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ORIGINAL PAPER

Maximum Power Point Tracking of Variable-Speed Wind Turbines Using Self-Tuning Fuzzy PID

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Abstract

This paper designs a new controller to increase efficiency of maximum power point tracking (MPPT) at nominal wind speed based on adaptive PID controller where its coefficients are optimized using a fuzzy controller. PID controllers are widely used in linear systems due to their simple structure and proper response. Due to stochastic changes of wind speed, wind turbines generally have nonlinear nature. In addition, turbines have different dynamic structures regarding their construction conditions. Thus, using a controller which can preserve system stability considering changes of system parameters and obtain reach steady state in the shortest possible time is necessary. In this method, information adopted from wind speed and nonlinear turbine model are used to identify system using closed loop identification. In the following, Hill climbing search (HCS) algorithm is used to determine optimal operating point of the turbine in the nominal wind speed range, online. Advantage of perturb and observe (P&O) methods includes simple structure and adaptability with different stochastic and nonlinear systems. The designed controller minimizes the error between output power of the turbine and the optimized power. This controller is simulated practically on a 3KW wind turbine. Simulation results indicate efficiency and robustness of the designed controller.

Keywords Wind turbine · Maximum power point tracking · Self-tuning fuzzy PID · Hill climbing search

Introduction

With the development of industrial revolution, energy requirement turned into a new form. Fossil fuels which are the main energy source in the current century have created many environmental problems for human. In addition, limitation of fossil fuels has made governments to obtain clean, cheap and renewable energy to even their way towards national development and security. Among renewable energy resources, wind energy has attracted scholar more attention due to easy access and high efficiency. In recent years due to development of power electronic, most wind turbine major manufacturers have manufactured MW generators with variable speed generator along with pitch angle control using permanent magnetic synchronous generator (PMSG) or double fed induction generator (DFIG) technologies [1]. Since PMSG have smaller size, brushless structure, more generating power and less waste compared to DFIG, its share is increasing the market. Among other advantages of wind turb
ines using PMSG technology, it's no gear structure, elimination of DC excitation system, complete controllability in extracting maximum power, generation at each rotation speed and contact distribution network [2, 3]. The power flow of the grid side converter should be controlled in order to maintain the DC-link voltage within constant limit, while the control of the generator side is set to suit to capture the maximum power converted by the wind.

Some researchers have studied and concentrated on modelling and control based on wind energy conversion system using PMSG, to show the system integration using grid connected models [4, 5]. The control methods of PMSGs can be divided into scalar and vector control [6]. Different types of vector control can be achieved for PMSG side such as direct torque control or indirectly by using field oriented control, and direct power control or voltage oriented control for the grid side [7]. In [8], the authors concentrated on power electronics firing angles of generator side converter and grid side inverter,

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which are controlled and adjusted to acquire desired values. A simple sensor less control technique using variable speed PMSG has been proposed in [9]. Controlling pitch angle of blades is performed with the aim of eliminate system instability and avoid repeat of necessary shutting down [10]. In [11], improvement of MPPT algorithm for PMSG of wind energy system has been proposed. In general, various techniques are employed for MPPT in wind energy conversion systems including 4 groups known as: tip speed ratio (TSR) [12, 13], optimum torque control (OT) [14–16], power signal control [17, 18] and perturbation and observation method (P&O) [18–20]. In order to control TSR using an expensive anemometer is necessary. Optimal torque control tries to control generator torque to maximize output power. Similarly, in signal control, maximum output power is obtained through controlling power signal via tracking optimal power curve. OT control method is not suitable for implementation due to high cost of torque meter especially in low power turbines. In [21, 22], a PMSG, fully-controlled rectifier and DC-DC converter are used to control load current and turbine torque. Using torque meter increases costs. In addition, using conventional PI controller in wind turbines which are nonlinear in most operating points reduce system efficiency. In [23], Modified particle swarm optimization (MPSO) is used to control MPPT system so that system reaches its balance point and effect of turbine inertia is minimized. In [24], authors have used voltage of *q* and *d* axes of the generator as inputs of the control system and current of *d* axis and rotation speed of the generator as outputs of the controller. This system is inside a control loop with passivity based sliding mode control (PB-SMC). Turbines which are connected to the distribution network should be able to deliver a specific value of active and reactive power to the network or track a time-variant characteristic of load profile. Therefore, a proper control approach should be designed for distributed generation (DG) system of the wind turbine. Main advantage of variable speed wind turbines is the ability to extraction maximum power from wind energy source. In order to obtain maximum power from wind, MPPT system should be employed. Many studied have been done to track maximum power point so that measurement sensors in wind conversion systems can be eliminated. Among which using maximum power curve which requires empirical information about the turbine characteristics can be mentioned. One of P&O control techniques is Hill climbing search (HCS) algorithm. HCS algorithm explores maximum output power at each time instant and its structure is more simple and flexible compared to other methods. In addition, it does not require background of turbine characteristics. In practice, wind speed varies instantaneously. Therefore, when wind speed increases or decreases, if speed of the generator's rotor does not change proportionately, power obtained from wind drops significantly. In [25], the HCS technique has been used to obtain MPPT of wind turbine speed controller. In this paper, the authors suggest a self-tuning technique associate with changeable efficiencies of the wind subsystem that can be run under stochastic wind speed. The reliability of the wind turbine systems and the cost of the equipment have been taken into account. The development of HCS to avoid the mechanical sensors using smart sensor-less speed controller was also an important issue in model design [8].

