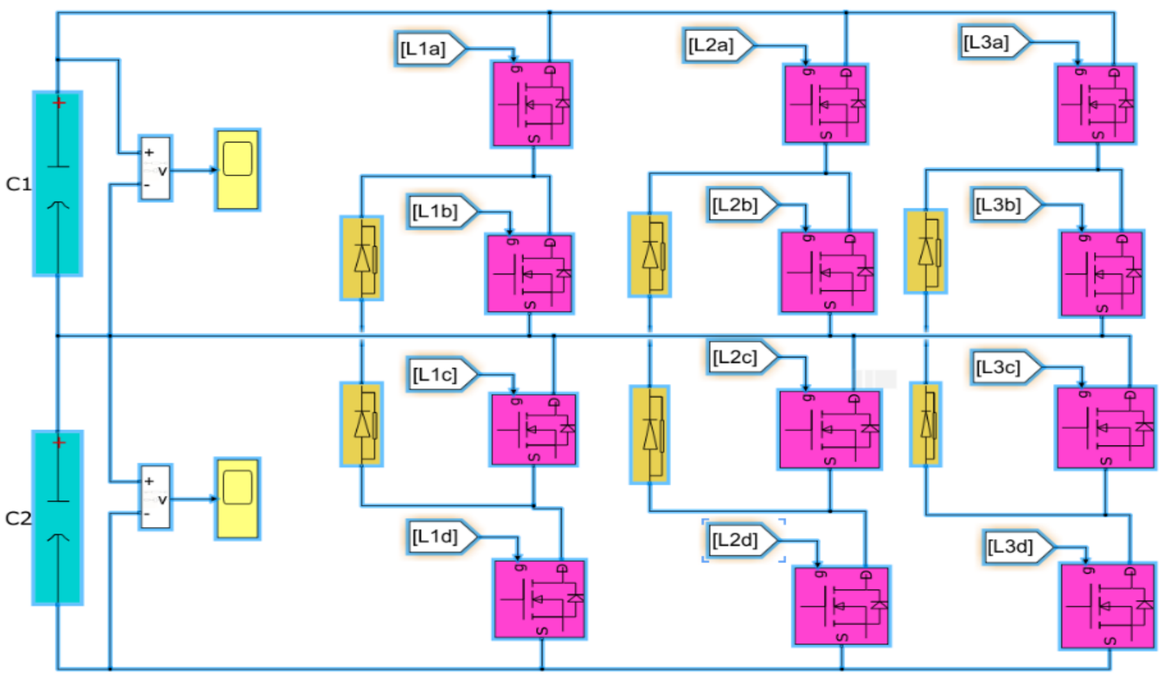

Figure 11. Three level Inverter subsystem

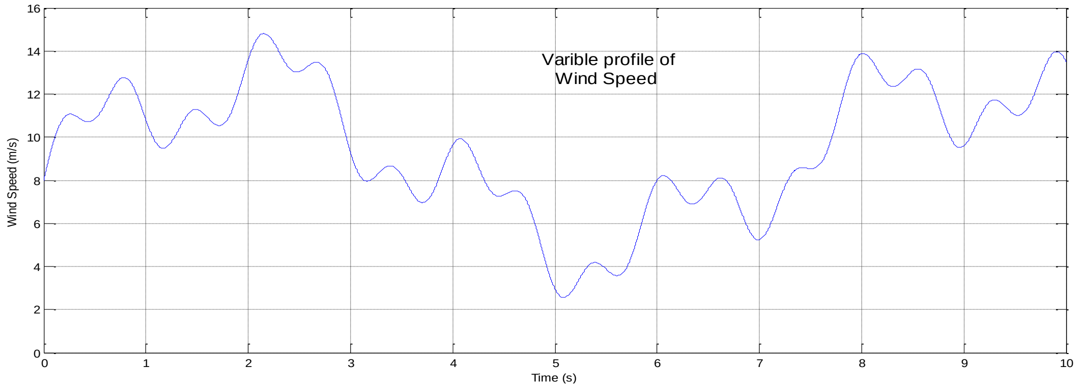

Figure 12. Wind speed profile

