Pitch angle control using hybrid controller for all operating regions of SCIG wind turbine system

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Received 4 October 2013
Accepted 18 March 2014
Available online 9 May 2014

1. Introduction

Wind power generation technology was dominated by Squirrel-Cage Induction Generator (SCIG) based wind turbines before the year 2000. The SCIG machine, connected directly to a grid through a transformer, has been popular because of its reliability, low cost and robustness for any harsh environment. In this context, windmills begin to influence power systems more extensively, thus bringing new challenges to the power system with the high penetration of SCIG WT [1–3].One of the challenges is that wind speed is not constant and wind turbines output is proportional to the cube of wind speed, which causes the generated power of SCIG wind turbine to fluctuate, leading to the fluctuation of frequency and the occurrence of voltage flicker at the buses of the power source where SCIGs are connected. This fact can cause instability problem in the power system, especially when there are loads very sensitive to accept the variations of voltage and frequency [4,5].

There are some researches that focus their effects on providing new methods in order to smooth power output fluctuations. In Ref. [6] it is shown that a wind park with asynchronous wind turbines has the natural tendency of smoothing output power fluctuation, but if synchronization of output power fluctuation from synchronization phenomena is generated, the effect of smoothing power may be lost. The issue of power quality of WTs is also studied in Refs. [4,5,7–9] by means of power storage system. This is a very effective strategy when power quality is targeted for high sensitive loads, but it is not efficient from the economic point of view. In Refs. [10,11], a fly wheel energy storage system is proposed for smoothing wind farm output, but the flywheel energy system requires a complicated control strategy. Superconducting Magnetic Energy Storage (SMES) represents a very good system for wind power smoothing due to its response speed and high efficiency [12]. However its installation is still critical from a practical point of view due to high operational costs. Battery Energy Storage System (BESS) integrated with a static synchronous compensation

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(STATCOM) is proposed in Refs. [13,14], but its application in wind farm seems to be not a good choice because BESS has some issues such as its chemical process, low response speed and short service life.

The outstanding part of these wind turbines is only equipped with conventional blade pitch angle controller that is used to maintain the output power of wind generator at its rated level when the wind speed is higher than rated speed but below the cut-out speed. In recent times, there are several modern methods which are applied to this part of WT to improve output power quality. For example, a fuzzy logic controller and a minimum variance controller for smoothing operation is presented in Refs. [4,5,15], to compensate respectively the influence of parameter variations. Moreover Refs. [16,17], present a wind farm output power command which relies on average wind turbine output power: here output power standard deviation is corrected by using fuzzy and neuro-fuzzy approaches, respectively. On the other hand, output power command for each WT is determined by relying on wind turbine output power command. For this reason, applying the proposed method, it is possible to bring a stable operation for a considerable change in operating point. However, the control ways stated above partially smooth the output power fluctuations and hence problems originated by the output power fluctuations are partially solved, but they still result in a major drop in output power.

Obviously, pitch angle control has now become a very popular method for improving power quality in SCIG WTs. In this context, the authors propose a hybrid control strategy based on PI and fuzzy technique for pitch angle control that is based on the motivation of improving almost complete smoothing of wind power fluctuations as well as drops in output power in an optimal way when the wind speed is above and below rated speed. The effectiveness of the proposed model has been demonstrated in several parameters of energy generated from SCIG WT during wind speed variation. In Section 2, a model of a grid-connected wind farm with SCIG is presented, Section 3 presents hybrid control design for pitch angle controller, Section 4 are results and discussions and the last section shows conclusion.

2. Model of a grid-connected wind farm with SCIG

Fig. 1 illustrates SCIG-based wind farms coupled to a grid at the point of common connection (PCC). Mathematical modeling of SCIG wind farms is well documented in the literature [18]. The wind turbine rotor transforms the absorbed kinetic energy of the air into mechanical power. The energy available in the air is:

$$P_{\mathrm{wt}} = \frac{1}{2}\rho\pi R^2 V^3 \tag{1}$$

where P_{wt} is extracted power from the wind, ρ is the air density [kg/m^3], R is the blade radius [m] and V is the wind speed [m/s]. The turbine mechanical power which a wind turbine can extract depends on the power coefficient C_{p} and is given by:

