Control of permanent magnet synchronous generator wind turbine for stand-alone system using fuzzy logic

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Abstract

In this paper, the control scheme of a wind energy conversion system for remote sites using fuzzy logic is presented. Two fuzzy controllers are proposed: the first one is dedicated to the maximum power point tracking (MPPT) of a variable speed permanent magnet synchronous generator wind turbine. The second fuzzy controller has the the objective to manage both the production and the storage of electricity for optimum performances of the system in respecting load demand. Several simulation results are given to show the effectiveness and the good performances of the proposed control structure.

Keywords: wind energy, permanent magnet synchronous generator, maximum power point tracker, stand-alone system, battery, fuzzy control.

1. Introduction

In recent years, the production of electricity from renewable energy sources like wind energy increases due to environmental problems and the shortage of traditional energy sources in the near future [1]. Wind power depends mainly on geographical conditions and weather conditions. Therefore, it is necessary to construct a system capable of generating maximum power under these constraints [2].

Nowadays, permanent magnet synchronous generators (PMSGs) are used in wind turbine because of its advantages: better reliability, less maintenance and more effective ([3],[4]). In addition, exploting the case of of variable speed allows to obtain an optimal efficiency of the system [5].

For remote sites located far from the utility, a practical approach for power generation is to use a variable speed wind turbine to create an autonomous system. It often includes batteries, used when the wind cannot provide sufficient power. If wind conditions are favorable, these autonomous wind energy systems can provide electricity at low cost. If wind power exceeds the load demand, the surplus can be stored in batteries and if wind power cannot meet load demand, the batteries can compensate it ([1],[6]).

Recently, M. Dali worked on the duty cycle of a boost converter, managed in the same time the MPPT control and the load voltage by using a PI controller for current and voltage [4]. Although conventional PI controller have been well developed and applied for industrial automation and process control due to their simplicity of operation, ease of design and effectiveness for most linear systems, it generally does not work well for nonlinear systems, higher order and time-delayed linear systems, and particularly complex and vague systems that have no precise mathematical models [7]. To overcome these difficulties, various types of controllers using artificial intelligent such as fuzzy logic, genetic algorithm... were developed lately [8]. In wind energy, T. F. El-Shatter has designed two fuzzy controllers to deal with two boost converters, one for the MPPT and the other for voltage regulation [9].

In this paper, we propose a wind energy conversion system for remote site using a variable speed PMSG, a battery bank and two fuzzy controllers to optimize the operation of both the wind turbine and the battery according to wind speed and load demand.

The first boost converter (DC/DC 1) is used to change the voltage output of the generator. Thus, by controlling the converter, the rotor speed of PMSG is controlled to achieve the optimum value to maximize the power recovered.

To manage the energy production, we use another fuzzy controller to set the duty ratio of the second boost converter (DC/DC 2) in order to (i) adjust the DC output voltage, (ii) to choose the moment to charge/discharge the battery and (iii) the moment to dissipate excess energy in a dumb resistance. Fuzzy logic provides a formal methodology for the representation, manipulation and implementation of knowledge of a human being. We no longer need an accurate model of the complex system (synchronous generator with converters, inverters...) when designing of our controllers. With proposed controllers, wind energy is primarily provided directly to load without going through a passive element (battery). As a result, the number of charge/discharge rate is greatly reduced thereby extend battery life.

2. System description

Our system consists of a PMSG (67Nm, 1700rpm) to power a 2kW pump, a 3kW induction machine, a 4kW water heater, and a lead acid battery for backup storage. A diode bridge rectifier and two boost converters are used for MPPT purpose and for electrical production management. A pulse width modulation inverter is used to provide a 380V, 50Hz voltage to load.

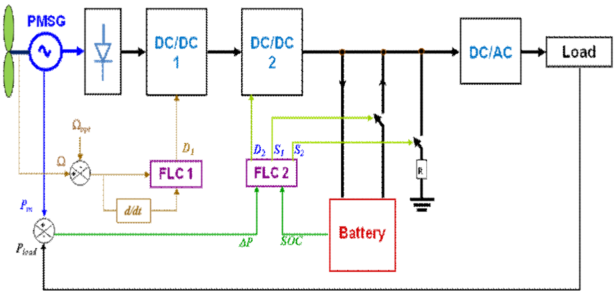

Fig. 1: Proposed system.

A fuzzy logic controller (FLC 1) is designed to vary the operating time (or duty cycle) D_1 of the first converter to track the optimum rotor speed, thus maximizing the power recovered by the turbine. Input is the error between the actual speed of the rotor and the optimal speed reference. Output is the duty ratio D_1 of the first converter to achieve optimal rotor speed.

