STUDY OF MAXIMUM POWER POINT TRACKING OF A WIND ENERGY CONVERSION SYSTEM USING FUZZY LOGIC

NGHIÊN CỨU XÁC ĐỊNH ĐIỂM CÔNG SUẤT CỰC ĐẠI CỦA HỆ THỐNG BIẾN ĐỔI NĂNG LƯỢNG GIÓ SỬ DỤNG KỸ THUẬT LOGIC MỜ

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Abstract:

This paper, we are present fuzzy controller for the maximum power point tracking of a wind energy conversion system using Fuzzy logic. The performance of the proposed controller design methodology is finally presented through a wind energy conversion system to maximize the extraction of power from wind energy (WE) system. It is effective optimal control for improvement of the performance of a variable-speed wind energy conversion system, for a squirrel-cage induction generator-based wind energy conversion system, the controller has successfully maximized the extraction of the wind energy. This was verified by the high power coefficients achieved at all the time.

Keywords:

Fuzzy controller, MPPT, power signal feed back (PSF), induction generator.

Tóm tắt:

Trong bài báo này, chúng tôi trình bày một phương pháp điều khiển để tìm điểm phát công suất cực đại của hệ thống biến đổi năng lượng gió (WE) thông qua việc sử dụng kỹ thuật logic mờ. Qua kết quả mô phỏng đã cho thấy: đây là kỹ thuật điều khiển tối ưu, hiệu quả để cải thiện hiệu suất của máy phát điện gió khi tốc độ gió thay đổi, áp dụng cho loại máy phát điện không đồng bộ rôto lồng sóc, bộ điều khiển đã cho phép khai thác tối đa điện năng từ nguồn năng lượng gió. Kết quả này đã được đánh giá qua các giá trị công suất cao thu nhận được ở tất cả các thời điểm vận hành.

Từ khóa:

Điều khiển mờ, tìm điểm phát công suất cực đại (MPPT), phản hồi tín hiệu công suất, máy điện cảm ứng.

1. INTRODUCTION

Huge exhaustion of fuel and growing concern in environment protection from using fossil fuel and nuclear energy sources. A lot of renewable power generation sources like wind energy, solar energy, wave energy, hydro power and more developed systems depend on hydrogen. Wind energy conversion systems is the fastest growing energy technology in the world. Wind energy

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changes throughout the day. The performance output power depends on the accuracy of tracking the peak power points by the maximum power point tracking (MPPT) controller. In the last years, there is significant research effort in control design for wind energy conversion systems [1], [2]. Fuzzy logic control of generator speed was used [3]. The advantages in using fuzzy logic controller against conventional PI controllers are pointed out in better response to frequently changes in wind speed. Ref. [1] shows the problem of output power regulation of fixed-pitch variable-speed wind energy conversion systems. Ref. [2] introduced an integral fuzzy sliding mode control. Ref. [3] maximize energy capture by determining the optimal rotor speed. In [2] pitch control was employed to capture a maximum energy from the wind. In this paper we will deal with variable-speed wind energy conversion systems (VS-WECS) with induction generator [4, 5], squirrel cage induction generator (SCIG) [6, 7, 8], which we will control on it to maximize the power efficiency. To achieve this goal the tip-speed-ratio of turbine must be keep at its desired value, in spite of, variations of wind. We deal with how can extract maximum power from available wind by suitable algorithm. and there is no methodical way for finding sufficient stability condition and good performance.

This paper is organized as follows. In section II, we introduce the wind energy conversion system model. Two techniques is presented for maximum power in section III. In section IV, sufficient fuzzy control systems and for the solvability of the controller design problem are proposed. Simulation is concluded in section V. Finally, section VI states the conclusions.