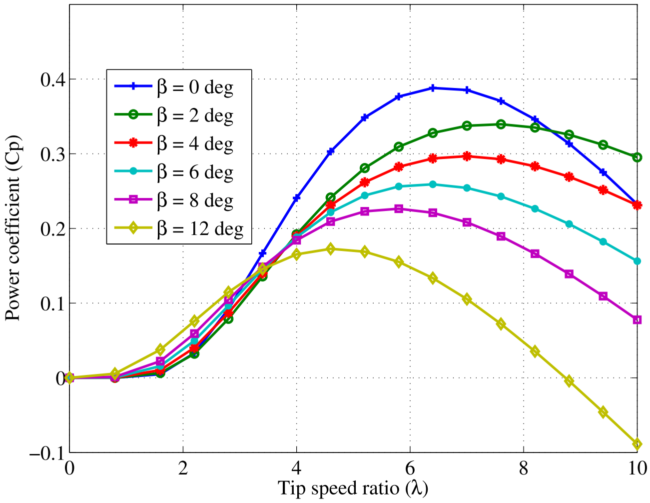

Fig. 2. C_{p}–λ curves for different pitch angles.

$$P_{\mathrm{mec}} = C_{\mathrm{p}}P_{\mathrm{wt}} = \frac{1}{2}C_{\mathrm{p}}\rho\pi R^2 V^3 \tag{2}$$

The power coefficient is a function of the turbine tip–speed ratio λ and the pitch angle β. The general expression is defined as in Ref. [18]:

$$C_{\mathrm{p}} = c_1\left(\frac{c_2}{\lambda_i} - c_3\beta - c_4\right)e^{\frac{-c_5}{\lambda_i}} + c_6\lambda \tag{3}$$

where the value of λ_i is:

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.008\beta} - \frac{0.035}{\beta + 1} \tag{4}$$

The coefficients c_1 to c_6 can also be found in Ref. [18]. From the wind turbine characteristics reported in Figs. 2 and 3, the optimal rotor speed for extracting maximum power can be found that based on wind speed. Moreover, at wind velocity higher than rated wind velocity where the turbine power output will exceed the nominal power, so it is necessary to reduce the mechanical power using pitch control, as previously shown in Ref. [19].

3. Hybrid control design for pitch angle controller

Eqs. (2) and (3) show the relation between the extracted power P_{wt} and wind speed V as well as C_{p} and the pitch angle β, respectively. Thus, the limitation of power output (the torque) and relative turbine speed is carried out using the pitch control. From this background, in this research we will design a hybrid controller that will adapt pitch angle in response to different power output. The power output can be supposed proportional to pitch angle β by linearization as a first order system [16,20,21]. Therefore, the whole

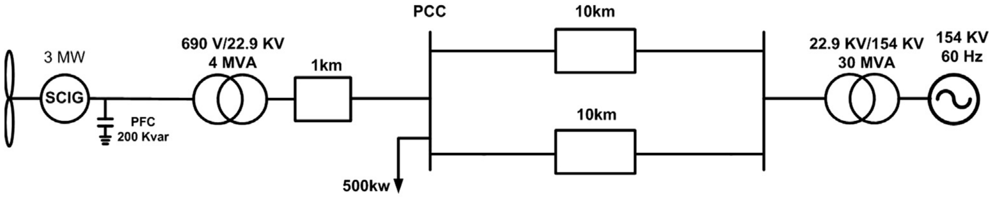

Fig. 1. Coupled SCIG based wind farms with PCC.

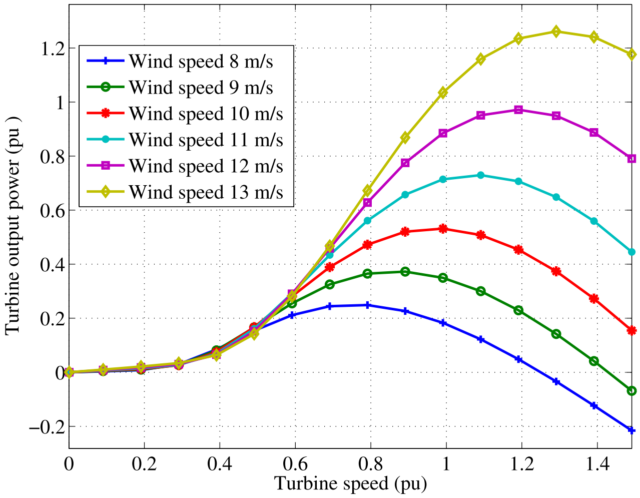

Fig. 3. Mechanical power curve.