Another fuzzy logic controller (FLC 2) is designed to adjust the DC voltage to a value suitable for battery charging and also suitable for the proper operation of the PWM inverter. If wind conditions are favorable, the wind turbine will be the main supplier for load. If the wind does not give enough power to load, and the battery capacity is sufficient, the battery will start to provide the necessary power. If the power of the wind turbine exceeds the load demand, the surplus is stored in the battery and if the battery is full, the surplus will be dissipated in a resistor. Thus, the battery is not the main supplier, so that the number of charge/discharge rate is reduced, and consequently the life of the battery is extended.

For this, we need two informations: the battery state-of-charge (SOC) and the error between available wind power and load demand (DeltaP). The controller will decide the value of the duty cycle (D_2), the moment to switch the battery (S_1) and the moment to dissipate the excess in the resistor (S_2).

3. Model of wind turbine

The static characteristic of the turbine (output as a function of wind speed) can be described by the relationship between the total power and mechanical energy of the wind ([1],[2]):

$$P_{wind} = \frac{1}{2}\rho\pi R_{turbine}^2 v_{wind}^3 \qquad (1)$$

where ρ is the air density (1,225 kg/m3), $R_{turbine}$ is the rotor radius (m), v_{wind} is the wind speed (m/s). It is impossible to extract all the kinetic energy of wind, so it extracts a fraction of the power of wind as shown in (2) as the power coefficient C_p.

$$P_m = \frac{1}{2}C_p\rho\pi R_{turbine}^2 v_{wind}^3 \qquad (2)$$

P_m is the mechanical power of the wind (Nm/s). The maximum power coefficient C_{pM} is 0.59. This coefficient is also known as Betz limit. It can be expressed in terms of reduced velocity λ and angle of light δ: $C_p = C_p(\lambda, \delta)$.

If Ω is the rotor speed, the reduced speed λ is defined:

$$\lambda = \frac{\Omega R_{turbine}}{v_{wind}} \qquad (3)$$

Assuming a constant wind speed v_{wind}, the reduced speed λ varies proportionally to the rotor speed [10]. The maximum value of C_p is generally obtained for values of λ around 8 to 9 (when the tip of the movements of blade is 8 to 9 times faster than the wind). On modern wind turbines, it is possible to adjust the angle of the blades through a control mechanism [11]. If C_p-λ curve is known for a specific wind with a radius of turbine rotor $R_{turbine}$, it is easy to construct the curve of C_p as a function of rotational speed Ω for a wind speed v_{wind}.

The output torque of the turbine is calculated :

$$T_m = \frac{P_m}{\Omega} = \frac{1}{2}\frac{C_p\rho\pi R_{turbine}^2 v_{wind}^3}{\Omega} \qquad (4)$$

If the speed ratio λ is maintained at its optimal value λ_{opt}, the power coefficient is at its maximum value $C_{pM}=C_p(\lambda_{opt})$, the maximum power of the wind turbine will be:

$$P_m^{opt} = \frac{1}{2}C_{pM}\rho\pi R_{turbine}^2 v_{wind}^3 \qquad (5)$$

On the other hand, the speed ratio assumed to be maintained at the optimum value, we obtain the optimum speed rotor:

$$\lambda^{opt} = \frac{\Omega R_{turbine}}{v_{wind}} \Rightarrow \Omega^{opt} = \frac{\lambda^{opt} v_{wind}}{R_{turbine}} \qquad (6)$$

Thus, for each wind speed v_{wind}, there is a maximum rotor speed Ω_{opt} which made a maximum power recovered from the wind turbine (Fig. 2).

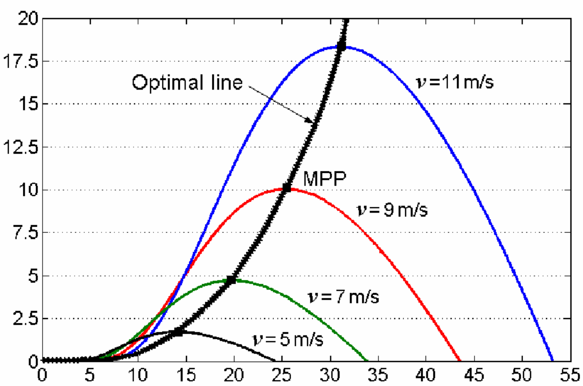

Fig. 2. Maximum power in function of rotor speed

In this paper, a wind turbine is simulated by using a look-up table, where inputs are wind speed and rotor speed and output is the mechanical torque.