2. WIND ENERGY CONVERSION SYSTEM MODEL

This part demonstrates the wind turbine model by presenting the dynamic model of the wind turbine generator unit. Depending on the generation system, the SCIG used as generator in wind turbine. SCIG win turbines are coupled to the wind turbine rotor via a gearbox and linked to the grid by inverters to match the frequency of the power supply grid and its voltage. A wind energy system can be explained by a model that includes the modeling of the whole wind turbine. The wind energy system model is clarified by the equations of each of the wind turbine-generator units, meaning the turbine, the drive train, the induction generator, the control system and the grid, as is shown in figure 1. The exhaustive representation of the wind farm elements is given in [9].

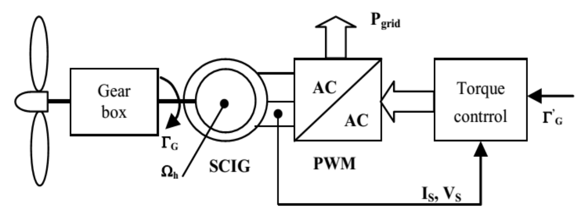

Figure 1. Diagram of the single wind turbine model

2.1. Wind turbine model

The aerodynamic torque and the mechanical power of the wind turbine are given by [10].

$T_m = 0.5C_p(\lambda, \beta)\rho\pi R^2 v_s^3/\Omega_l$ (1)

$P_m = T_m\Omega_l = 0.5\rho\pi R^2 v_s^3 C_p(\lambda, \beta)$ (2)

Where:

ρ is the air density;

R is the radius of the turbine;

v_s is the wind speed;

$C_p(\lambda,\beta)$ is the power coefficient; with $\lambda = \Omega_l R/v_s$ is the tip speed ratio;

Ω_l is the turbine speed.

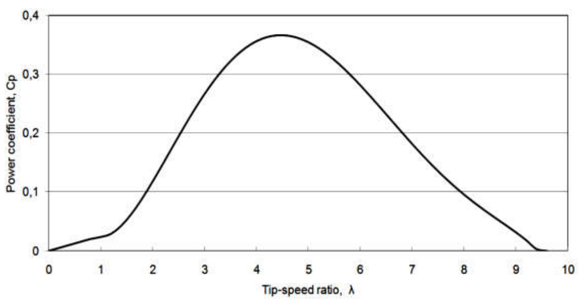

Figure 2. Power coefficient C_p versus tip speed ratio

Seeing as the maximum $C_p(\lambda,\beta)$ is obtained at a nominal tip speed ratio of $\lambda = \lambda_{opt}$, the control system should adapt the turbine speed at λ_{opt} to achieve maximum power. At this rotational speed, the maximum turbine power $P_{m,max}$ and the torque $T_{m,opt}$ result in $C_{p,max}$ being the maximum power coefficient. So fig.2 shows the relation between λ and $C_p(\lambda,\beta)$. The power extracted from the wind is limited in high wind speeds, by pitch of the rotor blades. The control is done with a PI controller which must take into consideration limitations in blades pitch angle and slew rate and the nonlinear aerodynamic characteristic [10]. The power coefficient C_p is function of the tip speed ratio λ and the pitch angle of rotor blades β, but for controlling SCIG wind turbines, C_p is a function of only λ, since β stays fixed in these turbines.

2.2. Drive train model

There are many types of generator as permanent magnet synchronous generators (PMSG), squirrel cage induction generators (SCIG) and doubly fed induction generator (DFIG). We prefer using SCIG in order to the use of induction generators (IG) is advantageous since they are relatively inexpensive, robust, and require low maintenance. The SCIG connected with the drive train through the gear-box gathering the Low-Speed Shaf (LSS) to the High-Speed Shaft (HSS). By canceling the viscous friction, this interaction can be showed as [9]:

$$J_h \frac{d\Omega_h}{dt} = \frac{\eta_s}{\eta_g}.T_m - T_g \quad (3)$$

$$J_l \frac{d\Omega_l}{dt} = T_m - \frac{n_g}{\eta_s}.T_g \quad (4)$$

Where:

T_g is the electromagnetic torque;

Ω_h is the rotor speed of the generator, $\Omega_h = n_g\Omega_l$, n_g is the gear ratio;

η_s is the gear efficiency;

J_h and J_l are the inertias at the high-speed shaft and low-speed shafts, respectively, which are computed as:

$$J_h = \eta_s(J_1 + J_{wt})/n_g^2 + (J_2 + J_g) \quad (5)$$

and:

$$J_l = \eta_s(J_1 + J_{wt}) + n_g^2(J_2 + J_g)/\eta_s \quad (6)$$

Where:

J_1 and J_2 are the inertias of the multiplier gears;

J_{wt} and J_g are the turbine and generator inertias, respectively.