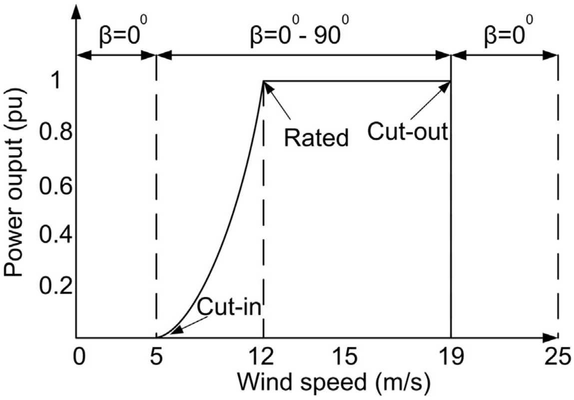

Fig. 4. SCIG output power curve and pitch angle control law.

hybrid control strategy is implemented as follows and as depicted in Fig. 4:

$$\beta_{\mathrm{ref}} = \frac{\Delta\beta}{\Delta P}(P_{\mathrm{mec}} - P_{\mathrm{nom}}) + \beta_0 \tag{5}$$

where β_0 is the initial pitch angle (optimal value), P_{nom} is the nominal mechanical turbine speed, $\Delta\beta$ and ΔP are small-signal state variables of β and P_{mec}, respectively.

Then, in order to take into account the blades direction, the system is controlled by a hydraulic or electric pitch servo, which is modeled as the first order transfer function as follows:

$$\beta = \frac{1}{1 + T_{\beta}s}\beta_{\mathrm{ref}} \tag{6}$$

Table 1
PI controller parameters.

Parameter	Formula	Value
Proportional gain	$K_c = 0.45K_u$	5
Integral gain	$T_i = 0.85T_u$	25

where s is the Laplace operator and T_{β} is the time constant of the orientation system of the blades. Pitch servo is employed for proper positioning of the blades. Moreover, the pitch actuation system could not respond immediately and it is also limited by its actuation speed. Thus pitch rate is included to get more realistic responses from the pitch angle control system. The maximum response speed of pitch rate and the regulations range of pitch angle are set to $\pm 3(°/s)$ and $0°-90°$, respectively.

Based on the above presented analysis, the diagram in Fig. 5 describes the proposed controller, namely a hybrid control strategy for pitch angle controller of SCIG WT, which is based on the conventional PI and fuzzy technique integration. When the rotor speed is higher than the base generator speed given by the manufacturer (measured wind speed is higher than rated speed), the β selection switch move to β_{PI} input; thus, $\beta_{\mathrm{ref}} = \beta_{\mathrm{PI}}$. On the other hand, the β selection switch moves to the β_{fuzzy} input (measured wind speed below rated speed), thus $\beta_{\mathrm{ref}} = \beta_{\mathrm{fuzzy}}$.

3.1. *Conventional PI controller*

From eq. (5) and [17], a proportional integral (PI) control block is designed using this linear model that maintain output power constant when the wind speed is above rated speed. Fig. 5 shows that a difference between the measured power P_{mec} and power reference P_{nom} goes through the PI controller, which regulates the output accordance with the relative error $\varepsilon = (P_{\mathrm{mec}} - P_{\mathrm{nom}})/P_{\mathrm{nom}}$. In this research, we use Ziegler–Nichols equations [22] to choose a proper set of control gain parameters that is based on the empirical knowledge of the ultimate gain K_u and period T_u [22] as reported in Table 1:

Fig. 2 shows that the maximum power extraction is achieved at $\beta = 0°$. At high wind speed, β must be adjusted to limit the aerodynamic power. Thus the control strategy implemented in this controller is summarized in eqs. (7) and (8):

$$\beta_{\mathrm{ref}} = \frac{\Delta\beta}{\Delta P}(P_{\mathrm{mec}} - P_{\mathrm{nom}}) + \beta_0 \ \text{for} \quad 0 < P_{\mathrm{mec}} < P_{\mathrm{nom}} \tag{7}$$

$$\beta_{\mathrm{ref}} = \beta_0 = 0° \qquad \text{for } P_{\mathrm{mec}} \geq P_{\mathrm{nom}} \tag{8}$$

