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Fuzzy Control for Stand-Alone Wind/Photovoltaic System

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Abstract— **In this paper, a hybrid generation system for remote site is proposed. Two renewable energy sources : photovoltaic (PV) and wind, are controlled to deliver energy at optimum efficiency. Fuzzy logic control (FLC) is employed to achieve maximum power point (MPP) for both wind and PV generator using direct method, which requires no information about the generator's characteristics nor climatic conditions. Several simulation results are given to show the effectiveness and the good performances of the proposed control.**

I. INTRODUCTION

In recent years, the use of renewable energy resources is more and more increased due to the increasing need for energy and the shortage of traditional energy sources in the near future [1]. The literature review shows that, renewable energy systems are not cost competitive against conventional fossil fuel power systems. However, the need for cleaner power and improvements in alternative energy technologies gives good potential for wide-spread use of such systems.

Community facilities such as rural hospitals, schools, telecommunication and water pumping stations can contribute significantly to the welfare of people and rural development. Renewable energy systems have demonstrated the potential to provide support in some of the basic infrastructure needs in remote and urban areas. One of the interesting utilization of the renewable energy in community development is to electrify remote villages and rural areas located so far from power stations and distribution networks which are uneconomical to install [2]. Recent research and development in renewable energy sources have shown excellent potential, as a form of supplementary contribution to conventional power generation systems. In order to meet sustained load demands during varying natural conditions, different energy sources and converters need to be integrated with each other for extended usage of alternative energy [3].

In this paper, a stand-alone hybrid system including a variable speed wind turbine, a PV arrays and a battery bank is proposed. Wind and PV power generation both depends mainly on climatic conditions. Therefore, it is necessary to construct a system capable of generating maximum power under these constraints [4]. Conventional PI controller generally does not work well for nonlinear systems, higher order systems, and particularly complex and vague systems that have no precise mathematical models [5]. Fuzzy logic, was developed lately, is one of various types of artificial intelligent controller which can overcome these difficulties [6]. Here, two fuzzy logic controllers (FLCs) are designed to achieve the MPPT of the wind turbine and PV generator by controlling the duty cycle of two DC/DC converters. The MPPs are determined online using the Hill-Climb searching (HCS) method (for PV system) and the modified HCS method (for wind generating system). With this direct searching method, the generators give maximum power without any knowledge about power curve or ambient condition. The control algorithm is independent on generator's characteristics, achieving the fast dynamic responses for such a complex non linear system.

II. SYSTEM DESCRIPTION

Our system consists of a 20x20 PV arrays (15.12V, 0.902A at 1000W/m, 25^{o}C), a wind turbine driven PMSG (67Nm, 1700rpm) and a lead acid battery to power a 2kW pump, a 3kW induction machine and a 4kW water heater (Figure 1).

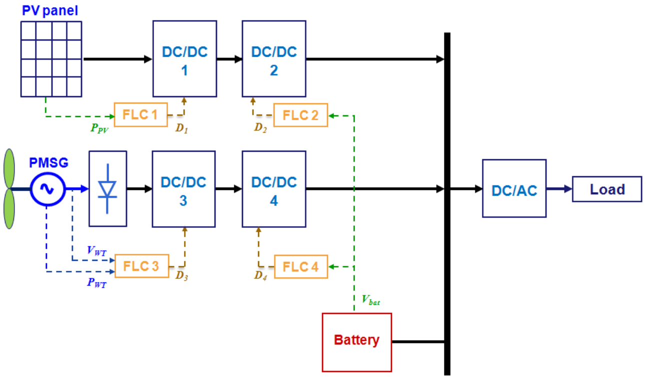

Fig. 1. The proposed hybrid PV-wind system.

The first fuzzy logic controller (FLC 1) vary the duty cycle of the converter DC/DC 1 to track the maximum power of the PV generation system. Input is PV power and output is duty cycle of the converter. Then we use a fuzzy voltage controller (FLC 2) to set the duty ratio of another converter (DC/DC 2) in order to adjust the DC output voltage of PV system following battery voltage.

