

Power Management of a Variable Speed Wind Turbine for Stand-Alone System using Fuzzy Logic

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Abstract—In this paper, a wind energy conversion system (WECS) using a variable speed synchronous generator and a battery to store extra wind energy is proposed. A fuzzy logic supervisor is developed to manage both the energy production and its storage to obtain an optimal behaviour of the system and to ensure the load requirement. Many simulation results are presented to show that the proposed method gives good performance for its application in autonomous wind energy systems and can extend battery life.

Keywords—Variable speed wind turbine, synchronous generator, fuzzy logic controller, stand-alone system.

I. INTRODUCTION

Wind power generation is more and more growing all over the world. Wind energy is called to play a crucial role in the future energy supply of the European Union and of the world. There are now thousands of wind turbines operating, with a total capacity of 121,188 MW of which wind power in Europe accounts for 55% in 2008 [1].

Wind power also offers a feasible solution to distributed power generation for isolated communities where utility grids are not available. In such cases, stand-alone wind energy systems can be considered as an effective way to provide continuous power to electrical loads. For isolated settlements located far from a utility grid, one practical approach to self-sufficient power generation involves using a wind turbine with battery storage to create a stand-alone system. If wind conditions are favourable, these stand-alone wind energy systems can provide communities with electricity at the lowest cost. Stand-alone wind energy systems often include batteries, because available wind does not always produce the required quantities of power. If wind power exceeds the load demand, the surplus can be stored in the batteries [2,3].

Synchronous generator has the capability of direct connection to wind turbines, with no gearbox. This advantage is favourable with respect to lifetime and maintenance. Synchronous machines can use either electrically excited or permanent magnet rotor [4,5].

A comparison between the variable speed wind turbine and the constant speed wind turbine shows that variable speed

reduces mechanical stresses: gusts of wind can be absorbed, dynamically compensate for torque and power pulsations caused by back pressure of the tower. This backpressure causes noticeable torque pulsations at a rate equal to the turbine rotor speed times the number of rotor blades. Variable speed use is good for extracting more prime mover power as in wind turbine or for providing optimum efficiency for the prime mover by increasing its speed with power. It also allows for a more flexible generator system [6].

In ancient autonomous systems, electrical power supplied by the turbine is transmitted to a battery and then the battery transfer energy for the load [7,8]. In modern structure, wind energy is primarily provided directly to the load and the battery is in second priority [9,10]. As a result, the number of charging and discharging of the battery is greatly reduced thereby extending battery life.

Intelligent controller based on fuzzy logic capable to ensure to the networks with distributed renewable energy generation. An increasing value of the energy available to users of the power system is expected as results of the implementation of the proposed intelligent load device [11].

Fuzzy logic provides a formal methodology for representing, manipulating, and implementing human's knowledge. We do not need the accurate model of the complex system. Fuzzy logic controller is also suitable for real time applications [12]. A fuzzy logic control for the photovoltaic systems with battery has designed in [13]. It controls the rate of current injection into the battery for energy storage or increases or decreases the load in priority order to match the optimal requirement.

In this paper, we propose a fuzzy power management for a WECS including a variable speed synchronous generator and a battery bank. This controller manages power production and power storage according to wind condition and load demand. Load is provided mainly by wind power, and when this power is not enough, the battery will be switched on to discharge. A resistance is switched on to waste the surplus if needed. By controlling duty cycle of the boost converter, we can manage battery charging process according to the available power and also can provide a suitable voltage for the inverter.

II. SYSTEM DESCRIPTION

Consider a stand-alone system with a 5.5kW pump, a 7.5kW induction motor and a 10kW water heater, powered by a 30kVA synchronous generator wind turbine and a battery storage.

In this variable speed wind turbine, a diode rectifier will rectify the AC power, then a boost converter will increase the DC voltage obtained to be suitable for both battery charging process and PWM inverter's operation.

If wind conditions are favorable, the wind turbine will be the main provider for load. If available wind does not produce the required quantities of power and battery's capacity is enough, the battery will be switched on to give power to load. If wind power exceeds load demand, the surplus can be stored in the battery and if the battery is full, the surplus will be discharged into a dumb resistance. Thus, the battery is not the main provider to load, so the charge-discharge cycle is reduced, battery life is extended.