2.3. Generator model

The squirrel cage generator work close to the angular synchronous speed with a very small slip. These squirrel cage induction generator are the least expensive and simplest technology comparing with wounded rotor and permanent magnet generator. The electrical equations of a SCIG expressed in a direct (d)-quadrature (q) coordinate reference frame rotating at synchronous speed ω_s are the following [11]:

$$\begin{cases} \frac{di_{sd}}{dt} = \frac{V_{sd}}{L_s} - \frac{R_s}{L_s} i_{sd} - \frac{L_m}{L_s}\frac{di_{rd}}{dt} + +\omega_s \left(i_{sq} + \frac{L_m}{L_s} i_{rq} \right) \\ \frac{di_{sq}}{dt} = \frac{V_{sq}}{L_s} - \frac{R_s}{L_s} i_{sq} - \frac{L_m}{L_s}\frac{di_{rq}}{dt} - \omega_s \left(i_{sd} + \frac{L_m}{L_s} i_{rd} \right) \\ \frac{di_{rd}}{dt} = -\frac{R_r}{L_r} i_{rd} - \frac{L_m}{L_r}\frac{di_{sd}}{dt} + (\omega_s - \omega)\left(i_{rq} + \frac{L_m}{L_s} i_{rq} \right) \\ \frac{di_{rq}}{dt} = -\frac{R_r}{L_r} i_{rq} - \frac{L_m}{L_r}\frac{di_{sq}}{dt} + (\omega_s - \omega)\left(i_{rd} + \frac{L_m}{L_s} i_{rd} \right) \end{cases} \quad (7)$$

Where:

i_{sd}, i_{sq}, i_{rd} and i_{rq} are the stator and rotor current (d,q) components, respectively;

V_{sd} and V_{sq} are the stator voltage (d,q) components;

L_s, L_r, L_m are the stator self-inductance, the rotor self-inductance, and the stator-rotor mutual inductance, respectively;

R_s and R_r are the stator and rotor resistances, ω_s is the stator field frequency;

$\omega_s = n_p\Omega_h$ is the speed in electrical radians per second (n_p is the number of pole-pairs).

The electromagnetic torque of the stator windings is stated as:

$$T_g = 1.5 n_p L_m (i_{sq} i_{rd} - i_{rq} i_{sd}) \quad (8)$$

The active and reactive powers of induction generator can be expressed by:

$$\begin{cases} P_g = 1.5\left(V_{sd} i_{sd} + V_{sq} i_{sq} \right) \\ Q_g = 1.5\left(V_{sq} i_{sd} - V_{sd} i_{sq} \right) \end{cases} \quad (9)$$

Power converter: The power converter is a standard IGBT-based voltage source controller (VSC). The nominal power of the power converter is equal to the nominal power of the generators that it has to control at maximum power point tracking conditions.

3. THE MAXIMUM POWER POINT TRACKING TECHNIQUES

3.1. Hill-climb search (HCS) control

The HCS control algorithm continuously searches for the peak power of the wind turbine. It can overcome some of the common problems normally associated with the other two methods [10]. The tracking algorithm, depending upon the location of the operating point and relation between the changes in power and speed, computes the desired optimum signal in order to drive the system to the point of maximum power.

HCS control of SCIG are demonstrated in [12]. HCS used a controller for MPPT control. In this method, the controller, using P_o as input generates at its output the desired rotor speed. The increasing or decreasing in output power due to an increment or decrement in speed is estimated. If change in power is positive with last positive change in speed, the search is continued in the same direction. If, on the other hand, increasing in speed causes decreasing in power obtained, the direction of search is reversed.