4. Model of PMSG

Permanent magnet machines have been widely used. Indeed, this technique can replace the field winding of synchronous machines and has more well known advantages of compact size, the higher power density, the loss reduction, high reliability and good robustness. In addition, the simple design of the rotor without field windings, no rings and no excitation system also increases the efficiency of the machine [12]. The dynamic model of PMSG can be represented in the Park's system using the following equations [3]:

$$V_d = -R_S i_d - L_d \frac{di_d}{dt} + \omega L_q i_q \qquad (7)$$

$$V_q = -R_S i_q - L_q \frac{di_q}{dt} - \omega L_d i_d + \omega \lambda_m \qquad (8)$$

The expression of electromagnetic torque in the rotor is given by:

$$T_e = \frac{3}{2} p[(L_d - L_q) i_q i_d - \lambda_m i_q] \qquad (9)$$

$$\Omega = p\omega \qquad (10)$$

where p is the number of pole pair, λ_m is the magnetic flux, L_d is the direct axis inductance, L_q is the inductance in quadrature, R_s is the stator resistance and ɤ is the electrical angular frequency.
If the rotor is cylindrical, L_d **å** L_q **å** L_s so:

$$T_e = \frac{3}{2} p \lambda_m i_q \qquad (11)$$

PMSG in the relationship between the torque and induced voltage [13] is:

$$T_e = k_T I_a \qquad (12)$$

$$E = k_E \omega \qquad (13)$$

where I_a is the stator current. On the other hand:

$$E^2 = V^2 + (I_a L_s \omega)^2 \qquad (14)$$

V is the voltage phase and L_s is the inductance of the generator.
The output voltage of the rectifier is given by [14]:

$$V_{rec} = \frac{3\sqrt{6}}{\pi} V \qquad (15)$$

and the output voltage of the first converter [15]:

$$V_{DC} = \frac{1}{1 - D_1} V_{rec} \qquad (16)$$

$$V_{DC} = \frac{1}{1 - D_1} \frac{3\sqrt{6}}{\pi} \omega \sqrt{k_e^2 - (\frac{T_e L_s}{k_T})^2} \qquad (17)$$

So the torque is determined by the rotor speed and wind speed: a specific value of the voltage is estimated for a specific rotor speed and wind speed.

Now, for a given value of rotor speed, voltage can be obtained and applied to the system. By applying this control strategy, speed and voltage vary continuously until they reach their equilibrium. In this case, the maximum power of wind energy is achieved.

Hence, the voltage optimal value is reached by varying the duty ratio D_1 of the first converter as follows:

$$D_1 = \frac{V_{DC} - V_{DC\_opt}}{V_{DC}} = \frac{\Omega - \Omega_{opt}}{\Omega} \qquad (18)$$

5. Fuzzy controller for the MPPT of the PMSG

In this section, we present the fuzzy controller used for tracking the rotor speed to achieve the MPPT. Fuzzy controllers belong to the class of knowledge based systems. Their main goal is to implement human knowledge in the form of a computer program.

The fuzzy controller has four main components: (i) the ñrule-baseò holds the knowledge, in the form of a set of rules, of how best to control the system; (ii) the inference mechanism evaluates which control rules are relevant at the current time and then decides what the input to the plant should be; (iii) the fuzzification interface simply modifies the inputs so that they can be interpreted and compared to the rules in the rule-base and (iiii) the defuzzification interface converts the conclusions reached by the inference mechanism into the inputs to the plant [16].

In our MPPT controller (FLC 1), we use the error between reference speed and the real rotor speed and the change of this error as inputs. Output is the duty cycle D_1 of the first boost converter.

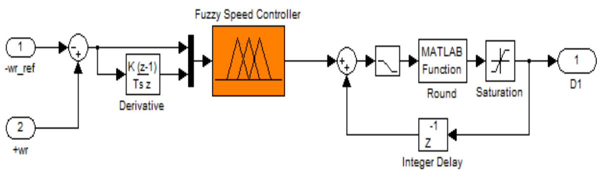

Fig. 3. Controller MPPT

The linguistic term sets used are:

- Error [Very Negative, Negative, Small Negative, Zero, Small Positive, Positive, Very Positive].
- Derivative of error [Negative, Zero, Positive].

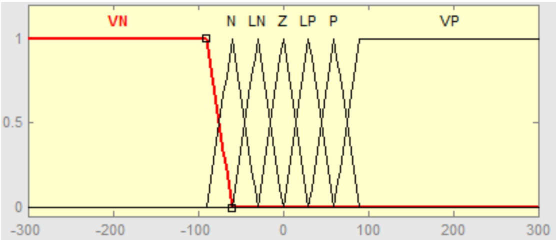

Fig. 4. Seven terms of variable "Error"