For the wind turbine's maximum power tracking purpose, we adjust the rotor speed of the PMSG by using the FLC 3 to vary the duty cycle of the third converter DC/DC 3. A fuzzy voltage controller (FLC 4) is desiged to set the duty ratio of the converter DC/DC 4 in order to keep the DC output voltage of the wind system equal with battery voltage.

III. PV GENERATING SYSTEM

A. PV generator

The most commonly used model for a PV cell is the one-diode equivalent circuit. This model is generally considered adequate for PV system level design purposes [7]. PV modelling is based on the following mathematical equation:

$$I \quad = \quad I_{sc} - I_0 \left(\exp \frac{e(V + IR_s)}{nkT_c} - 1 \right) - \frac{V + IR}{R_{sh}} \qquad (1)$$

where the saturation current I_0 is temperature dependent, e is the charge of an electron, k is Boltzmann's gas constant and n is the idealizing factor of the diode.

In this paper, $V - I$ and $V - P$ characteristic curves of PV cell under different irradiances at 25^oC used are given in figure 2,3. Since a typical PV cell produces less than 2W, it is necessary to connect PV cells in series-parallel configurations to produce desired power and voltage ratings. Here we use a PV module consist of 20x20 cells. All are considered to be identical, and to work in identical conditions of temperature and irradiance.

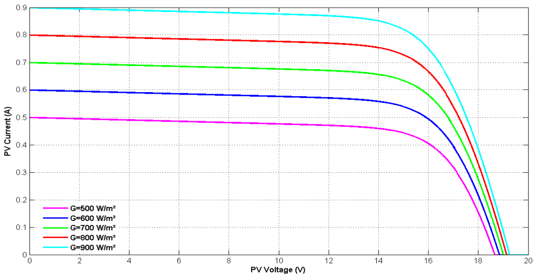

Fig. 2. Irradiance effect on PV array's performance : V-I curve

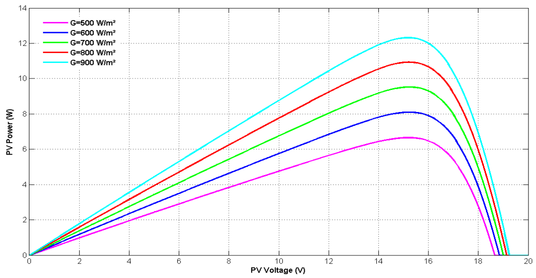

Fig. 3. Irradiance effect on PV array's performance : V-P curve

B. MPPT control for PV generator

The photovoltaic module operation depends strongly on the load characteristics to which it is connected. Indeed, for a load, with an internal resistance R, the optimal adaptation occurs only at one particular operating point, called Maximum Power Point (MPP). Thus, when a direct connection is carried out between the source and the load, the output of the PV module is seldom maximum and the operating point is not optimal [8].

Furthermore the characteristics of a PV system vary with temperature and irradiation. To overcome this problem, it is necessary to add an adaptation device between the source and the load. So, a MPPT controller is required to track the new modified maximum power point in its corresponding curve whenever temperature or irradiation variation occurs.

Many MPTT control techniques have been conceived for this purpose these last decades [9], [10], [11]. They can be classified as :

- Indirect methods : the MPP is estimated from the power curve of the PV generator.
- Direct methods : obtain the actual maximum power from the measure of the PV generator's voltage and current.

C. Proposed fuzzy HCS MPPT controller

In this paper, we use Hill-Climb searching method [10], applied in a fuzzy logic controller where inputs are change in PV power (dP_{PV}/dV_{PV}) and its derivative, output is duty cycle D_1 of the DC/DC converter. If $dP_{PV}/dV_{PV} = 0$, that means we are on the MPP. If we are in the up-hill region ($dP_{PV}/dV_{PV} > 0$), we should choose the duty cycle to increase the PV voltage to reach the MPP. If we are in the down-hill region ($dP_{PV}/dV_{PV} < 0$), we should decrease the PV voltage to reach the MPP (Figure 4).