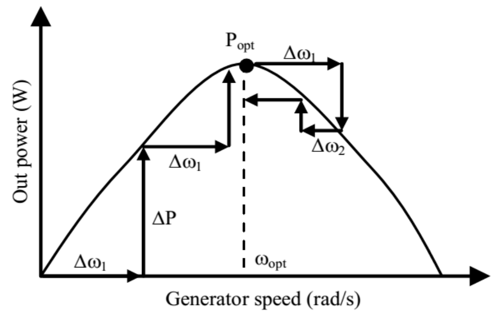

Figure 3. HCS technique for maximum power

3.2. Power signal feedback (PSF) control

In PSF control, it is required to have the knowledge of the wind turbine's maximum power curve, and track this curve through its control mechanisms. The maximum power curves need to be obtained via simulations or off line experiment on individual wind turbines. In this method, reference power is generated either using a recorded maximum power curve or using the mechanical power equation of the wind turbine where wind speed or the rotor speed is used and the maximum power is obtained [7-9].

PSF method uses a reference power which is maximum power at that particular wind speed. This presents an issue, as the prior knowledge of the wind turbine characteristics and wind speed measurements is required. Once this reference power is obtained from the power curve at particular wind speed, a comparisonof yield is done with the present power. Then error produced drives a Control algorithm. PI control refers to Proportional (P), integral (I) control. It contains P and I part that are manipulated to reduce the error between a known set point and the instantaneous values of the measured values.

The block diagram of a wind energy conversion system with power signal feedback (PSF) control method is shown in figure 7. The maximum output power datapoints corresponding to wind turbine speed can be stored in a lookup table [19-21]. Therefore maximum DC power output and the DC-link voltage were taken as input and output of the lookup table [13].

This curve can be obtained by off-line experiment on individual wind turbines or reference power is generated by using the mechanical power equation of the wind turbine where wind speed or the rotor speed is measured. Figure 4 displays the block diagram of a wind turbine SCIG with PSF controller for maximum power extraction [14].

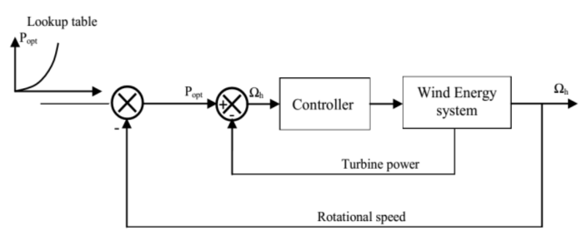

Figure 4. Block diagram of power signal feedback

In [13, 14], the turbine maximum power equation is used for obtaining reference power for PSF based MPPT.

$$P_{m(\max)} = 0.5C_{p(\max)}(\lambda_{opt},\beta)\,\rho\pi R^2 v_s^3 \qquad (10)$$

The PSF control block generates the reference power $P_{m(\max)}$ using (10) which is then applied to the controller. It can be seen that there is a maximum power coefficient $C_{p(\max)}$. If $C_{p(\max)} = 0.48$, the maximum value of C_p is achieved for $\beta = 0^o$ and λ_{opt}. A variable speed wind turbine follows the $C_{p(\max)}$ to capture the maximum power up to the rated speed by varying the rotor speed to keep the system at λ_{opt}.

4. THE PROPOSED CONTROLLER

Due to the nature of wind energy systems, the power available from the wind turbine is a function of both the wind speed and the rotor angular speed. The wind speed being uncontrollable, the only way to alter the operating point is to control the rotor speed. Rotor speed control can be achieved by using power electronics to control the loading of the generator. Without any given knowledge of the aerodynamics of any wind turbine, the HCS principle searches for the maximum power point by adjusting the operating point and observing the corresponding change in the output. The HCS concept is essentially an "observe and perturb-O/P" concept used to traverse the natural power curve of the turbine. With respect to wind energy systems, it monitors the changes in the output power of the turbine and rotor speed. The maximum power point is defined by the power curve in fig. 3 where $\Delta P/\Delta\Omega_h = 0$.