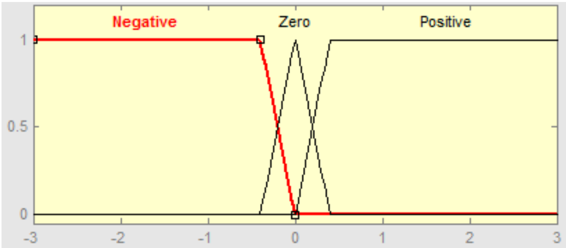

Fig. 5. Three terms of variable "Derivative of error"

The method of inference rules for describing the dynamic method used is the min-max one. This type of method involves a simple treatment of data and generates linear features (for two or more sizes of entries) with marked discontinuities.

$$\mu_{A\cap B}(x) = \min(\mu_A(x), \mu_B(x)) \qquad (19)$$

$$\mu_{A\cup B}(x) = \max(\mu_A(x), \mu_B(x)) \qquad (20)$$

Here, we used Takagi-Sugeno system [17]. Example: "If the error between reference speed and rotor speed is Positive and the derivative of that error is Zero, then **æ**D = +5%".

Then: $D_1(k) = D_1(k\text{-}1) + \Delta D(k)$ (21)

The various fuzzy rules used in our system are summarized in table 1.

æD (%)		Derivative of error		
		Negative	Zero	Positive
Error	VN	-5	-5	-5
	N	-5	-5	-3
	SN	-5	-3	-1
	Z	0	0	0
	SP	+1	+3	+5
	P	+3	+5	+5
	VP	+5	+5	+5

Table 1. Rules of **æ**D

The output level **æ**D_i of each rule is weighted by the firing strength w_i of the rule. For example, with (Speed error is P) and (Derivative of speed error is Zero), the firing strength is:

$$w_i = \min(\mu_{Error}(P), \mu_{DerivativeOfError}(Zero)) \qquad (22)$$

The final output of the system is the weighted average of all rules output, computed as:

$$FinalOutput = \frac{\sum_i^N w_i . \Delta D_i}{\sum_i^N w_i} \qquad (23)$$

where N is the number of rules.

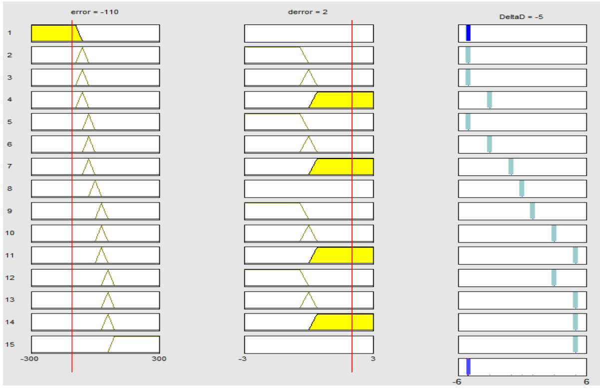

Fig. 6. Defuzzification in case error=-110 and derror=2

6. Fuzzy controller for the production process

Inputs for this controller are the battery state of charge (SOC) and the error power DeltaP (difference between wind power and load power). The outputs are the duty ratio D_2 applied to the second boost converter for charging the battery (ensuring a safe and effective) and ensure that the input voltage is sufficient for the PWM inverter, the time to charge/discharge the battery and the time to dispel the surplus to a discharge resistor.

The linguistic term sets used for:

- Power error DeltaP [Negative, Small Positive, Positive, Very Positive].
- Battery's state-of-charge SOC [Empty, Average, Full].
- Duty cycle D_2 [Very Small, Small, Medium, Big, Very Big].
- Switch S_1 and S_2 [Opened, Closed].

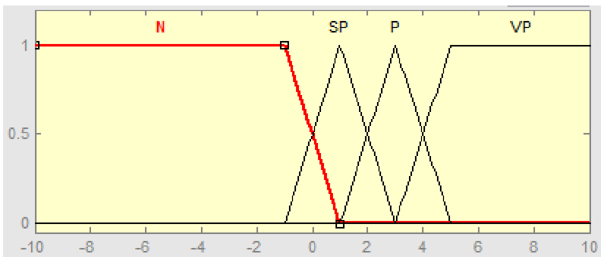

Fig. 7. Four terms of variable "DeltaP"

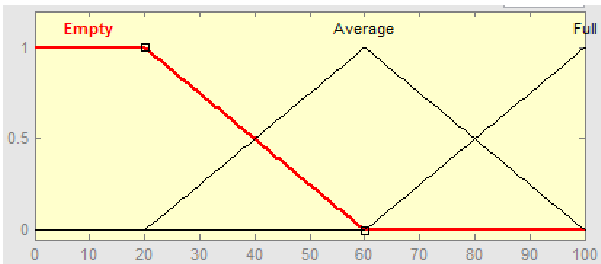

Fig. 8. Three terms of variable "SOC"