We proposed a fuzzy controller to achieve these purposes. To do this, our controller needs two informations: the battery state-of-charge (SOC) and the error between wind power and load demand (DeltaP). Then our controller will decide the duty cycle of the boost converter (D), the moment to switch on and off the battery (S₁) and the moment to discharge the surplus into dumb resistance (S₂) (Fig. 1).

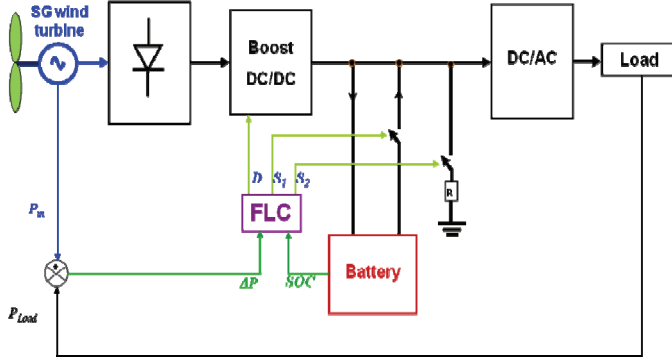


Figure 1. Proposed system with fuzzy controller.

III. MODEL OF WIND TURBINE

The static characteristic of wind turbine can be described by the relation between total power in the wind and mechanical power of wind turbine as in (1). It presents a basic model for wind turbine in electric power system.

$$P_w = \frac{1}{2} \rho \pi R_{turbine}^2 v_{wind}^3 \cdot \quad (1)$$

In wind power equation (1), ρ is air density (1.225 kg/m³), $R_{turbine}$ is the turbine radius in meters, v_{wind} is the wind speed in m/s. It is not possible to extract all kinetic energy of wind, thus it is extracted a fraction of power in wind as given in (2) and it is called power coefficient C_p of the wind turbine.

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

P_m is the mechanical power of wind turbine. The maximum power coefficient is given as $C_p = 0.59$. This coefficient is also known as Betz's limit. It can be expressed as a function of tip speed ratio- λ and pitch angle- θ .

The tip speed ratio λ is defined as (3):

$$\lambda = \frac{\omega_{turbine} R_{turbine}}{v_{wind}} \cdot \quad (3)$$

Assuming constant wind speed v_{wind} , the tips speed ratio λ will vary proportionally to the rotational speed of wind turbine rotor [14]. The highest value of C_p is typically obtained for λ values in the range of 8 to 9 (when the tip of the blades moves 8 to 9 times faster than incoming wind). On modern wind turbines, it is possible to adjust the pitch angle of the entire blade through servo mechanism [15]. If $C_p - \lambda$ curve is known for specific wind turbine with a turbine rotor radius $R_{turbine}$, it is easy to construct the curve of C_p against rotational speed for any wind speed.

In this paper, we use a simple wind turbine model, where inputs are wind speed and rotor speed, output is the mechanical power.

IV. POWER ELECTRONIC DEVICE

A. Diode rectifier

Output voltage of the three phase diode bridge rectifier [16]:

$$V_{rec} = V_{RMS} \sqrt{2} \frac{\sin(\pi/6)}{\pi/6} = 1.35 V_{RMS} \cdot \quad (4)$$

where V_{RMS} is root-mean-square value of input line voltage.

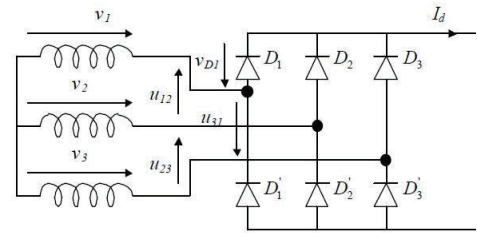


Figure 2. Three phase bridge rectifier.