Thus, the objective of HCS is to 'climb' the curve by changing the rotor angular speed and measuring the output power until the condition of $\Delta P/\Delta\Omega_h = 0$ is met. There are several different ways of implementing the HCS idea. In this paper, the algorithm generates the reference speed by measuring the output power of the wind energy conversion system and adjusts the system's operating point accordingly. The $\Delta P/\Delta\Omega_h = 0$ condition is achieved when $\Delta P \approx 0$ because the amount of adjustment in the rotor speed is chosen to be proportional to the change in power.

4.1. Hill climb search (HCS) technique by fuzzy controller

The conventional HCS algorithm implementation is simple and is independent of turbine characteristics [12], but there still exist issues like the selection of step size. A big step size can track the maximum power point (MPP) fast but at the same time it can result in severe oscillations around the maximum power point. Reducing the perturbation step size can minimize the oscillations around MPP. However, a small step size can slow down the MPPT process especially when wind speed varies fast. To give a solution to this conflicting situation, a fuzzy logical control (FLC) algorithm which has a variable perturbation step size is proposed in this paper. The FLC algorithm can effectively track the MPP fast and smoothly. In the part of setting reference wind turbine rotational speed, the conventional HCS algorithm is replaced by the proposed FLC algorithm, which can realize variable step-size control.

Through fuzzy control, the step size can be large when the operating point is far away from the MPP while the step size can become small when the operating point comes close to the MPP. Therefore, the FLC algorithm can dynamically change its step size, depending on the turbine operation condition. The set of the fuzzy logical controller is described as follows: the input variables are $\Delta P(k)$ and $\Delta\Omega_h(k)$, while the output variable is $\Delta\Omega_{h-ref}(k)$. $\Delta P(k)$ and $\Delta\omega(k)$ can be obtained by:

$$\Delta P(k) = P(k) - P(k-1) \quad (11)$$

$$\Delta\Omega_h(k) = \Omega_h(k) - \Omega_h(k-1) \quad (12)$$

The member function of input variables of fuzzy logical controller with MATLAB is defined as follows: there are seven member functions of input variable $\Delta P(k)$: NL (Negative Large), NM (Negative Medium), NS (Negative Small), ZO (Zero), PS (Positive Small), PM (Positive Medium), PL (Positive Large). The fuzzi fication of the input variables by triangular membership functions (MFs). In table 1, it is showed the fuzzy rules for track the maximum power point.

Table 1. Fuzzy rules of HCS method

Error/ ΔError	NL	NM	NS	ZO	PS	PM	PL
NL	PL	PL	PM	PM	PS	ZO	ZO
NM	PL	PL	PM	PS	PS	ZO	NS
NS	PM	PM	PM	PS	ZO	NS	NS
ZO	PM	PM	PS	ZO	NS	NS	NM
PS	PS	PM	ZO	NS	NS	NM	NM
PM	PS	ZO	NS	NM	NM	NM	NL
PL	ZO	ZO	NM	NM	NM	NL	NL

4.2. Fuzzy Logic Controller (FLC) Model

Figure 5 shows a diagram block of pitch angle control of wind turbine using a FLC for low rated wind speed. The pitch angle of the blade is controlled to maximize the rotational speed of wind turbine and thus the output mechanical power of wind turbine. From figure 5, a measured rotational speed of wind turbine rotor in rpm from rotary encoder $\Omega_{h\text{-}measured}$ is compared to the desired rotational speed $\Omega_{h\text{-}ref}$. The FLC processes error, a delta error, and wind speed data of:

$$\Delta\Omega_h = \Omega_{h\text{-}measured} - \Omega_{h\text{-}ref}$$

$$\delta(\Delta\Omega_h) = \Omega_{h\text{-}n} - \Omega_{h\text{-}n\text{-}1}$$

The FLC variation of wind speed. In this paper, a wind turbine mechanical power is maximized. The wind turbine mechanical power (P) can be expressed using [8] and the model of the proposed of the fuzzy logic controller is shown in figure 6.