3.2. *Fuzzy logic control (FLC) for smoothing power output*

Since the PI controller is used for a specific linearized model related to nominal frequency, this can provide insufficient damping for any different operating point caused by disturbances

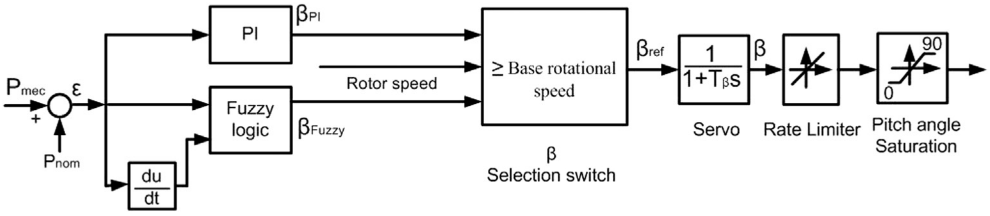

Fig. 5. Hybrid pitch angle controller.

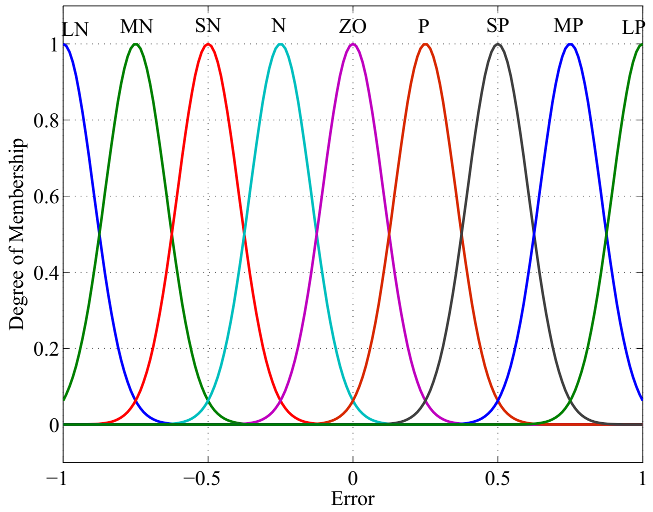

Fig. 6. Input fuzzy set for power error ε.

and parameter unsuitability. This can lead to unpredictable oscillations in power and voltage. Moreover, a major wind variations can lead to a remarkable change of power output as well as to an unstable system. In this paper, to improve the damping characteristics of the SCIG wind turbine system over a wide range when the wind speed below rated speed, fuzzy logic controller is proposed. FLC, first proposed by Lotfi Zadeh [23], is one of the most successful applications of fuzzy set theory: the main feature is the use of linguistic variables rather than numerical variables. It provides a principle of translating ambiguous verbal expressions, imprecise and qualitative, common in human communication, in numerical values [24]. The FLC process is composed of fuzzification, membership function, rule base, fuzzy inference engine and defuzzification [25].

With the aim of smoothing wind power fluctuations and limitation of output drops, here the most important factor is to determine the output power P_{mec} or the power coefficient C_{p} based on suitable pitch angle β. The control strategy implemented in this controller is inverted as follows:

$$\beta_{\text{ref}} = \beta_0 = 0^\circ \quad \text{for} \;\; P_{\text{mec}} \geq P_{\text{nom}} \tag{9}$$

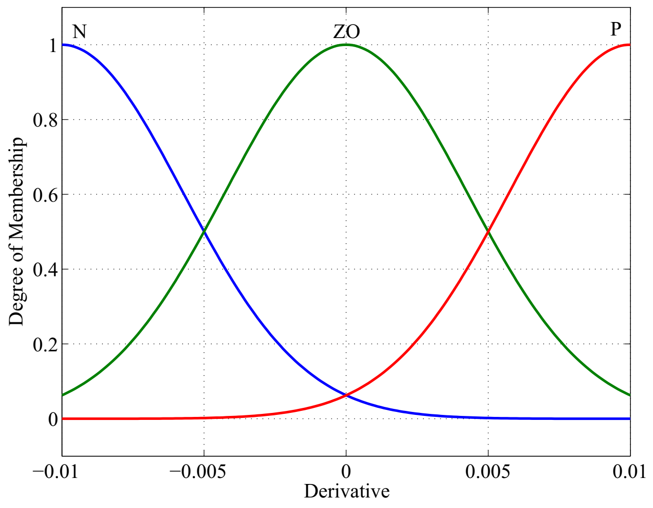

Fig. 7. Input fuzzy set for derivative.