B. DC-DC boost converter

Output voltage of the boost converter [17]:

$$V_{DC} = V_{rec} \cdot \frac{1}{1-D} \cdot \quad (5)$$

where the switching frequency f_s of switch S equal to the inverse of the switching period T_s generally lies in the range of 1 kHz to 1 MHz, depending on the switching speed of the semiconductor devices. The duty ratio D is the fraction of time that the switch spends in position 1, and is a number between zero and one. Our fuzzy controller will decide the duty cycle D for this boost converter to have an output voltage suitable for the PWM inverter's functioning and battery charging process.

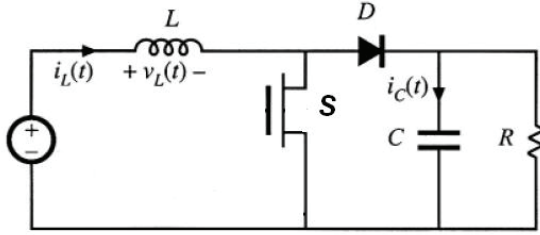


Figure 3. Boost converter.

Value of inductor L is chosen to minimize the ripple in current Δi :

$$L = \frac{V_{rec}}{2\Delta i} DT_s \quad (6)$$

Select the capacitor value C to obtain a given output voltage ripple peak magnitude Δv :

$$C = \frac{V_{DC}}{2R\Delta v} DT_s \quad (7)$$

Here we choose $L=4\text{mH}$, $C=5000\mu\text{F}$ to have an acceptable ripple in voltage and current.

C. Voltage source PWM inverter

The modulation ratio is defined using reference and triangular voltage amplitudes [11]:

$$m = \frac{u_{ref}}{u_{tri}} \quad (8)$$

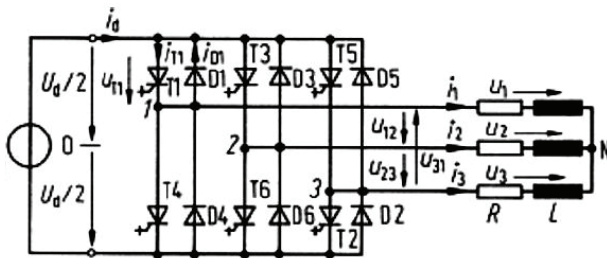


Figure 4. Voltage source PWM inverter.

In the region $m \cdot I$ the fundamental output line-to-line voltage is a linear function of m :

$$U_{ab} = \frac{\sqrt{3}}{2\sqrt{2}} m U_{DC} \quad (9)$$

Here we use the low-pass filter:

$$f_c = \frac{1}{2\pi\sqrt{LC}} \quad (10)$$

Choose $L=8\text{mH}$, $C=100\mu\text{F}$ to pass the 1st and 3rd harmonic of the output voltage ($f_c=177\text{ Hz}$), assure the smooth sinusoidal output voltage for the load.

V. FUZZY CONTROLLER

Fuzzy controllers belong to the class of knowledge based systems. Their main goal is to implement human know-how or heuristic rules in the form of a computer program, so to provide a mathematical formalism for this goal. Fuzzy controllers make human experience in the form of linguistic if-then rules; a fuzzy inference engine computes the control actions for each given situation [12,18].

A. Fuzzification

The FLC controller input variables are the battery state-of-charge (SOC) and the power error DeltaP (difference between wind turbine power and load demand). The output is the duty cycle D applied to the boost converter in order to charge the battery (ensuring a safe and efficiency functioning) and to guarantee the voltage's input sufficient for the voltage-source PWM inverter.

The linguistic term sets used for:

- Error of power DeltaP [N(Negative); SP(Small Positive); P(Positive); VP(Very Positive)].
- Battery state-of-charge SOC [Empty, Average, Full], varying from 0% to 100%, SOC is smaller than 20% means the battery is empty.
- Duty cycle D [Small, Average, Big, VeryBig], varying from 22% to 34% because of the input voltage's limit of the PWM inverter and the charging voltage for the battery.
- Switch S_1 and S_2 [Open, Close].