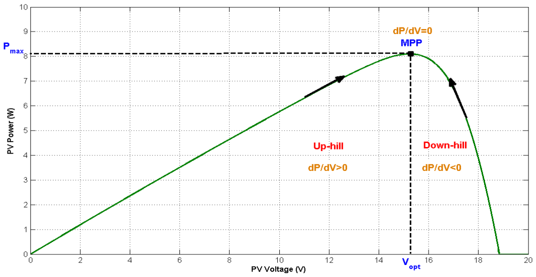

Fig. 4. Power-voltage characteristic of a PV generator

To do this, we use these linguistic term sets:

- dP_{PV}/dV_{PV} [VeryNegative, Negative, Zero, Positive, VeryPositive].
- $(dP_{PV}/dV_{PV})'$ [Negative, Zero, Positive].

The method of inference rules used is the min-max inference [12] and for implementation of rules we used Takagi-Sugeno system [6]. Example: If dP_{PV}/dV_{PV} is VeryPositive and $(dP_{PV}/dV_{PV})'$ is Zero, then $\Delta D_1 = -2\%$.

Fuzzy rules are summarized in table I.

TABLE I
RULES OF ΔD_1

ΔD_1		$(dP_{PV}/dV_{PV})'$		
		Negative	Zero	Posotive
dP_{PV}/dV_{PV}	VeryNegative	+2%	+2%	+2%
	Negative	+2%	+1%	+1%
	Zero	0%	0%	0%
	Positive	-1%	-1%	-2%
	VeryPositive	-2%	-2%	-2%

Then we calculate the output of the converter DC/DC 1:

$$D_1(k) = D_1(k-1) + \Delta D_1(k) \tag{2}$$

Output level ΔD_i of each rule is weighted by the firing strength w_i of the rule. For example, with dP_{PV}/dV_{PV} is PositiveBig and $(dP_{PV}/dV_{PV})'$ is Zero, the firing strength is:

$$w_i = \min(\mu_{dP_{PV}/dV_{PV}}(PB), \mu_{(dP_{PV}/dV_{PV})'}(Zero)) \tag{3}$$

Final output of the system is the weighted average of all rules output:

$$FinalOutput = \frac{\sum_{i=1}^{N} w_i \Delta D_i}{\sum_{i=1}^{N} w_i} \tag{4}$$

where N is the number of rules.

IV. WIND GENERATING SYSTEM

A. Wind aerodynamic

Mechanic power of a wind turbine can be expressed in terms of the air density ρ, the blade radius R_{blade}, and is the wind speed v_{wind} [13]

$$P_m = \frac{1}{2} C_p \rho \pi R_{blade}^2 v_{wind}^3 \tag{5}$$

where C_p is the power coefficient. This coefficient is also known as Betz limit. It can be expressed in terms of reduced velocity λ and blade angle θ : $C_p = C_p(\lambda, \theta)$. If ω is the rotor speed, the reduced speed λ is defined :

$$\lambda = \frac{\Omega R_{blade}}{v_{wind}} \tag{6}$$

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:

$$P_m^{opt} = \frac{1}{2} C_{pM} \rho \pi R_{blade}^2 v_{wind}^3 \tag{7}$$

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 (Figure 5).

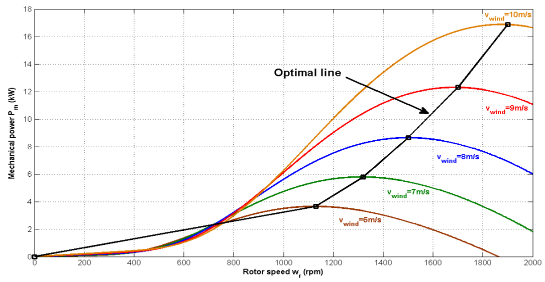

Fig. 5. MPP in function of rotor speed

B. PMSG driven wind turbine

Wind generating system consist of a variable speed PMSG driven wind turbine and a boost converter for MPPT purpose. Recently, PMSGs are used in wind turbine because of its advantages: higher reliability, less maintenance and more effective [14]. In addition, the use of variable speed allows for a better efficiency by extracting more efficient power in the wind by adjusting its speed to the wind. A system of variable speed PMSG is more flexible because it can adapt to wind variations [15].