Purpose of this paper is to provide a stable control for increasing efficiency of the turbine at nominal wind speed. In this paper, MPPT using HCS with variable step is used for PMSG wind turbine. In addition, in order to decrease deviation error from optimum power, self-tuning fuzzy-PID controller is designed. PID controllers are one of the simplest and most applicable known controllers in industry but they might not perform well in highly nonlinear systems. Adaptive PID controllers tune their proportionality, integration and differentiation coefficients considering dynamic change of nonlinear systems.

Main contributions of the paper are as follows:

- Proposed practical and economical of self-tuning fuzzy PID controller for MPPT without any speed measurement sensor.
- Implementation of self-tuning fuzzy PID controller in MPPT of variable speed wind turbine based on HCS
- Grantee stability of the power grid using adaptive tuning of the controller parameters

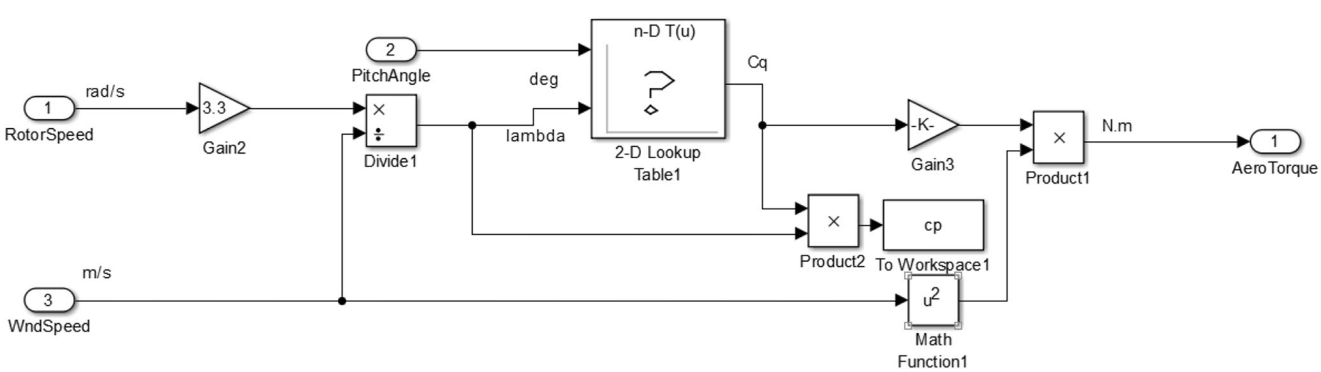


Fig. 1 Wind Turbine Model

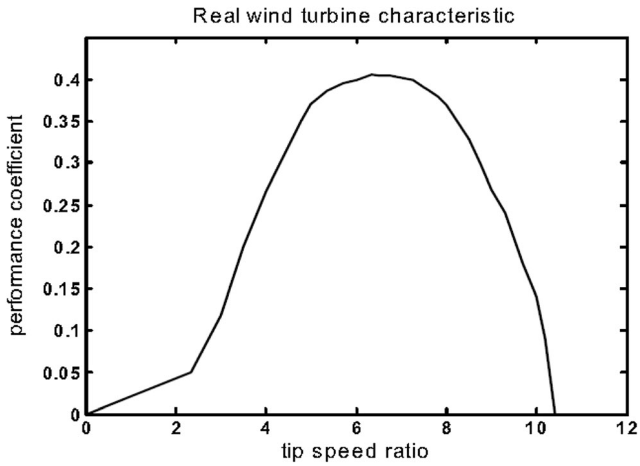


Fig. 2 Power performance coefficient

- Proposed controller can be implemented in real world wind turbines with nonlinearity or unknown parameters through additivity nature

The rest of this paper is organized as follows. Section 2 describes structure of PMSG turbine. Section 3 presents structure of self-tuning PID controller and HCS algorithm. Section 4 presents simulations and performance of proposed method. Finally, the paper is concluded in section 5.

Analysis of Wind Energy Conversion Systems

If friction of the rotor is ignored, mechanical equations of the wind turbine would be defined as follows.