$$\beta_{\text{ref}} = \frac{\Delta\beta}{\Delta P}(P_{\text{mec}} - P_{\text{nom}}) + \beta_0 \;\; \text{for} \;\; 0 < P_{\text{mec}} < P_{\text{nom}} \tag{10}$$

As seen from Fig. 5, the input control variables to the FLC are the power error signal ε and its rate of change. With an increment (or decrease) of β or C_{p}, the corresponding incremental (or decremental) value of P_{mec} is estimated. If ε increases with last positive derivative, it indicates that the search of β is continued in the same direction. Otherwise, negative derivative causes decrease in ε, and the direction of search suitable β is immediately reversed. All variables are described by using a fuzzy language.

3.2.1. *Fuzzification*

Each input/output variable used in the controller design is expressed in fuzzy set notation using linguistic variables. The notations of power error Large Negative (LN), Medium Negative (MN), Small Negative (SN), Negative (N), Zero (ZO), Positive (P), Small Positive (SP), Medium Positive (MP), Large Positive (LP), are characterized by the Gaussian membership function shown in Fig. 6, where the error is $\varepsilon = (P_{\text{mec}} - P_{\text{nom}})/P_{\text{nom}}$. For power error rate of change notation, we chose three linguistic variables, Negative (N), Zero (ZO), Positive (P), characterized by the Gaussian membership function shown in Fig. 7, while, for output pitch angle control, nine membership functions are chosen to be characterized by the triangular membership function according to Fig. 8. Obviously, the power error and its time derivative are all normalized, fuzzified, and expressed as fuzzy sets.

3.2.2. *Fuzzy logic rules*

After defining the fuzzy sets, a control strategy is defined by a set of IF-THEN rules. Based on our expert control knowledge of the SCIG wind turbine system operation, these heuristic rules are expressed in fuzzy domain as shown in Table 2. For example if (Error is LN) and (Derivative is N) then (Pitch angle control is LN).

3.2.3. *Defuzzification*

As following step, we need to transform the output linguistic variables to crisp values for controlling the pitch angle. The method used to complete our controller is the center of gravity (COG) which is given by equation in Ref. [26]

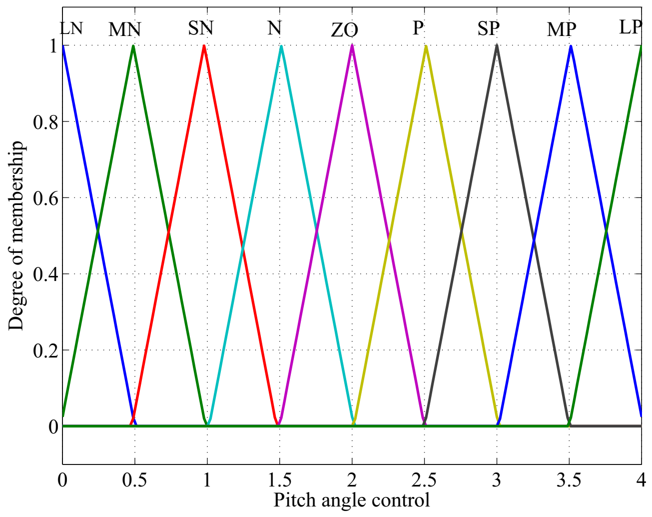

Fig. 8. Output fuzzy set for pitch angle control.

Table 2
Fuzzy pitch angle regulator rules.

du/dt	Error								
	LN	MN	SN	N	ZO	P	SP	MP	LP
N	LN	MN	SN	N	N	ZO	P	SP	MP
ZO	LN	MN	SN	N	ZO	P	SP	MP	LP
P	MN	SN	N	ZO	P	P	SP	MP	LP

$$y(x) = \frac{\sum_{j}^{N} w_j \mu_j(x)}{\sum_{j}^{N} \mu_j(x)} \tag{11}$$

where $y(x)$ is the output reference pitch angle, w_j is the weight corresponding to a given output fuzzy set, $\mu_j(x)$ is the degree of the fuzzy rule, and x is the input vector.