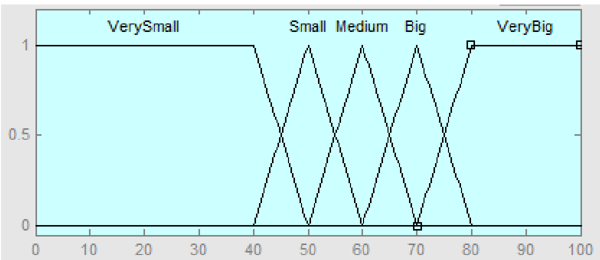

Fig. 9. Five terms of variable "D_2"

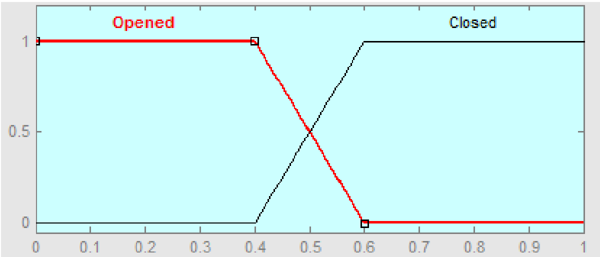

Fig. 10. Two terms of variable "S_1" and "S_2"

The method of inference rules is also the min-max inference and the implementation of the rules was based on fuzzy rules of Mamdani type [17]. Example: "If the error between wind power and load demand is Positive and battery state-of-charge is Full, then, switch 1 should be Opened and switch 2 should be Closed".

The fuzzy rules used in our FLC 2 are summarized in table 2, 3 and 4.

D_2		SOC		
		Full	Average	Empty
DeltaP	N	Big	Big	Small
	SP	Very Big	Big	Small
	P	Very Big	Very Big	Medium
	VP	Very Big	Very Big	Medium

Table 2. Rules of D_2

S_1		SOC		
		Full	Average	Empty
DeltaP	N	Close	Close	Open
	SP	Open	Open	Open
	P	Open	Open	Open
	VP	Open	Open	Open

Table 3. Rules of S_1

S_2		SOC		
		Full	Average	Empty
DeltaP	N	Open	Open	Open
	SP	Open	Open	Open
	P	Open	Open	Open
	VP	Close	Open	Open

Table 4. Rules of S_2

The overall fuzzy subset representing output control variable is defuzzified using centre of gravity method:

$$\mu_C = \frac{\sum_i \mu_C(x_i).x_i}{\sum_i \mu_C(x_i)} \qquad (11)$$

Where x_i is a point in the universe U of the conclusion (i = 1, 2é), and $\boldsymbol{\varepsilon}_c(x_i)$ its membership of the resulting conclusion set.

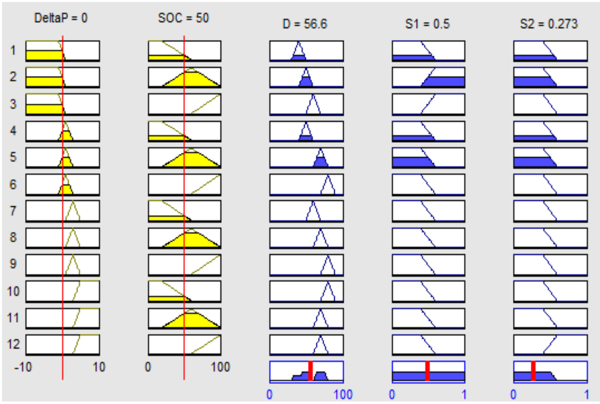

Fig. 11. Defuzzification in case DeltaP=0 and SOC=50%

7. Simulation and results

The system described in Section 2 is implemented in Matlab Simulink (Fig. 12). For the MPPT purpose, we use both fuzzy and PI controllers to compare the results between these two controllers. For power management purpose, a PI controller is not suitable so we keep this controller unchanged.

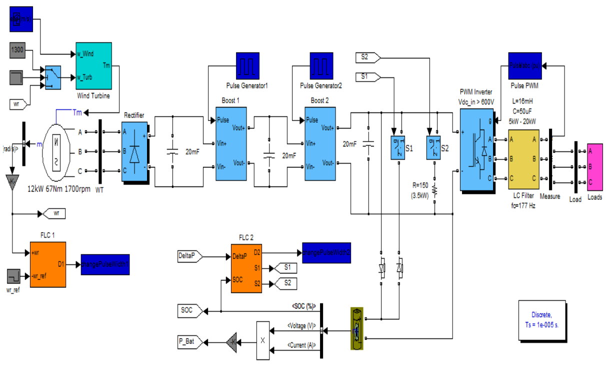
Fig. 12. Simulation in Simulink

Suppose that the battery state-of-charge is 95% (Full), in this case we can verify the dissipation of surplus power to prevent the battery from gassing (operation of switch 2). First the water heater and pump function (request for a total load of 6 kW). After 4 seconds the machine is started (total load 9kW) and 8 seconds later, the heater is disconnected (total load 5kW). The wind speed decreases from 9m/s to 8m/s at the 8^{th} second, then increases to 10m/s at the 16^{th} second (Fig. 13, 14).