$$T_m = \frac{1}{2}\rho\pi R^2 V^3 C_P(\lambda,\beta)\omega_r \tag{1}$$

$$P_m - P_{load} = j\omega_r \frac{d\omega_r}{dt} \tag{2}$$

$$\lambda = \frac{R\omega_r}{v} \tag{3}$$

in which, T_m is mechanical torque in N/m, ρ is air density in kg/m^3, R is radius of turbine blade in meter, V is wind speed in (m/s), $C_P(\lambda,\beta)$ is performance coefficient which is a dependent of tip speed, (λ) is tip speed, (β) is pitch angle of turbine blades, (j) is inertia and (ω_r) is angular velocity of the rotor's shaft in (rad/s).

In general, dynamic equation of PMSGs is defined as follows.

$$j\frac{d\omega_r}{dt} = T_e - T_m \tag{4}$$

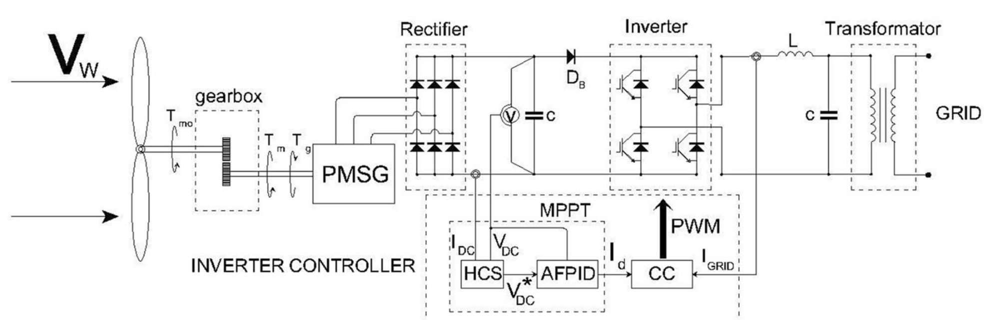
such that (ω_e) and (P) are electromagnetic field angular velocity and number of rotor poles, respectively. Eq. (2) shows that the subtraction between mechanical power and load power is directly proportional to speed variations of the generator shaft than time. Figure 1 shows simulated model of the wind turbine in MATLAB in order to obtain power performance coefficient curve $(C_P(\lambda,\beta))$. Wind speed, rotor's rotation speed and pitch angle of blades are inputs and aerodynamic torque is the output of the system applied to the generator. In addition, lookup tables of the turbine which record power performance coefficient of the turbine with respect to tip speed considering pitch angle can be seen in Fig. 1.

Most important characteristic of a wind turbine is its power performance coefficient. Figure 2 shows power conversion coefficient of the turbine with respect to tip speed of the blades. This curve is plotted according to Eqs. 1–4.