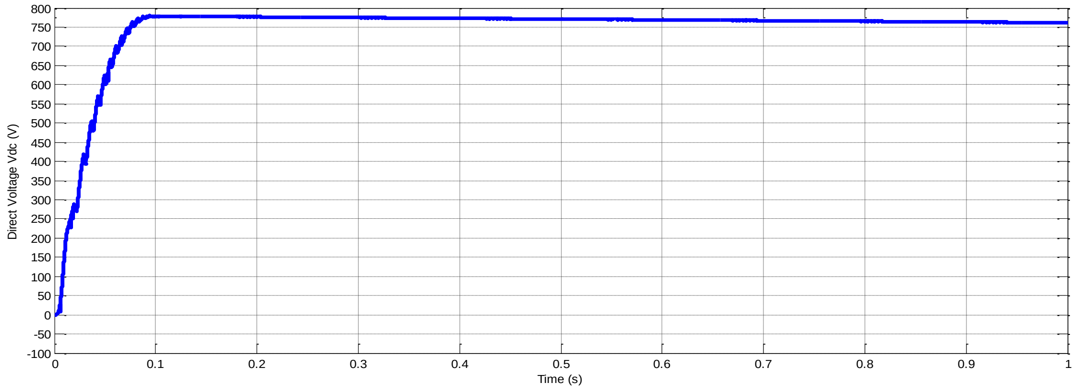

Figure 13. Voltage variation on the boost converter

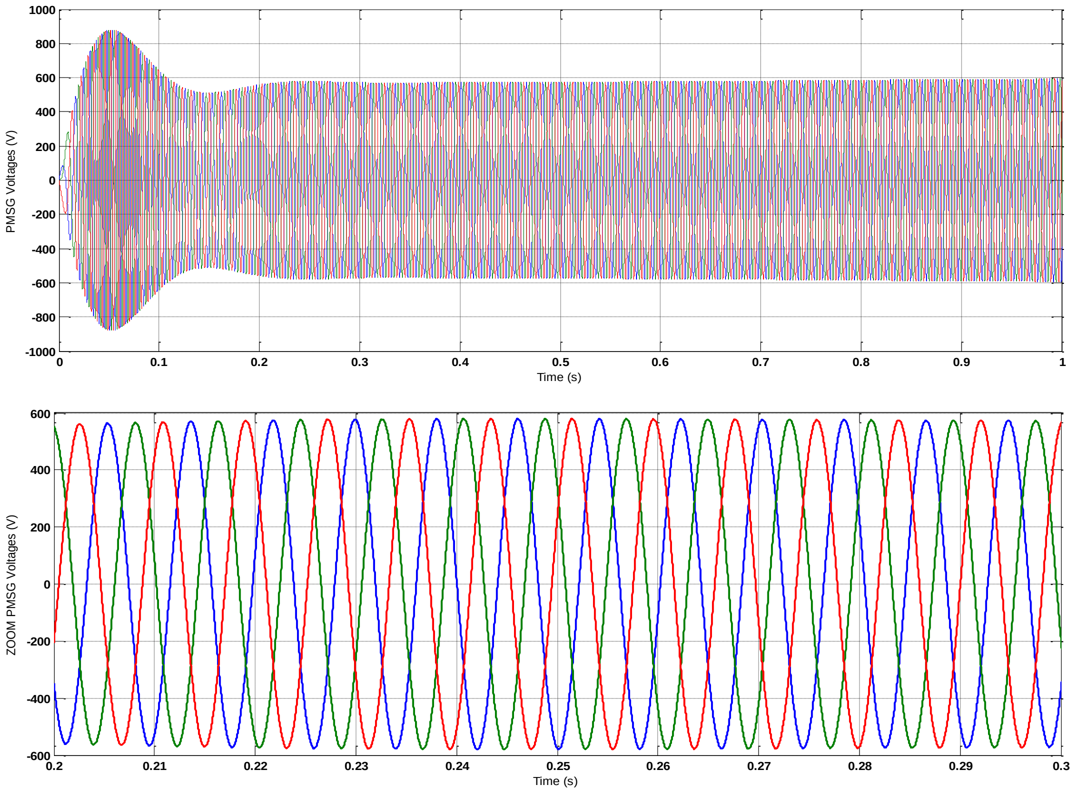

Figure 14. Voltage waveforms of the PMSG (with ZOOM)