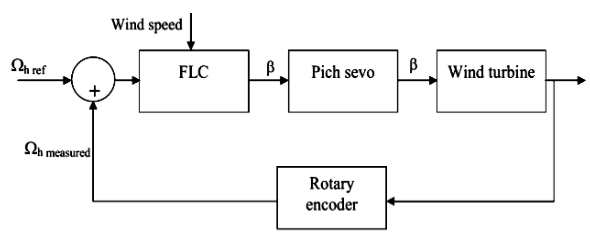

Figure 5. A block diagram of pitch angle control of wind turbine using FLC

The fuzzification module converts the crisp values of the control inputs i.e. error and change in error into fuzzy values or fuzzy MFs. The data base and the rules form the knowledge base which is used to obtain the inference relation. The data base contains a description of input and output variables using fuzzy sets. The rule base is essentially the control strategy of the system. It contains a collection of fuzzy conditional statements expressed as a set of IF-THEN.

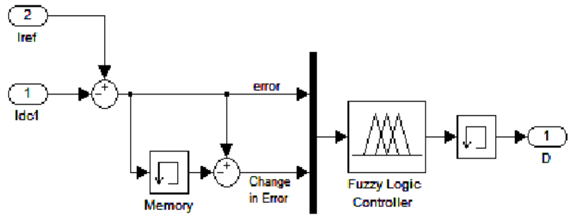

Figure 6. Model of the proposed FLC

For the given rule base, the FLC determines the rule base to be fired for the specific input signal condition and then computes the effective control action. The mathematical procedure of converting fuzzy values into crisp values is known as defuzzification. The designed control algorithm is as follows:

1. Measure generator speed, Ω_h.

2. Determine the reference power using (10)

3. This power reference is then used to calculate the current reference by measuring the rectifier output voltage

4. The error between the reference and measured and the change in this error are the inputs to the FLC.

4.3. Power signal feedback by fuzzy control

This technique use error between power reference power and change of error as inputs. Output is reference power. The variable inputs are linguistic variables as NL (Negative Large), NM (Negative Medium), NS (Negative Small), ZO (Zero), PS (Positive Small), PM (Positive Medium), PL (Positive Large). The fuzzy rules is the same in Table 1 and the input variables and the control O/P are like in figure 7 to figure 9 with other ranges.