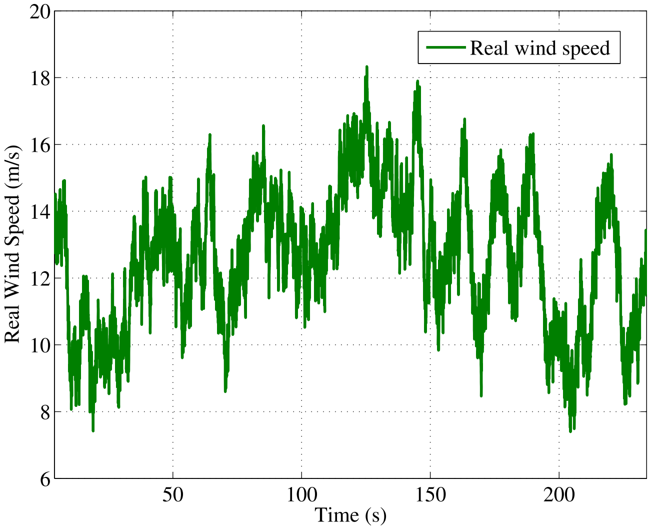

Fig. 9. Real wind speed profile.

4. Results and discussion

In this section, we compare the performance of the hybrid controller and the fuzzy controller versus the conventional PI controller in pitch angle control. The simulated system has the same configuration shown in Fig. 1, where SCIG is connected directly to the 22.9 kV lines. These lines are connected at the PCC which is then connected to the grid through a two 10 km parallel power lines. Some data about SCIG described in this work are taken from Ref. [27] and given in Table 3. The real wind speed (Fig. 9) and its relative measured value (Fig. 10) have been used to test the controllers and assess the performance of the SCIG in the whole range of operation as developed at RISO National Laboratory [28,29].

Figs. 11–15 show, respectively, the steady state pitch angle β, power coefficient C_p, active power P_{mec}, reactive power as well as terminal voltage. We tested three case studies: first case, with the pitch angle controlled using the conventional PI pitch controller; second case, with the pitch angle controlled using our proposed hybrid controller; third case, with only the fuzzy controller. The results can be summarized as follows.

Due to wind speed fluctuations (Figs. 9 and 10), the wind power generation has many fluctuations, because the wind power depends on the cube of the wind speed. In conventional PI controller, the controller works only when the generated power becomes larger than the rated value with a certain tolerance. As expected, the turbine is operating in the lower C_p (Fig. 12) due to high pitch angle β (Fig. 11) when the wind speed increase in order to decrease the incoming energy. The PI exciter performed well for one function that keep windmill output at rated power, i.e., the upper wind speed, but deteriorated at lower wind speed. When the wind speed is below rated speed, β is equal to zero and C_p is almost constant. In these conditions, high fluctuations in wind speed cause high fluctuations in active power injected (Fig. 13), reactive power absorbed (Fig. 14) by the wind generators and terminal voltage (Fig. 15).

Moreover, the proposed hybrid controller, combining the fuzzy exciter together with conventional PI control, is able to smooth the fluctuations of the generated power even when the wind speed and output power are less than their nominal values. At lower wind speed, the fuzzy controller works to smooth as well as try to track maximum power with suitable fluctuation to reduce the output power drop by adjusting β. From simulation results, the active power has been partially smoothed and the reduction of ones is almost insignificant. The reactive power absorbed is also automatically smoothed with the generation of smoothing active power. Furthermore, the oscillation of voltage at terminal decreases significantly. The fuzzy controller showed very good performance in the whole conditions operating of lower wind speed. On other hand, when the wind speed is higher than rated speed, the conventional PI controller will operate.

Table 3
Parameters of SCIG wind turbines.

Parameters	Value	Unit
Rated power	3	MW
Rated speed	12	m/s
Cut in wind speed	5	m/s
Cut out wind speed	19	m/s
Rated voltage/frequency	690/60	V/Hz
R_s/R_r	0.00488/0.00549	pu
L_{ls}/L_{lr}	0.09241/0.09955	pu
L_m	3.95279	pu
Q_{pf}	200	kvar