Characteristic of the Proposed Controller

Figure 3 shows structure of variable speed wind turbine. In this model, pitch angle of the blades is assumed to be constant and equal to zero. Mechanical torque extracted from wind turns a PMSG. MPPT controller can be studied from 3 aspects. First, matching output frequency of the generator with distribution network frequency, second, maximizing generated power and third, controlling output current to provide quality of the generated power. For this purpose, a three-phase rectifier, a DC link and a three to one-phase converter are used. In this paper, MPPT controller is studied. Two control loops are designed; in the external loop, voltage and current of the DC link are sampled. DC current and voltage represent a feedback from mechanical power obtained from wind.

Fig. 3 Structure of the wind turbine PMSG



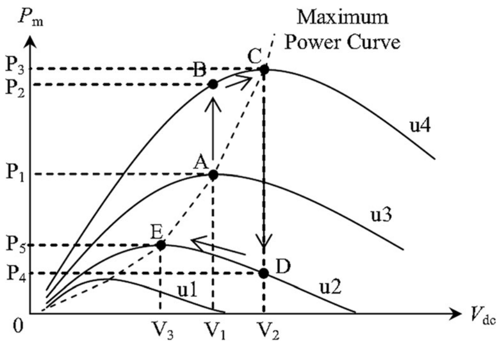


Fig. 4 HCS process [23]

Reference DC Voltage $\left(V^{*}_{dc}\right)$ Is Updated Instantly by Hill Climb Search Algorithm. In the Internal Control Loop, there Is a Self-Tuning Fuzzy PID Controller which Guides the Dc Voltage towards Reference Voltage by Adjusting Load Current (I_d) Requested from the Inverter

Optimal Search for Reference DC Voltage

In PMSG turbine, $C_P(\lambda, \beta)$ can be used to obtain mechanical power of the turbine as a function of DC voltage. There is an optimal DC voltage for each mechanical power. Figure 4 shows a number of $((P_m - V_{dc}))$ curves integrated with maximum power curve and optimal power points. In order to obtain optimal power using HCS, V^{*}_{dc} is explored at each instant. Basis of HCS is that if increase in V^{*}_{dc} lead to increase in $P_{m,}$ its increase continues, otherwise exploration path of V^{*}_{dc} become veer. Value of P_m is approximated with electrical power of the DC link.

Searching is performed in the discrete operating space where P_{dc} is approximately equal to P_m. Effect of turbine's inertia is minimized. Under specific dynamic conditions, V^{*}_{dc} would be constant and AFPID controller inside the internal control loop, controls the current requested from inverter (I_d) at each moment and the system is balanced immediately. Figure 4 shows exploration procedure for maximum power point when wind speed varies.

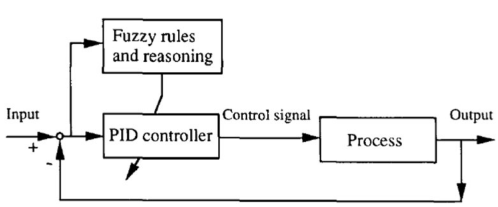


Fig. 5 Structure of the self-tuning fuzzy-PID controller

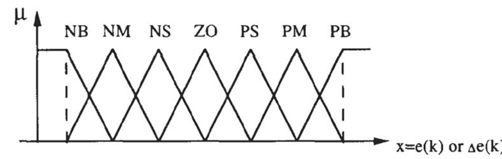


Fig. 6 Membership function of e(k) and $\Delta e(k)$

Design of Self-Tuning Fuzzy-PID Controller for Controlling V_{dc}

In the internal loop, an AFPID is designed so that V_{dc} leads it's reference. Input of the AFPID controller is defined as $(V_{dc} - V^{*}_{dc})$. Due to its simple structure and robustness, PID controller is known as the best industrial controller. Advantage of the adaptive PID controller compared to conventional PID is that it can adjust PID parameters at each moment and apply human experiences as fuzzy rules to control system parameters.

Discrete form of the PID controller transfer function is defined as follows

$$u(k) = K_p e(k) + K_i T_s \sum_{i=1}^{n} e(i) + \frac{K_d}{T_s} \Delta e(k) \quad (5)$$

Such that *Kp*, *Ki* and *Kd* are proportional, integral and derivative gain respectively and *u(k)* is the control signal, *e(k)* is the error between reference signal and process output. Due to limitations in extracting transfer function of the procedures and nonlinearity of most industrial procedures, one of the problems of PID controllers is obtaining optimal coefficient. In order to solve this problem and adapt with nonlinear procedures, a PID controller is designed by adjusting fuzzy gain.