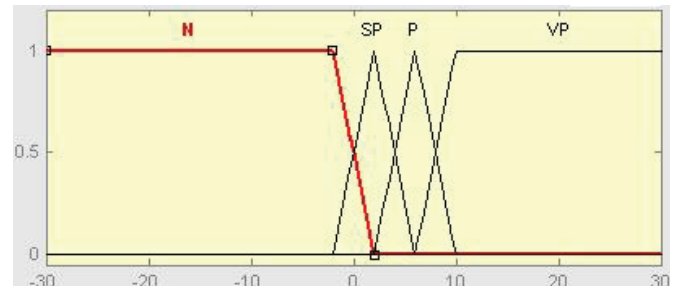


Figure 5. Five terms of error power DeltaP.

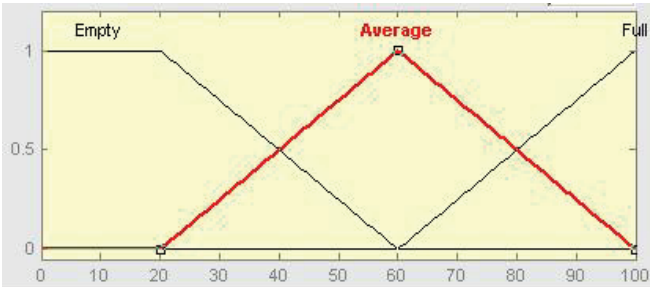


Figure 6. Three terms of battery state-of-charge SOC.

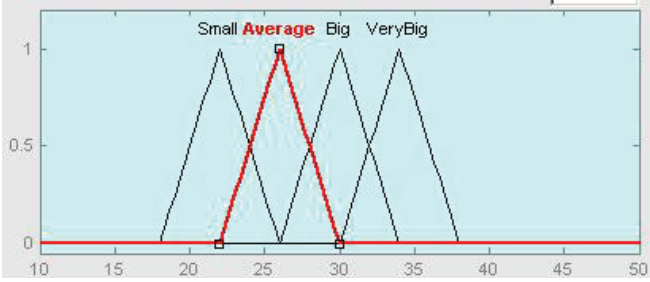


Figure 7. Five terms of duty cycle D.

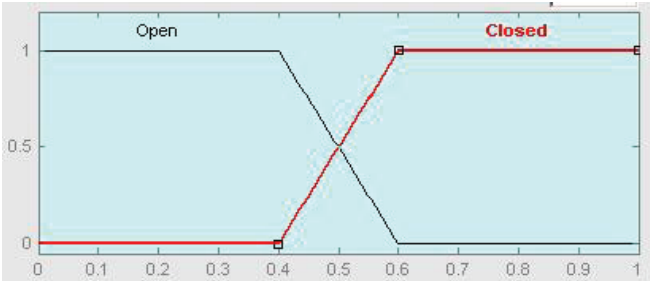


Figure 8. Two terms of state of switch S_1 and S_2 .

As inference method for the rules describing FLC dynamic is used the method of inference min-max. This type of method implies a simple treatment of data and generates linear characteristics (for two or several sizes of inputs) with marked discontinuities.

$$\mu_{A \cap B}(x) = \min(\mu_A(x), \mu_B(x)). \quad (11)$$

$$\mu_{A \cup B}(x) = \max(\mu_A(x), \mu_B(x)). \quad (12)$$

B. Fuzzy rules

The design of the rules was based on Mamdani fuzzy rules [19]. Example, “If the error between wind power and load demand is VeryPositive and the battery state of charge is Full, then the duty cycle should be VeryBig, switch 1 should be Opened and switch 2 should be Closed”.

The inference mechanism and the twelve IF-THEN rules defined in relation with the considerations, generates the approximation of the FLC output represented in tables 1, 2, 3.

TABLE I. RULES OF D

D		SOC		
		Full	Average	Empty
DeltaP	N	Big	Big	Small
	SP	VeryBig	Big	Small
	P	VeryBig	VeryBig	Average
	VP	VeryBig	VeryBig	Average

TABLE II. RULES OF S_1

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

TABLE III. RULES OF S_2

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

C. Defuzzification

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

$$\mu_C = \frac{\sum \mu_C(x_i) \cdot x_i}{\sum \mu_C(x_i)}. \quad (12)$$

Where x_i is a point in the universe U of the conclusion ($i = 1, 2, \dots$), and $\mu_C(x_i)$ its membership of the resulting conclusion set.