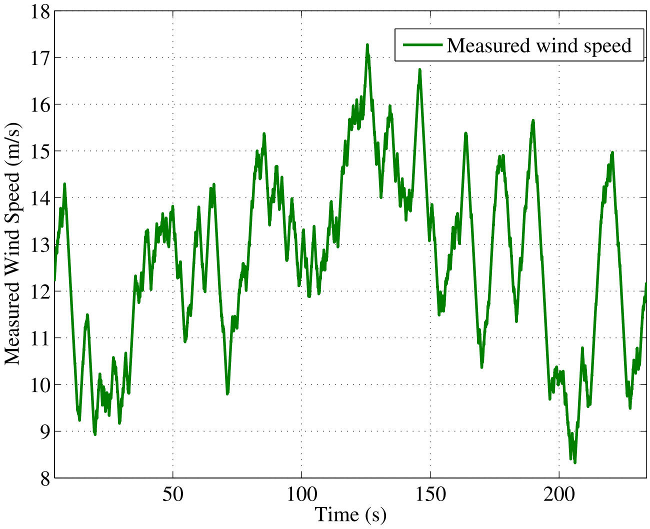

Fig. 10. Measured wind speed profile.

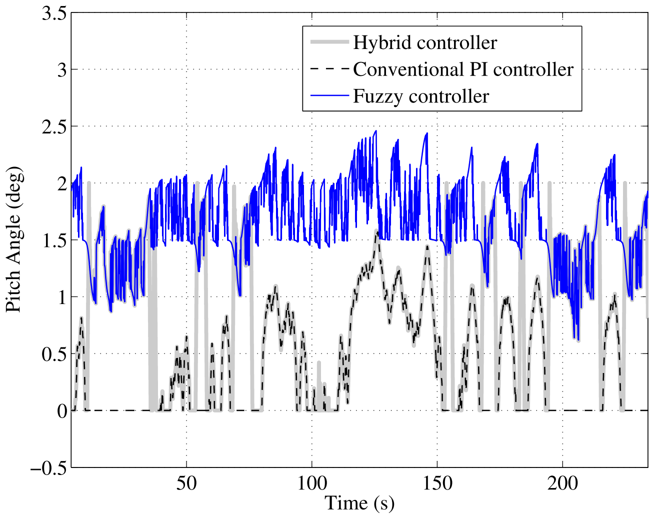

Fig. 11. Pitch angle.

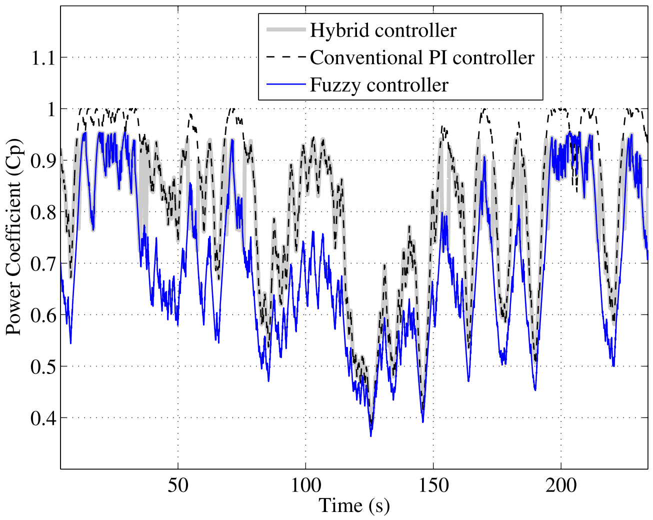

Fig. 12. Power coefficient.

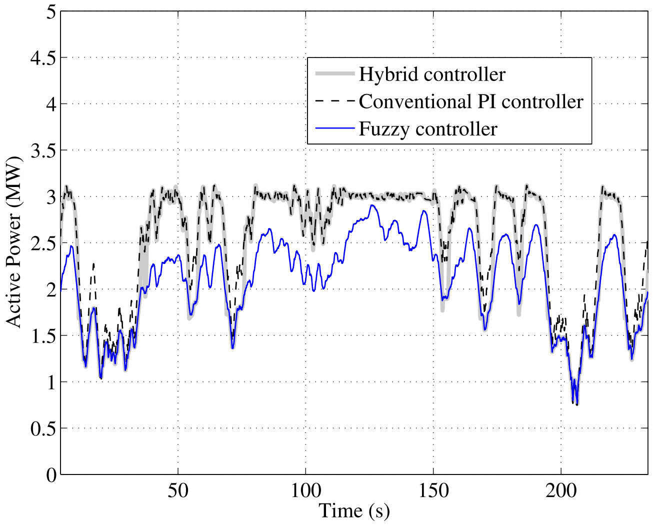

Fig. 13. Active power at terminal.