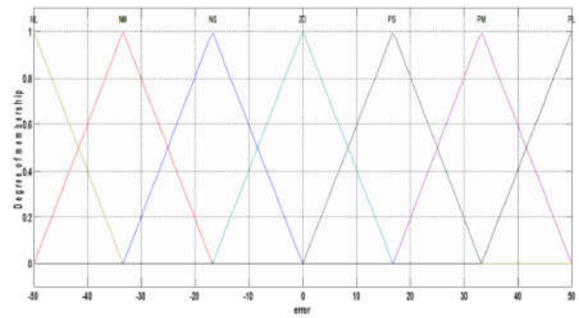

Figure 7. Membership function of error

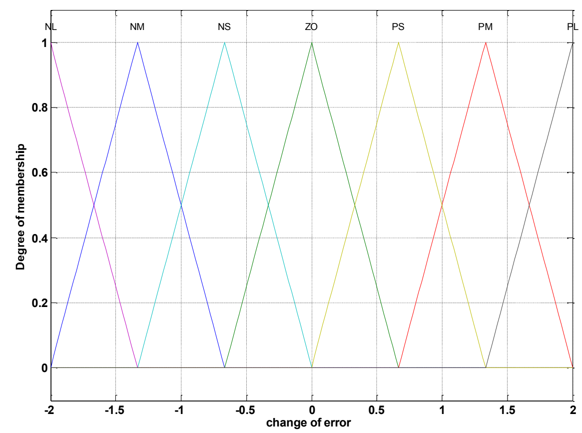

Figure 8. Membership function of change of error

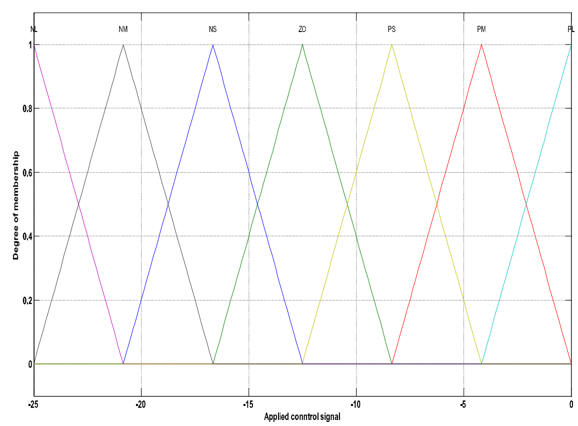

Figure 9. Membership function of control signal

5. SIMULATION AND RESULTS

The parameters of the case study wind energy conversion system are in table 2.

Table 2. Parameters of case study wind energy conversion system

Wind turbine		
Parameter	*Units*	*Value*
Rated power	W	4000
Base wind speed	m/s	11
Air density	kg/m^3	1.22
Number of balades		3
Rotor radius		2
SCIG		
Parameter	*Units*	*Value*
Rated power	W	4000
Armature resistance	Ω	0.425
Stator Inductance	mH	8.4
Flux linkage	Wb	0.433
Rated speed	Rad/s	150
Rated Current	A	10
Rated Torque	Nm	35
Load Resistance	Ω	900
Inertia J		0.0007
Viscous Damping		0.0015
Pole Pairs		4
Static friction		0.001

We introduce the comparison between four cases and show which technique approved the maximum power extraction. By applying the wind speed profile in figure 10 [9]. PSF by fuzzy control verify the largest value in power coefficient ≈ 0.48 which displayed in figure 11. In figure 12 Tip speed ratio for more stability and maximum value ≈ 7 for PSF by fuzzy controller. Figure 13 and figure 14 record the rotor rotational speed and generator speed, respectively. The most value of active power extraction clarified in figure 15. Figure16 listed the reactive power profile.

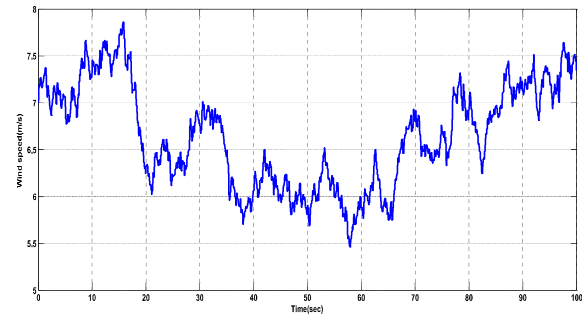

Figure 10. Wind speed profile [[9]