Fuzzy Gain Scheduling

Figure 5 shows structure of the PID controller with fuzzy gain scheduling.

Table 1 Fuzzy tuning rules for K'_p

		Δe(K)						
e(K)		NB	NM	NS	ZO	PS	PM	PB
	NB	B	B	B	B	B	B	B
	NM	S	B	B	B	B	B	S
	NS	S	S	B	B	B	S	S
	ZO	S	S	S	B	S	S	S
	PS	S	S	B	B	B	S	S
	PM	S	B	B	B	B	B	S
	PB	B	B	B	B	B	B	B

Table 2 Fuzzy tuning rules for $K_d^{'}$

		Δe(K)						
e(K)		NB	NM	NS	ZO	PS	PM	PB
	NB	S	S	S	S	S	S	S
	NM	B	B	S	S	S	B	B
	NS	**B**	**B**	B	S	B	B	B
	ZO	**B**	**B**	B	B	B	B	B
	PS	**B**	**B**	B	S	B	B	B
	PM	B	B	S	S	S	B	B
	PB	S	S	S	S	S	S	S

In order to employ fuzzy rules and generate control parameters, it is assumed that $K_p$and K_p are in prescribed range [$K_{p.\ min}$, $K_{p.\ max}$]and [$K_{d.\ min}$, $K_{d.\ max}$] respectively. For facilitation, $K_p$and K_d are normalized using the following linear transformation.

$$K_p^{'} = \frac{K_p - K_{p.min}}{K_{p.max} - K_{p.min}} \qquad K_d^{'} = \frac{K_d - K_{d.min}}{K_{d.max} - K_{d.min}} \tag{6}$$

Input of the inference motor are error variables (*e(k)*) and derivative of the error (Δ*e*(*k*)) with the membership function of Fig. 6.

Equation of the PID controller in time format can be defined as follows.

$$G_C(s) = K_p\left(1 + \frac{1}{T_i s} + T_d s\right) \tag{7}$$

Such that $T_i = \frac{K_p}{} K_i$ and $T_d = \frac{K_d}{} K_p$, T_d and T_i are integration and derivative time constants.

In order to simplify and reduce fuzzy rules, a dependent variable called α is introduced which describes a relationship between time constant of integrator and derivative. Relationship between time constant of the integrator and derivative are defined as follows:

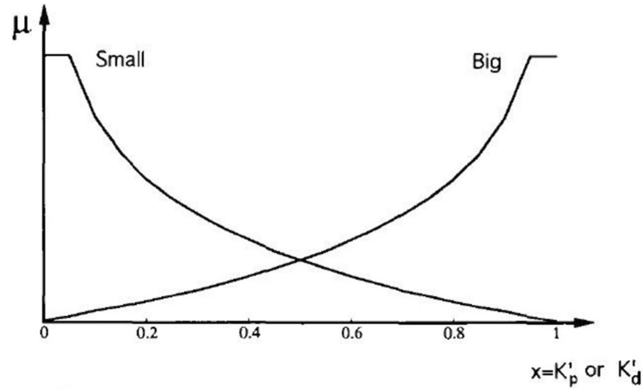


Fig. 7 Membership function of $K_p^{'}$ $K_d^{'}$

$$T_i = \alpha T_d$$

Integrator gain is obtained as follows:

$$K_i = \frac{K_p}{\alpha T_d} = \frac{K_p^2}{\alpha K_d} \tag{8}$$

parameters $K_p^{'}$ $K_d^{'}$ and α has fuzzy rules as follows:

$$\text{If } e(k) \text{ is } A_i \text{ and } \Delta e(k) \text{ is } B_i, \text{then } K_p^{'} \text{ is } C_i, K_d^{'} \text{ is } D_i \text{ and } \alpha = \alpha_i; \mathrm{i} = 1, 2, \ldots, \mathrm{m} \tag{9}$$

Such that A_i B_i and α_i have the qualitative values of Tables 1, 2, 3.