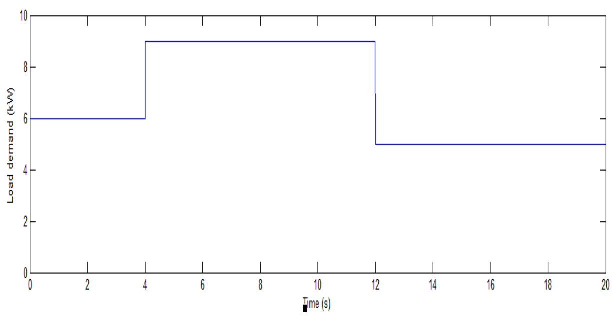

Fig. 13. Load demand (kW)

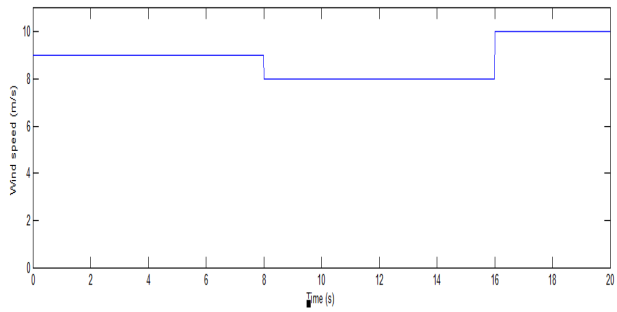

Fig. 14. Wind speed (m/s)

In the first four seconds, the load is 6kW. The wind speed is 9m/s, while D_1 is 1%, which rotates the rotor at a speed of 1450rpm to reach the maximum power of 7.2kW (Fig. 15, 16).

The error power DeltaP = 0.7kW (Small Positive), so S_1 is opened (S_1 = 0). D_2 is 74% (Fig. 21) which causes a voltage of $715V_{DC}$ at the output of the 2^{nd} boost converter, then the battery is charged.

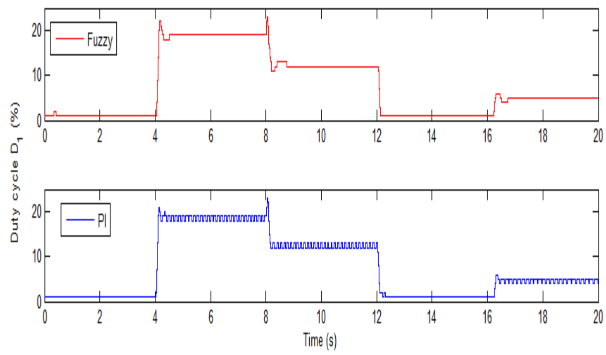

Fig. 15. Duty cycle of the 1^{st} converter D_1 (%)

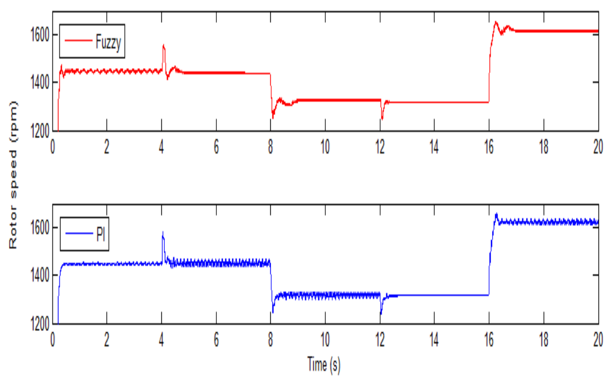

Fig. 16. Rotor speed (kW)

Both controllers give almost the same settling time and steady-state operation by responding step changes in reference input. However, we can see that fuzzy controller is more stable while PI controller has more ripple (noise). Moreover, with the PI controller, we have to choose a suitable value of k_p, k_i when system parameters change, while fuzzy controller works well with all system parameters. The responses from both fuzzy and PI MPPT controllers are plotted on the same graph for better comparison.

In the next four seconds, the induction machine operates, load demand now is 9kW, DeltaP is -2.2kW (Negative) then the battery is activated by the closure of S_1 (S_1 = 1) to give necessary power to load. The duty ratio D_1 is increased from 1% to 19% to keep the rotor speed in its optimal value of 1450rpm.