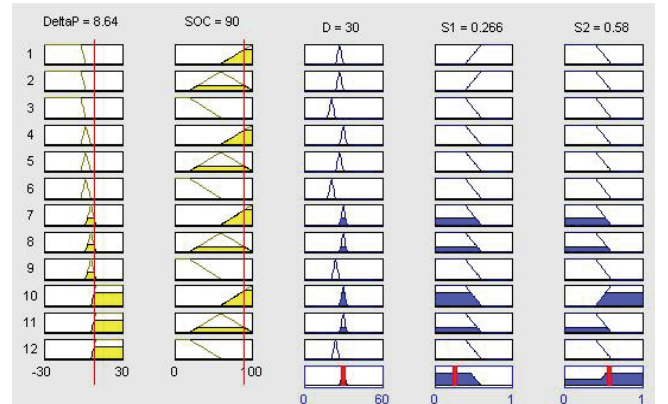


Figure 9. Defuzzification when DeltaP=8.64kW and SOC=90%.

VI. SIMULATION AND RESULTS

A. Initial condition

The system described in Section 2 is implemented in Matlab Simulink and the designed fuzzy logic controller is defined using the Fuzzy Logic Toolbox (Fig. 10).

The simulation is tested in 100 seconds, because of computer memory's limit. The water heater is supposed to work all the time, the pump and the induction motor will be switched on and off to vary load demand. Battery state-of-charge is supposed to be 95% (Full). In this case, we can verify the dissipation of surplus power to prevent the battery from gassing (operation of switch S_2). If wind power is not enough, switch S_1 will close to discharge the battery.

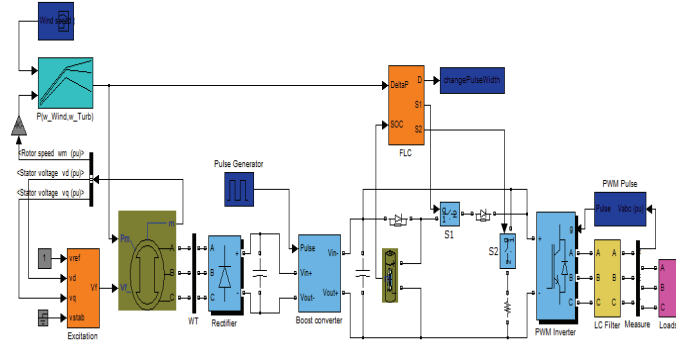


Figure 10. Implementation in Simulink.

The wind turbine output power according to wind speed and rotor speed is defined in (Fig. 11).

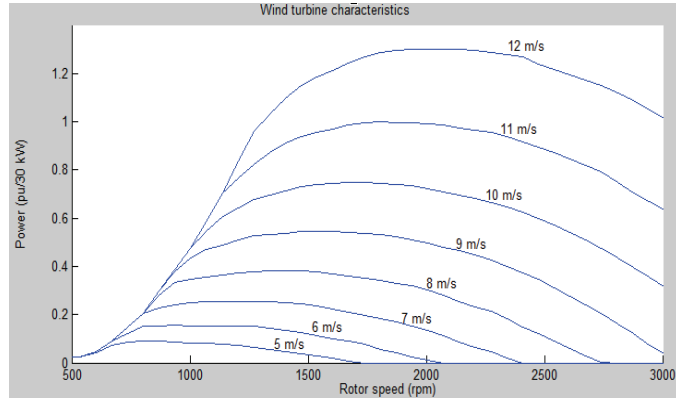


Figure 11. Wind turbine characteristics.

Supposed that at first the water heater and the pump are working (total load demand 15.5 kW). After 40 seconds, the pump is stopped (total 10 kW) and 40 seconds later, the induction motor is plugged in (total 17.5 kW). Wind speed changes from 9 m/s to 10 m/s and then slow down to 8 m/s (Fig. 12).