Membership function of parameters $K_p^{'}$ $K_d^{'}$ are defines as follows and shown in Fig. 7.

$$\mu_{small}(x) = \min\left(-\frac{1}{4}\ln(x), 1\right)$$
$$\mu_{big}(x) = \min\left(-\frac{1}{4}\ln(1-x), 1\right) \tag{10}$$

Variable α accepts discrete values of membership functions of Fig. 8.

Table 3 Fuzzy tuning rules for α

		Δe(K)						
e(K)		NB	NM	NS	ZO	PS	PM	PB
	NB	2	2	2	2	2	2	2
	NM	3	3	2	2	2	3	3
	NS	4	3	3	2	3	3	4
	ZO	5	4	3	3	3	4	5
	PS	4	3	3	2	3	3	4
	PM	3	3	2	2	2	3	3
	PB	2	2	2	2	2	2	2

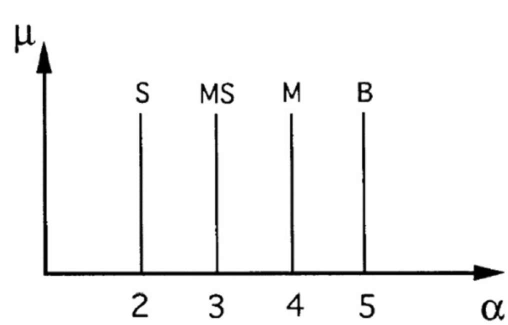


Fig. 8 Discrete membership function variable α

Table 4 Characteristics of 3Kw wind turbine of Sun-Air institute

Characteristics of 3Kw wind turbine of Sun-Air institute			
Performance range			
CUTIN WIND SPEED		3.75 $m\ \ s$	
CUTOUT WIND SPEED		15 $m\ \ s$	
RATED WIND SPEED		7.6 m/s	
Mechanical characteristics			
ROTOR DIAMETER		2*3.3 m	
HIGHT OF TOWER		12 m	
GEARBOX		1:1.6	
Generator characteristics			
MODEL		PMSG	
RATED POWER		3 KVA	
RATED VOLTAGE		380 v	
RATED CURRENT		4.5 A	
NUMBER OF POLES		22	
R_s		6.5 Ω	
$L_d = L_q$		52 mH	
j(MOMENT OF INERTIA)		0.1 $kg.\ m^2$	
Rectifier characteristics			
MODEL		3 phase rectifier(diode type)	
CUTOUT VOLTAGE		520 v	
PROTECTION BOX		Dummy load variable	
Dc link characteristics			
DC LINC CAPACITORS		3000 μF	
Inverter characteristics			
MODEL		3000 WB SMA inverter	
APPLICATION		On grid application	
COUNTINUOUS RATED POWER		3 KVA	
INPUT VOLTAGE		290–520 v DC	
OUTPUT VOLTAGE		220 v AC	
OUTPUT FREQUANCY		50 HZ	
Filter characteristics			
L		2 mH	
C		4.5 μF	
Transformator characteristics			
POWER		2.8 KW	
FREQUENCY		50 HZ	
PRIMARY WINDING	V = 184 v	R = 0.5 Ω	L = 5 mH
SECONDARY WINDIND	V = 230 v	R = 0.3 Ω	L = 6 mH
PARALLEL TIRBUTARIES		R = 4 Ω	L = 2.866 H

Fuzzy rules of Eq. (9) have obtained experimentally, shown in Tables 1, 2, 3. Fuzzy rules are implemented in the rules base.

Real value of i^{th} rule is calculated in Eq. (9) as μ_i.

$$\mu_i = \mu_{A_i}[e(k)].\mu_{B_i}[\Delta e(k)] \quad (11)$$

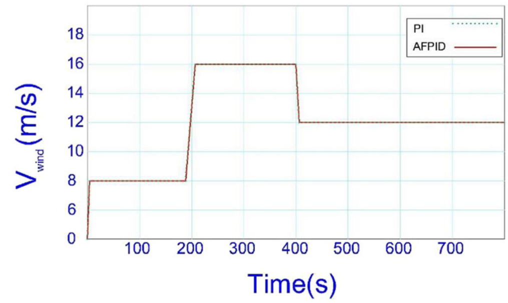


Fig. 9 Wind speed variations

such that the following condition is satisfied.

$$\sum_{i=1}^{m} \mu_i = 1$$

The chosen fuzzy controller is of Mamdani type with two inputs including error $V_{dc}-V^*_{dc}$ and error derivative and three outputs including K'_p K'_d and α. Triangular functions are used for membership functions of the inputs and Gaussian and triangular functions are used for outputs. Inference motor is of minimum-maximum Mamdani and the defuzzifier is of centroid type.