The relationship between the torque and induced voltage is [16]:

$$T_e = k_T I_a \tag{8}$$

$$E = k_e \omega \tag{9}$$

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

$$E^2 = V_{WT}^2 + (I_a L_s \omega)^2 \tag{10}$$

$V_W T$ is the generator phase voltage and L_s is the inductance of the generator.

C. MPPT for PMSG driven wind turbine

Output voltage of the rectifier is given by [16]:

$$V_{rec} = \frac{3\sqrt{6}}{\pi} V_{WT} \tag{11}$$

Output voltage of the DC/DC converter [16]:

$$V_{DC} = \frac{1}{1-D_2} V_{rec} \tag{12}$$

$$V_{DC} = \frac{1}{1-D_2} \frac{3\sqrt{6}}{\omega} \sqrt{k_e^2 - (\frac{T_e L_s}{k_T})^2} \tag{13}$$

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 [17].

Here we propose a modified HCS method which base on the following wind turbine power characteristic:

$$\frac{dP_{WT}}{d\Omega} = \frac{dP_{WT}}{dV_{WT}} \frac{dV_{WT}}{d\Omega} = 0 \tag{14}$$

In a PMSG, rotor speed is proportional to the generator phase voltage, so :

$$\frac{dV_{WT}}{d\Omega} > 0 \tag{15}$$

Then we have :

$$\frac{dP_{WT}}{d\Omega} = 0 \Leftrightarrow \frac{dP_{WT}}{dV_{WT}} = 0 \qquad (16)$$

With equation 16, we can apply HCS algorithm without concern of the difference between P_m and P_e nor measurement of wind speed and rotor speed. So we can use a FLC like in PV generator case, which has two inputs: change in wind turbine power (dP_{WT}/dV_{WT}) and its derivative, output is duty cycle D_3 of the converter DC/DC 3. If $dP_{WT}/dV_{WT} = 0$, that means we are on the MPP. If we are in the up-hill region ($dP_{WT}/dV_{WT} > 0$), we should choose the duty cycle to increase the voltage to reach the MPP. If we are in the down-hill region ($dP_{WT}/dV_{WT} < 0$), we should decrease the voltage to reach the MPP (Figure 6).

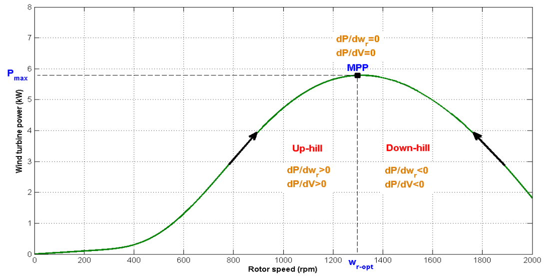

Fig. 6. MPP in function of rotor speed

Linguistic term sets used:

- dP_{WT}/dV_{WT} [VeryNegative, Negative, Zero, Positive, VeryPositive].
- $(dP_{WT}/dV_{WT})'$ [Negative, Zero, Positive].

Method of inference rules used is the min-max inference and implementation of rules used Takagi-Sugeno system like in section 3.

Fuzzy rules are summarized in table II.

TABLE II

RULES OF ΔD_3

ΔD_3		$(dP_{WT}/dV_{WT})'$		
		Negative	Zero	Posotive
dP_{WT}/dV_{WT}	VeryNegative	+3%	+3%	+3%
	Negative	+3%	+1%	+1%
	Zero	0%	0%	0%
	Positive	-1%	-1%	-3%
	Verypositive	-3%	-3%	-3%

V. FUZZY VOLTAGE CONTROLLER

The goal of this controller is to keep the DC output voltage of both PV generator and wind turbine follow the battery voltage.