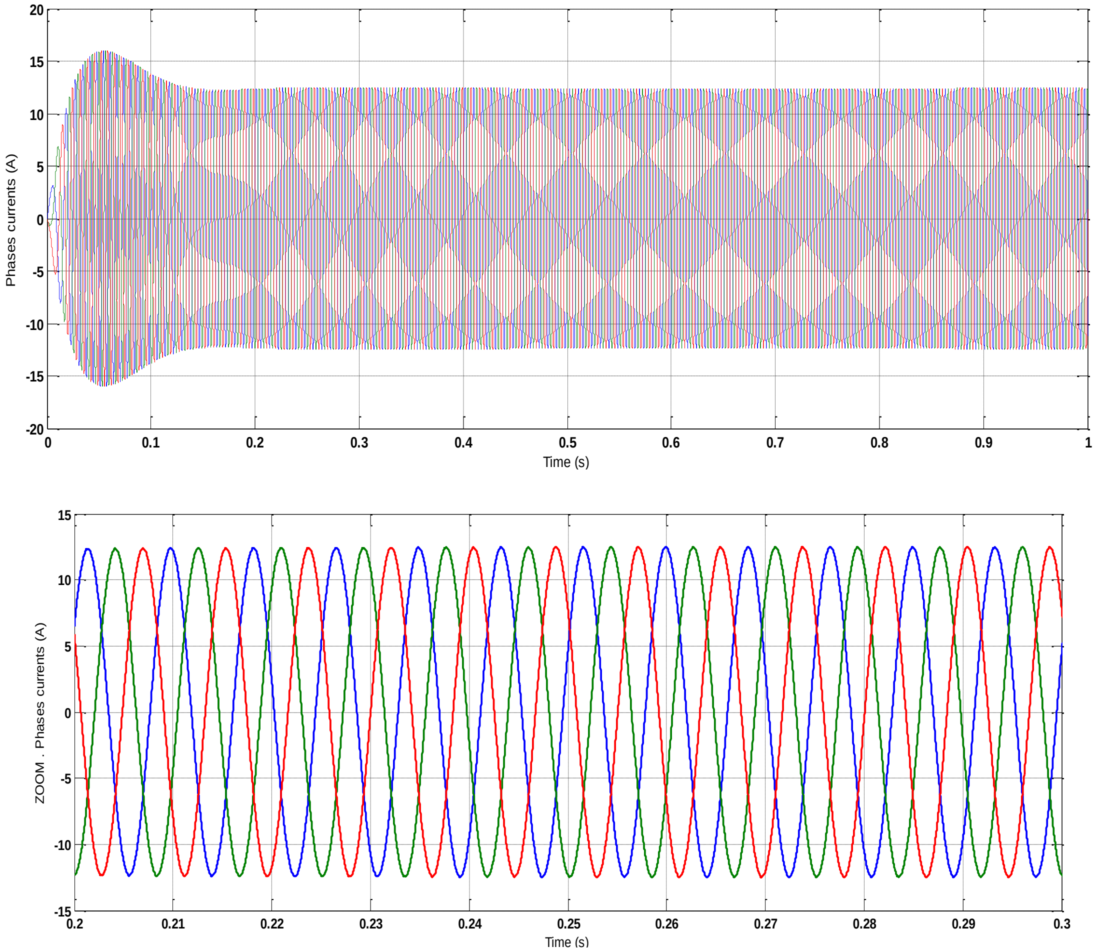

Figure 15. Current waveforms of the PMSG (with ZOOM)