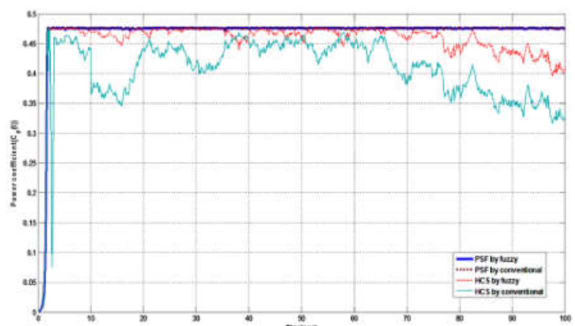

Figure 11. Power coefficient profile

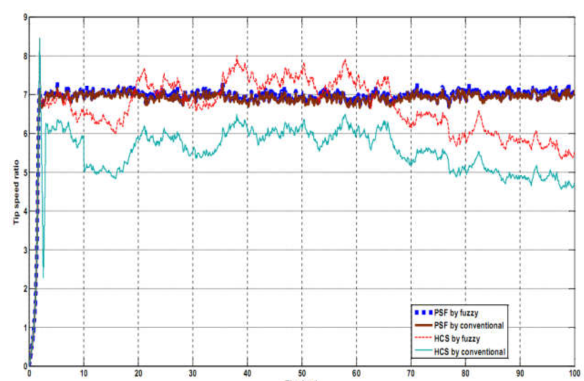

Figure 12. Tip speed ratio profile

The results explained the performance of PSF fuzzy control technique. This control can secure the stability of the system and can maximize the power coefficient at 0.48 as in figure 11. The integral term guarantees a system at zero steady-state tracking error for the reference inputs. The major advantage of integral controllers is that they have the ability to return the controlled variable back to the desired point. It can be seen that the introduction of the PSF fuzzy controller significantly increases the power putput.

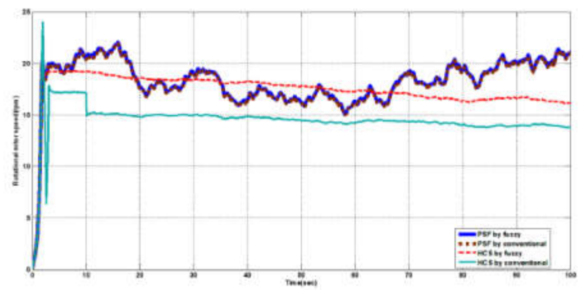

Figure 13. The trajectory of rotational rotor speed

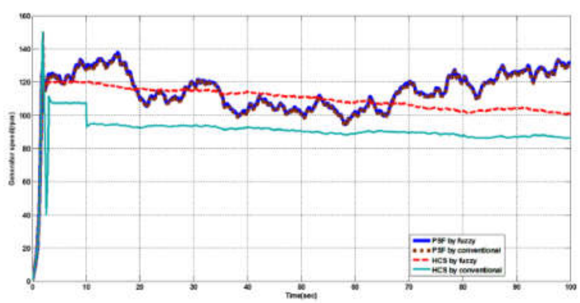

Figure 14. The trajectory of generator speed

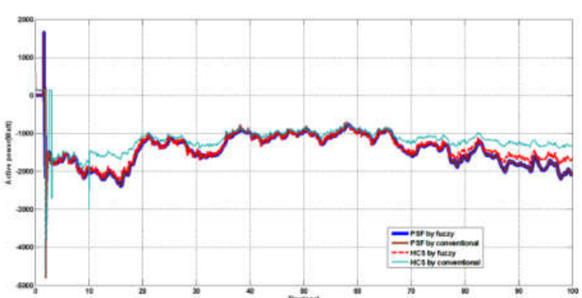

Figure 15. The trajectory of reactive power

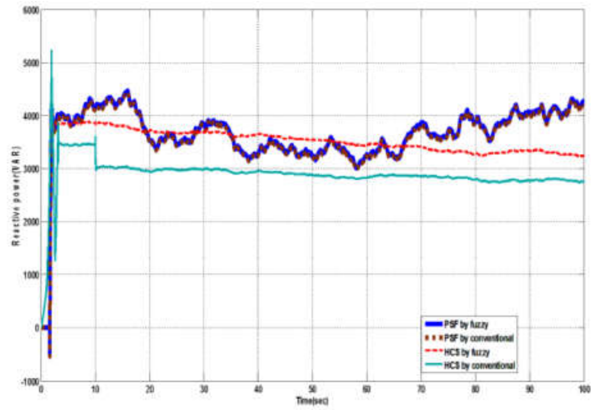

Figure 16. The trajectory of active power

6. CONCLUSION

We have presented fuzzy controller for the maximum power point tracking of a wind energy conversion system. It is effective optimal control for improvement of the performance of a variable-speed wind energy conversion system, for a squirrel-cage induction generator-based wind energy conversion system, the controller has successfully maximized the extraction of the wind energy. This was verified by the high power coefficients achieved at all the time.

The resulting PSF fuzzy controller is capable of tackling multivariable systems Compared with the other techniques, larger stability regions can be guaranteed. Wind energy conversion system has been given to illustrate the stabilizability and robustness property of the proposed fuzzy controllers.

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Biorgaphy:

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