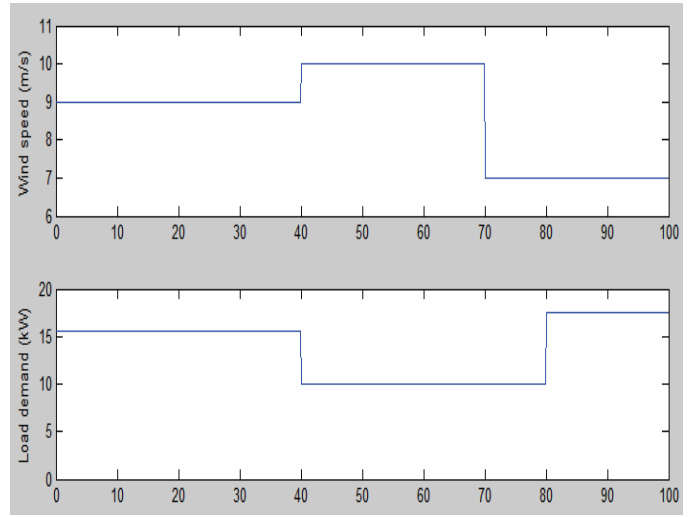


Figure 12. Wind speed and load demand

B. Results

In the first 40 seconds, the water heater and the pump are working (total 15.5 kW) while wind speed is 9 m/s, gives power output of wind turbine 16.6 kW (Fig. 13). The positive surplus (about 0.5kW) makes S_1 opened, but it's too small to charge the battery or to discharge through the dumb resistance, so S_2 is opened too. Duty cycle D is 29% (Fig. 14) makes a $715V_{DC}$ at boost converter's output, it is smaller than V_{bat} (738V) so the battery is not charged.

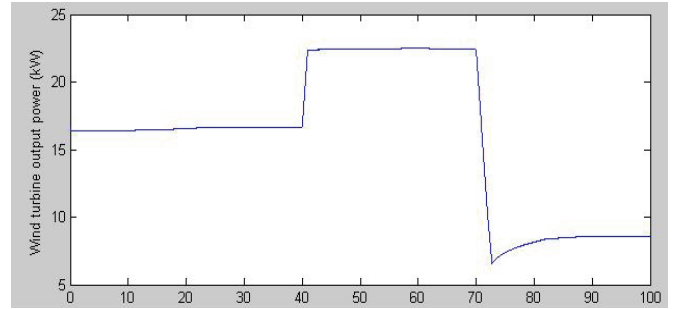


Figure 13. Wind turbine output power.

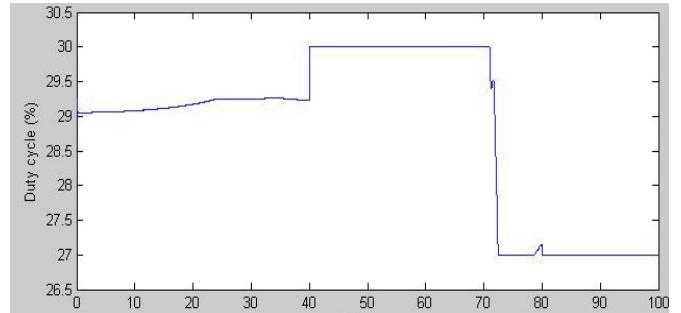


Figure 14. Duty cycle of the boost converter.

In the next 30 seconds, wind speed increases to 10 m/s while the pump is disconnected. The wind turbine output power is 22 kW while load demand is 10 kW.

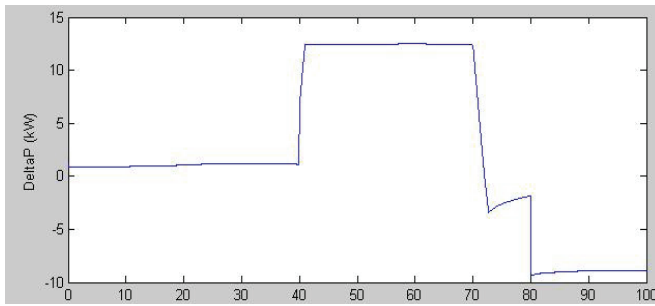


Figure 15. Error of power DeltaP.