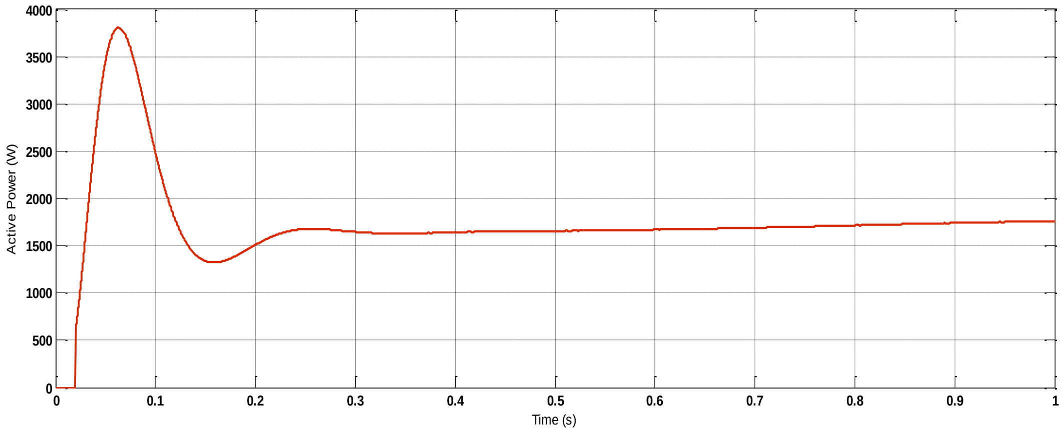

Figure 16. Active power of the PMSG

To evaluate the performance of our fuzzy MPPT strategy, we make a comparison of power, current and voltage profiles upstream inverter. For the voltage, and the current we note a decrease in the overshoot at the start; extracted output power is greater than the power upstream of the FLC as shown in Figures 17, 18, and 19. It is achieved that the fuzzy MPPT approach could have contributed more efficiently to the extraction of maximum power for a WECSwith variable speed.

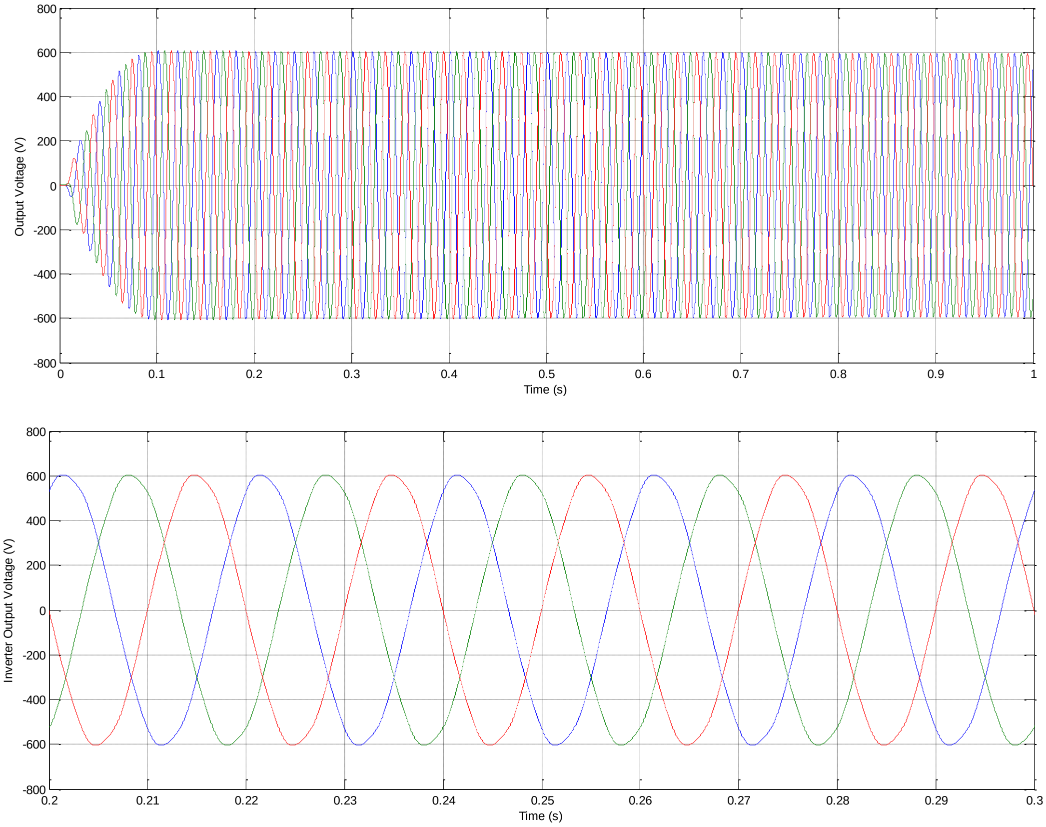

Figure 17. Inverter output voltages (with ZOOM)