Simulation Results

In order to study the MPPT control system, 3KW wind turbine is simulated in MATLAB and characteristics of the turbine are given in Table 4.

In order to compare performance, self-tuning fuzzy-PID controller and PI controller are implemented on the turbine model. PI controller is designed with Ziegler Nichols. For more details about PID controller parameter design and limitations refer to [26, 27]. Step changes of wind speed in the operating region are shown in Fig. 9. Figure 10 shows that as angular speed of the blades changes, DC link voltage changes proportionally. As can be seen, AFPID controller leads to smaller deviation in comparison with PI controller. Figure 11 shows network voltage. As can be seen in Fig. 11, RMS voltage applied to the network using self-tuning PID is smoother and with less changes respect to implementation of

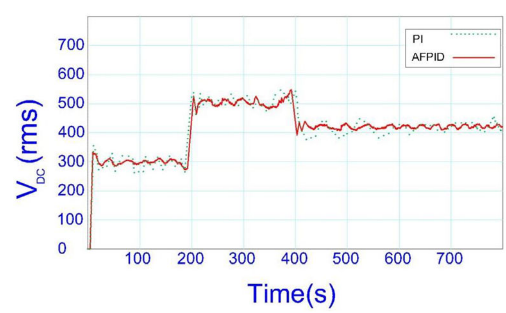


Fig. 10 DC link voltage

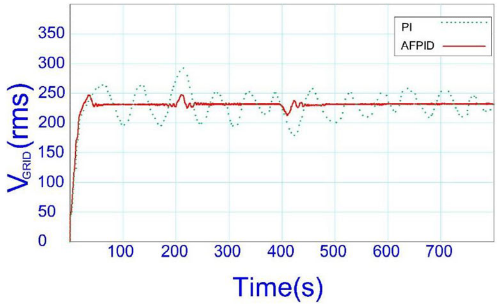


Fig. 11 RMS voltage applied to the network

PI controller. In other word, implementation of self-tuning PID controller improves performance of the system with respect to wind speed variations. Figure 12 shows that wind speed changes results in fluctuations of the output power. As can be seen, output power of the wind turbine using AFPID controller is robust against wind speed variations and it has less oscillations and deviations of optimum power. Output power of the turbine indicates that the MPPT system with PI controller does not perform appropriate due to its nonlinear nature but AFPID controller shows a suitable dynamic response according to variations of system parameters while being transferred to optimal operating point.

Conclusion

The MPPT algorithm employed in this paper reduces costs without any speed measurement sensor. On the other hand, it can be understood that PI controller can operate close to power curve but it fluctuates with a high frequency around the desired curve due to nonlinear nature of the system. Among advantages of self-tuning PID controller, its simple structure and easy implementation can be mentioned. It also performed well in identifying variable parameters and stability of the system. Numerous studies have been conducted in the context of searching optimal operating point. HCS is used widely in this context due to its simple structure and ease of implementation in MPPT systems. Using novel methods in search algorithms might be a challenge for future studies.

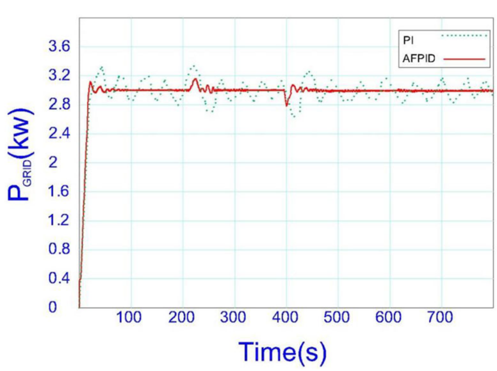


Fig. 12 Output power of the wind turbine

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