So from now DeltaP is 12 kW (VeryPositive) (Fig. 15) while SOC is still 95% (Full), this surplus is so high for battery charging process, which may cause gassing the battery, so S_2 is closed to waste the rest into a dumb resistance (Fig. 16). Duty cycle D increases to 30%, but the battery is not charged because the voltage applied to battery's end is still smaller than 738V.

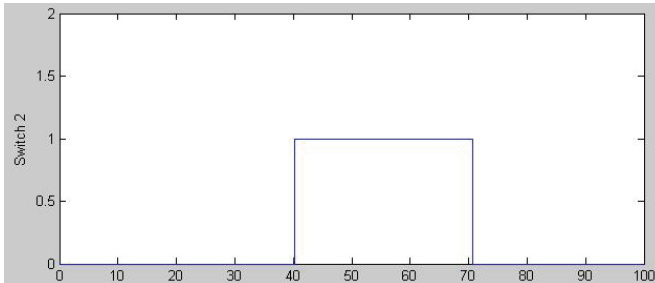


Figure 16. State of switch 2.

After 30 seconds, wind speed decreases to 8 m/s while load is still 10 kW. The wind turbine available power now is just 8 kW, we don't need to discharge no more then S_2 opened. The battery is used (S_1 closed) to provide power to load (Fig. 17), which leads to decrease SOC (Fig. 18). The duty cycle also decreases to 27% to keep the charging voltage below the battery voltage.

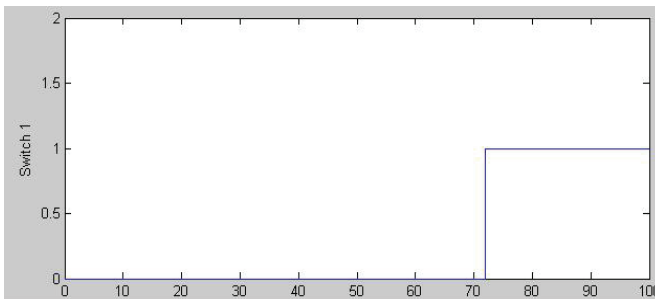


Figure 17. State of switch 1.

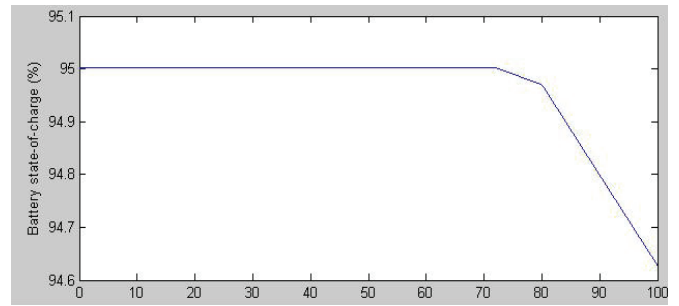


Figure 18. Battery state-of-charge.

In the last 20 seconds, the induction motor is on (load demand increases from 10 kW to 17.5 kW) while wind turbine output power now is still 8 kW, so the battery gives more power to meet load demand (Fig. 19).

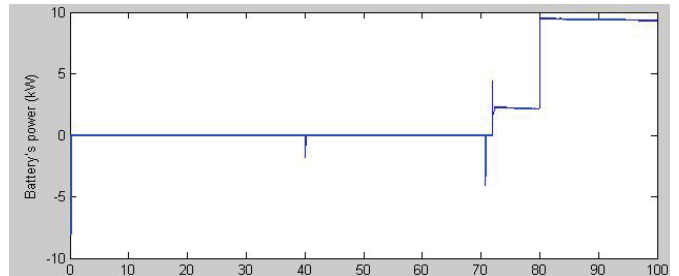


Figure 19. Battery power.