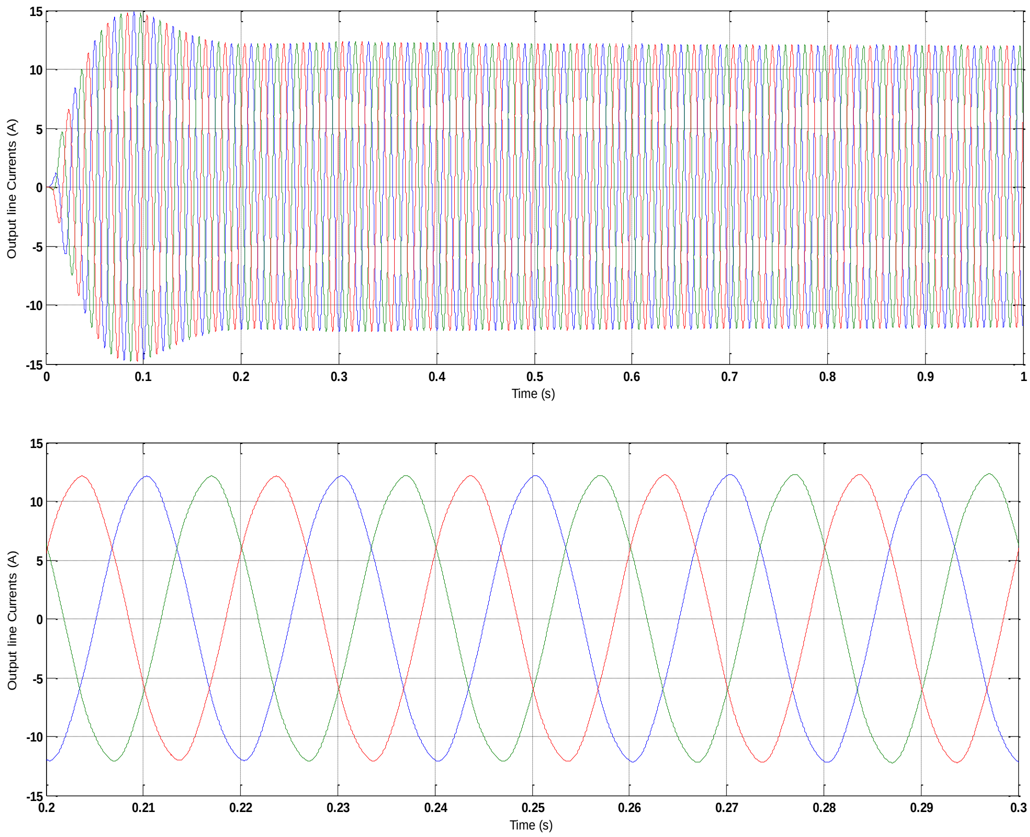

Figure 18. Inverter output currents (with ZOOM)

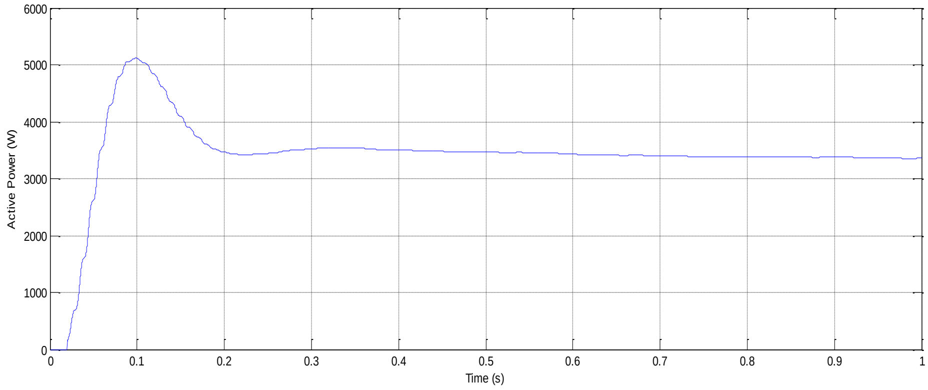

Figure 19. Active power upstream inverter

5. CONCLUSION

To increase efficacy of a WECS, we have designed an intelligent strategy, based on FLC-MPPT control. This approach makes it possible to boost the power delivered by the wind turbine at any time and for variable wind speed. Therefore, we started this work by the presentation of the production system (WECS). The generated voltage is boosted up, a DC/DC boost converter increases the voltage level of WECS and again this increased voltage is applied to an inverter. A regulator based on fuzzy logic controls the switching times of the boost converter. Simulation results prove effectiveness from adopted strategy. The fuzzy MPPT allows on one hand the detection of the MPPT according to wind speed variations and on the other hand, its performance compared to the undulation rates of voltage and current, which are minimized.

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