Inputs for this controller are error between the actual battery voltage and the actual DC voltage mesured, and its derivative. Output is the duty ratio applied to the DC/DC converter. If the actual DC voltage is below the battery voltage, we increase the duty cycle to boost this DC voltage up and contrary we decrease the duty cycle.

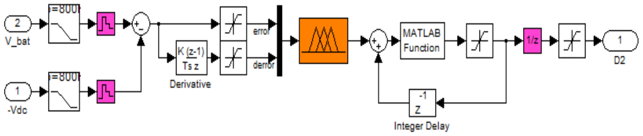

Fig. 7. Voltage controller

Linguistic term sets used for :

- Error [VeryNegative, Negative, SmallNegative, Zero, SmallPositive, Positive, VeryPositive].
- Change of error [Negative, Zero, Positive].

The method of inference rules used is the min-max inference [11] and for implementation of rules we used Takagi-Sugeno system. Example: If error is Positive and its change is Zero, then $\Delta D = +3\%$.

Fuzzy rules are summarized in table III.

TABLE III

RULES OF $\Delta D_2, \Delta D_4$

ΔD		Change of error		
		Negative	Zero	Posotive
Error	VeryNegative	-3%	-3%	-3%
	Negative	-3%	-3%	-2%
	SmallNegative	-2%	-2%	-1%
	Zero	0%	0%	0%
	SmallPositive	+1%	+2%	+2%
	Positive	+2%	+3%	+3%
	Verypositive	+3%	+3%	+3%

Then we calculate the output of the converter DC/DC :

$$D(k) = D(k-1) + \Delta D(k) \qquad (17)$$

Method of inference rules is the min-max inference and the implementation of the rules was based on Takagi-Sugeno system like in section 3.

VI. SIMULATION AND RESULTS

The system described in Section 2 is implemented in Matlab Simulink (Figure 8).

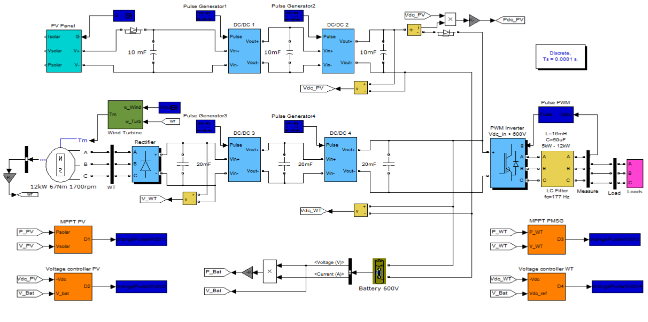

Fig. 8. Simulation in Simulink Matlab

Wind speed and irradiance are varied within 100 seconds to test our controllers in various conditions (Figures 9,10).

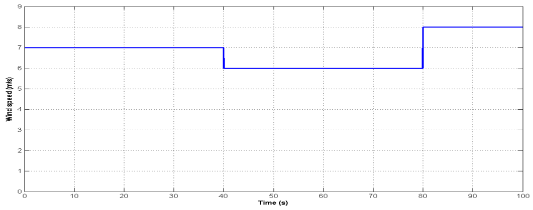

Fig. 9. Wind speed (m/s)

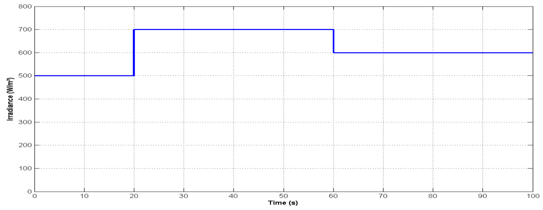

Fig. 10. Irradiance (W/m)

We can see that when irradiation and load change, FLC 1 works well to track the MPP of the PV arrays (Figures 11).