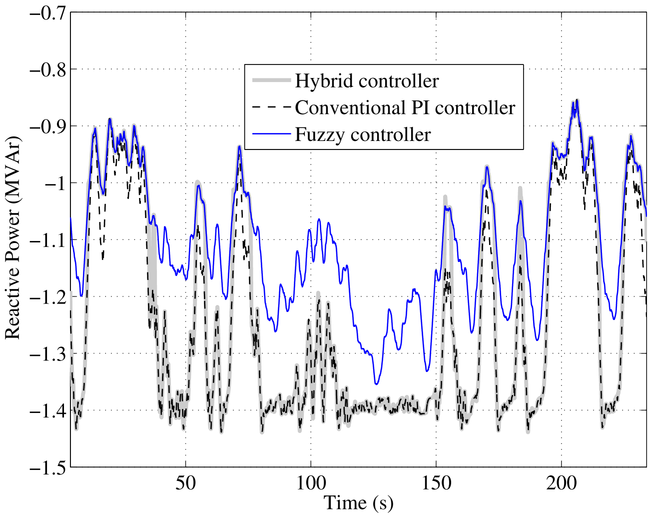

Fig. 14. Reactive power at terminal.

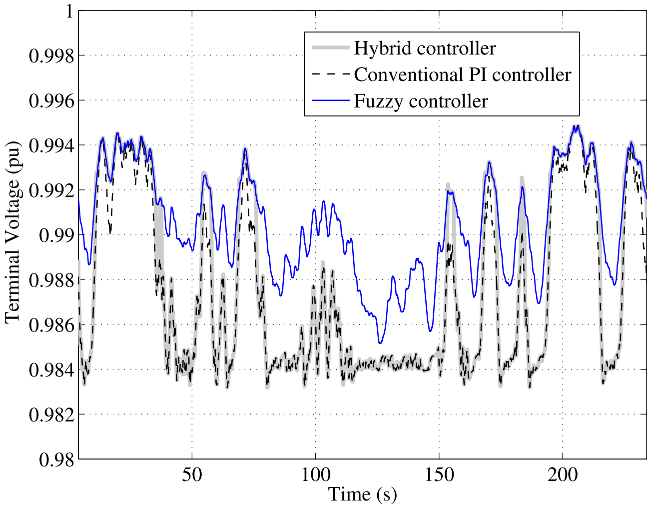

Fig. 15. Voltage at terminal.

Finally, in the fuzzy logic pitch controller case, the control strategy is implemented as follow:

$$\beta_{\mathrm{ref}} = \frac{\Delta\beta}{\Delta P}(P_{\mathrm{mec}} - P_{\mathrm{nom}}) + \beta_0 \quad \text{for} \;\; P_{\mathrm{mec}} \geq 0 \tag{12}$$

The output power of wind turbine has smaller value and smoothing of output power is partially improved if compared to conventional PI controller: this is because the fuzzy controller acts on the pitch angles following the wind speed, in order to smooth the output power, but at the same time it also reduces the output production from wind generators. From Fig. 13, we can see that the output generated is reduced significantly when the wind speed has higher rated speed. As a result, the reactive power absorbed from the grid is also reduced and the terminal voltage response in the high wind speed region is further enhanced if compared to the conventional PI controller. The decrease of output power is a critical issue with fuzzy controller, as already mentioned in literature [4]: in this case, some solutions (*e.g.* SSMT, single shaft micro turbine and SOFC, solid oxide fuel cell) were proposed to effectively compensate the amount of wind power reduction.

5. Conclusions

This paper proposes a hybrid control strategy for pitch angle control of an SCIG-based wind turbine in order to improve quality output power performance of the SCIG wind turbine in all operating regions by utilizing and combining the control capabilities of fuzzy and PI techniques. This approach in fact makes the control problem simple and more flexible, showing good performances. The pitch angle control behavior of SCIG wind systems was described using mathematical model. The simulation results have shown that when the proposed hybrid control system is used, the quality as well as amplitude of output power from the SCIG wind system is improved. Therefore, this controller configuration might be an effective solution to enhance reliability of SCIG wind turbine systems which may have a great impact in the near future.

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