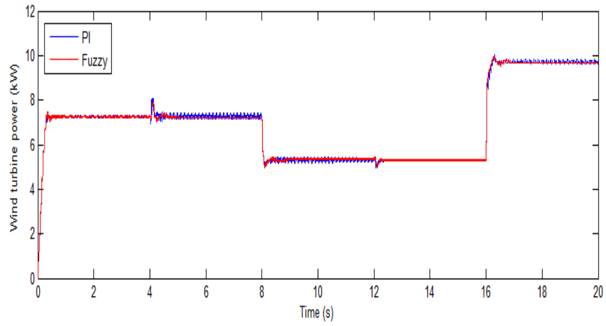

Fig. 17. Wind turbine power (kW)

After 8 seconds, wind speed decreases to 8m/s, in which optimal rotor speed is 1317rpm (D_1 = 12%). Wind turbine power decreases to 5.2kW while the power required by the load is still 9kW, then the battery gives more power to load (P_{bat} = -4.2kW).

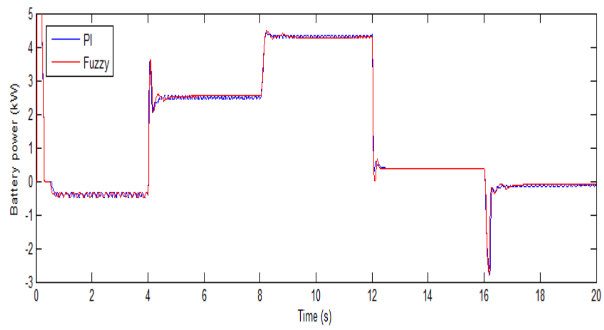

Fig. 18. Battery power (kW)

From 12^{th} to 16^{th} second, the water heater stop, the load is reduced to 5kW, D_1 decreased to 1% to keep the rotor speed in optimal value 1317rpm. DeltaP remains Negative (-0.2kW), so S_1 is still closed.

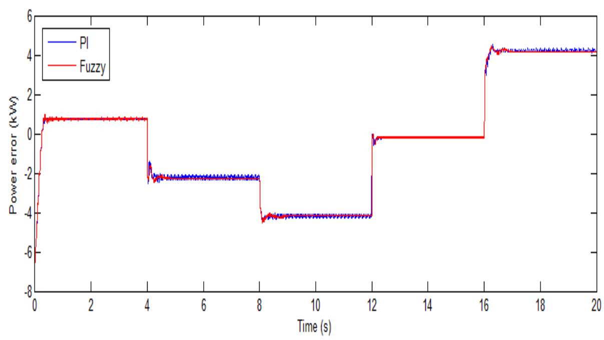

Fig. 19. Power error DeltaP (kW)

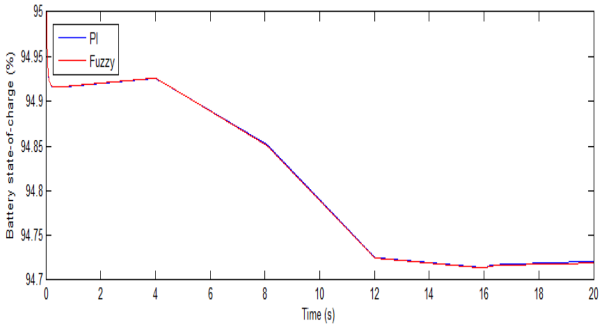

Fig. 20. Battery state-of-charge SOC (%)

The last four seconds, the wind speed is increased to 10m/s, so the rotor rotates at the optimum speed of 1623rpm and the wind gives a maximum power of 9.7kW. So DeltaP is 4.2kW (Very Positive) while the battery is fully charged (SOC = 94.7%), keep on charging may cause gassing phenomenon, thus S_2 is closed to dissipate the surplus to a discharge resistor.

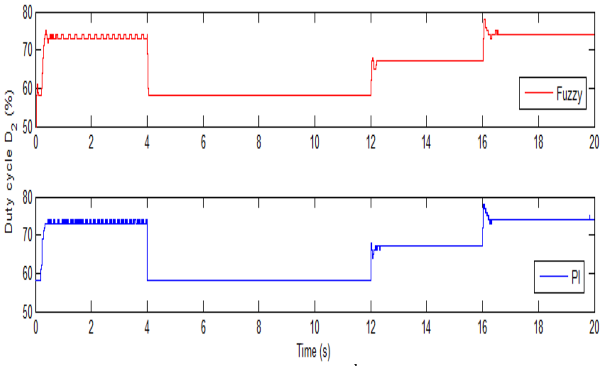

Fig. 21. Duty cycle of the 2nd converter D_2 (%)