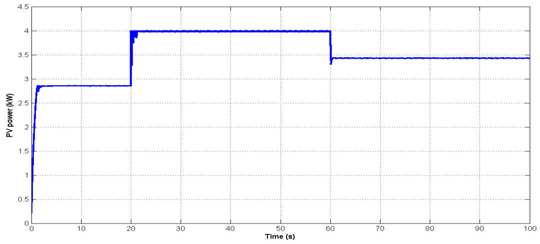

Fig. 11. PV output power (kW)

Duty cycle of the converter DC/DC 1 (Figure 12).

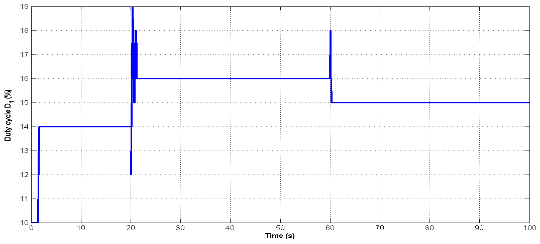

Fig. 12. Duty cycle D_1

FLC 3 work well to tracks the MPP of the wind turbine when wind speed change, it recovered the maximum power from wind to electric power without knowledge of wind speed and wind turbine's power curve, but there are small oscillations compare with PV systems because of the complex and nonlinear nature of the wind energy conversion system (Figures 13).

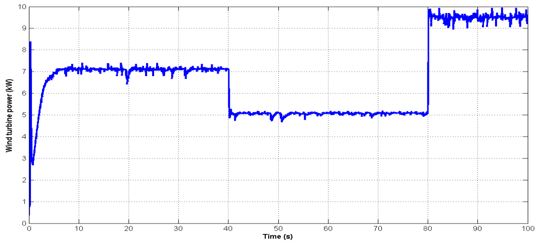

Fig. 13. Wind turbine power

The output duty cycle of the converter DC/DC 3 (Figure 14).

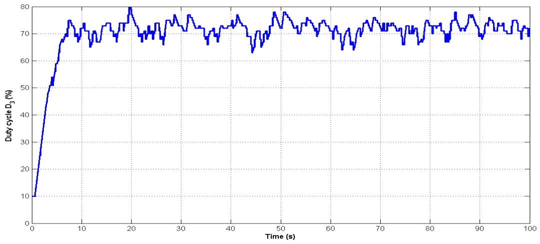

Fig. 14. Duty cycle D_3

DC output voltage of PV system and wind system follows battery voltage after a short time (Figures 15).

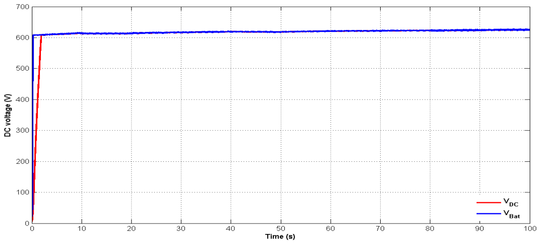

Fig. 15. Load power (kW)

Load demand is always respected despite climatic conditions (Figure 16).

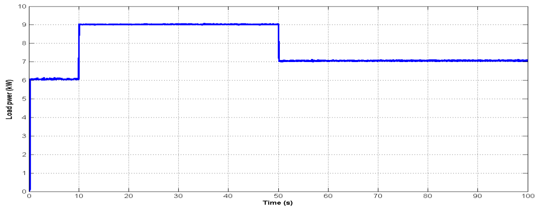

Fig. 16. Load power (kW)

We can see that our three FLCs work well to extract maximum power possible in any weather conditions (wind speed, solar radiance). Load demand of an isolated system is satisfied with good power quality.

VII. CONCLUSION

In this paper, a stand-alone hybrid generating system comprising two renewable energy sources, PV and wind, is proposed. Each of these sources is controlled to deliver energy at optimum eciency without any information about the generator power curve or climatic condition. Fuzzy voltage controllers are employed to keep the DC bus voltage unique before contected to a inverter. Simulation results show that our MPPT controller and voltage controller have worked well. It assured the load demand despite the wind speed and solar irradiation condition.

As perspective, we will apply these controllers in experimental work to verify its efficiency and feasible.

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