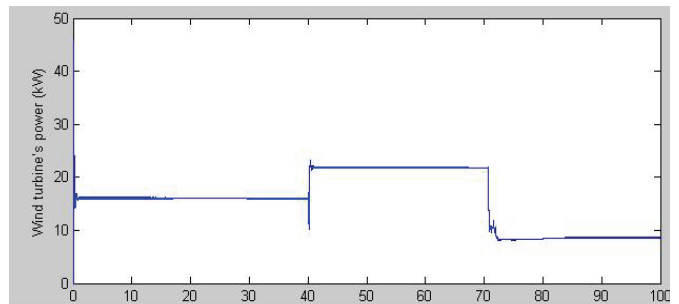


Figure 20. Wind turbine power.

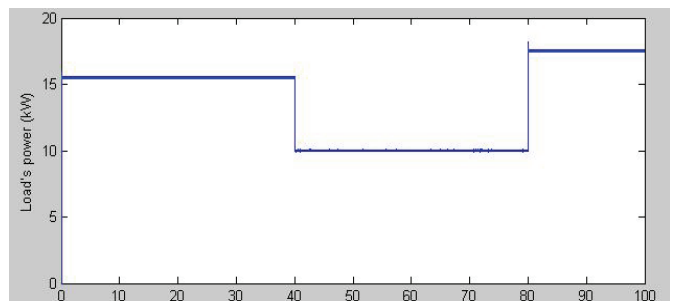


Figure 21. Load power.

Wind turbine available power is provided all before using the battery as supplement (Fig.20). Load demand is always respected despite wind speed conditions (Fig. 21).

In the load side, the DC voltage input for PWM inverter is kept in suitable value, so the load voltage quality is kept in good condition (Fig. 22). A 380V, 50 Hz voltage is always provided to load in any wind condition (Fig. 23, 24).

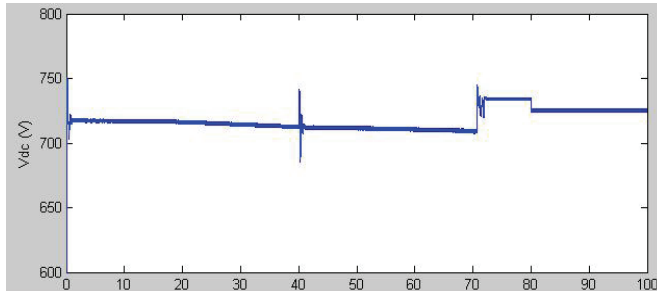


Figure 22. Output voltage of the boost converter.

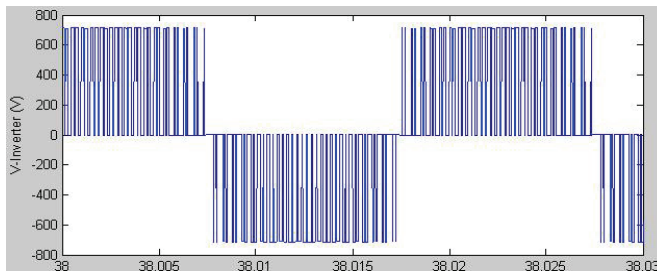


Figure 23. Output voltage of the PWM inverter.

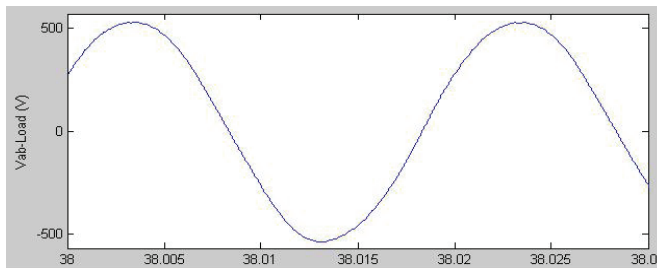


Figure 24. Load voltage.

These results show that our controller worked well. It assured the load demand despite wind condition with a good power quality and regulated battery charging process to prevent the battery from gassing and sulfating.

VII. CONCLUSIONS

This paper presents a fuzzy power management for electricity distribution for stand-alone system. With information about load and battery state-of-charge, control signals were generated to manage well the power production for any wind conditions in respecting load demand. The simulation results show a good behaviour of our controller.

Moreover, this performance has encouraged us to, in the future, develop our system by connecting with another source (photovoltaic, hydro...) and optimize the energy extraction for isolated systems. Then we'll verify it by experimental work.

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