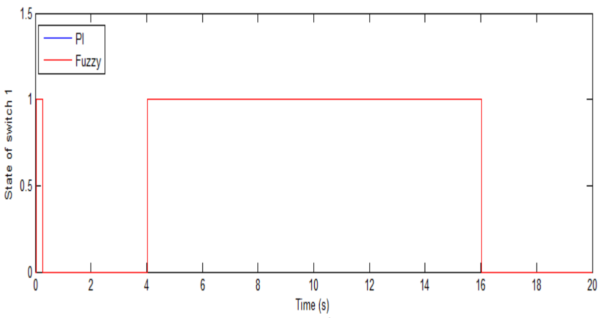

Fig. 22. State of switch S_1

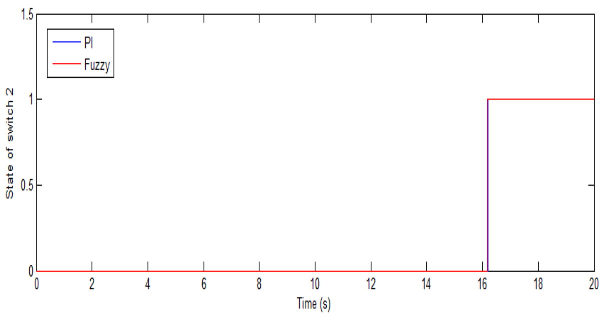

Fig. 23. State of switch S_2

Power management results are almost the same when we use the PI controller or the fuzzy controller for MPPT purpose because the power management controller (FLC 2) is unchanged.

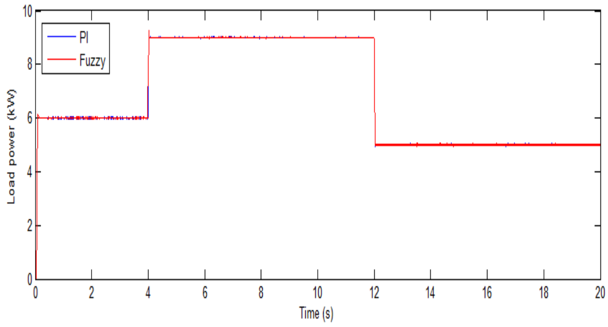

Fig. 24. Power delivered to load (kW)

We can see that available wind power is delivered to the load before using the battery as supplement (Fig. 18). Load demand is assured despite conditions of wind speed (Fig. 24).

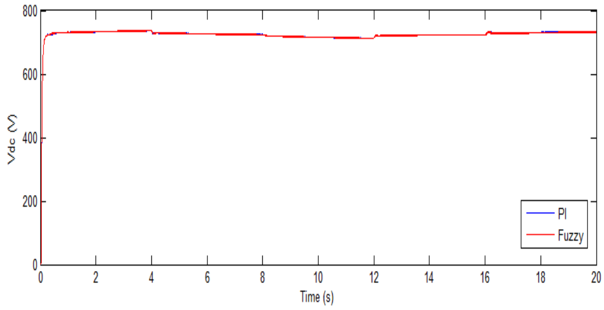

Fig. 25. DC voltage input of PWM inverter (V)

In the load side, the voltage input to the PWM inverter is maintained at a suitable value (Fig. 25), thus the quality of the charging voltage is maintained correctly in 380V, 50Hz in any wind conditions (Fig. 26).

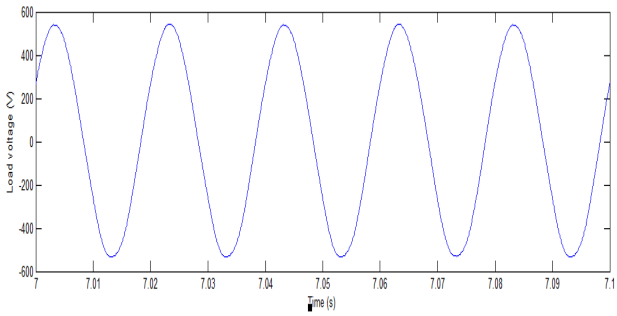

Fig. 26. Load line voltage (V)

These simulations show that our proposed controller has good results. It assured the load demand, despite the wind conditions with good strength and quality of the battery with the charging process of the battery to prevent a release of hydrogen and oxygen and/or sulfating.

8. Conclusion

This paper presents the control system using fuzzy logic for the distribution of electricity for stand-alone system. With information about rotor speed, load demand, battery state-of-charge and simple rules of fuzzy logic, control signals were generated for a maximum power recovered from the wind in respect of load demand, and can extend battery life. The simulation results show good behavior of our controllers to achieve these objectives.

As perspective, we will develop this system by adding an additional source (solar, hydro ...) and optimize the distribution of energy for remote sites. Then we will verify it by experimental work.

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