Fuzzy Gain Scheduling of PI Torque Controller to Capture the Maximum Power From Variable Speed Wind Turbines

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***Abstract*— Wind turbine torque control strategy is commonly used to maximize energy in low wind speed operating. One of the main limitations of wind turbine control is wind fluctuations, in order to solve this problem, the present article represents a fuzzy gain scheduling of PI gains (FGSPI) for torque control based on tip-speed ratio (TSR) method. This technique consists in choosing the optimal gains by using human expertise based on fuzzy rules. Controls Advanced Research Turbine (CART) based on the Fatigue, Aerodynamics, Structures, and Turbulence (FAST) simulator developed at the National Renewable Energy Laboratory (NREL) in the United States is used for simulations. The results show that the proposed method performs well compared to the conventional method with better monitoring of the reference speed and load mitigation.**

Keywords*— *Wind turbine, Torque control, PI control, Fuzzy gain scheduling PI, FAST.

I. INTRODUCTION

Reducing pollution, particularly greenhouse gas pollution, and protecting the environment have become a worldwide challenge. Moreover, it is necessary to produce energy in order to meet the ever-increasing demand. Renewable energy resources, such as wind, are clean alternatives to fossil energies [1]. Despite the availability of the wind, its exploitation is not easy because it requires favorable conditions, among others the wind speed and the roughness of the site [2]. Variable speed wind turbines are the preferred type of wind turbines because of their ability to extract optimum energy under various wind conditions. The design of an efficient control system is necessary to improve the efficiency of wind turbines and increase its reliability. There are two control strategies for variable speed wind turbines. When wind speed is below its rated value, the main objective is to maximize captured energy, this strategy is called Maximum power point tracking (MPPT) [3]. The second strategy is envisaged when the wind speed exceeds the nominal speed for which the machine is designed. It consists in regulating the rotation of each blade to limit the produced power and particularly to protect the mechanical components of the wind turbines [4].

Several control techniques have been proposed to ensure optimal power extraction [5]. In [6] authors proposed a PI torque controller for a variable speed wind turbine with a continuously variable transmission, results show that the PI controller gives a better result as compared to the PD controller. A fractional PIDD pitch angle has been proposed for an isolated wind energy conversion system with a self-excited induction generator (SEIG) [7]. In ref [8] a fuzzy logic controller is used for direct torque control of variable speed doubly fed induction generator (DFIG) based wind turbine. [9] Have proposed a Fuzzy-PI speed controller to maximize the power of wind turbines. The simulation results confirm the effectiveness of the PI fuzzy adaptive cruise control, but the major limitation is that a simple mathematical model with idealized wind conditions were considered. If a realistic wind model was used, the results would be more valuable. In [10], one can see a fuzzy PI controller to extract the maximum power for various wind condition. In order to deal with nonlinearities of wind turbine without neglecting model's uncertainties, authors suggest a new hybrid method including fuzzy logic reasoning and particle swarm optimization to adjust proportional and integral gains and find their optimal values. Authors suggest a fuzzy logic controller to extract the maximum power from variable speed wind turbine. For this purpose, a Takagi Sugeno Kang Fuzzy System (TSKFS) based hybrid learning methodology including recursive least-squares optimization and Genetic algorithm were used, this technique gave a good result but the data set used in training phase were collected from mathematical model which makes the result less valuable [11]. In [12] authors proposed a Quantum-Behaved Lightning Search Algorithm to improve Indirect Field-Oriented Fuzzy-PI Control for IM Drive, besides the effectiveness of the proposed method, it is very difficult to be implemented and requires a lot of calculation. This restricts the industrialists' interest in considering such methods because of economic reasons.

The main objective of this study is to extract the maximum power wind turbine using a fuzzy logic Mamdani system providing a real time adaptation of the PI controller's gains, for this purpose a set of IF-THEN rules that are easy to implement is proposed.

This paper is organized as follows: sections 2 describes the model of the wind turbine, section 3 devoted to the control strategies used, (PI, FGSPI). The simulation results and discussions are presented in section 4. The last section represents the general conclusion.

II. Wind Turbine Modeling

Wind turbines are a complex system that includes serval subsystems: aerodynamics,drivetrain, generator dynamics and pitch actuator dynamics as illustrated in Fig. 1.

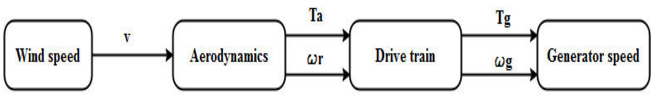

Fig. 1. Block diagram of the dynamic model of a wind turbine

A. Aerodynamics

The operating principle of wind turbines is to transform the wind energy into electrical energy. The energy that can be captured by the turbine is a cube of the wind speed given by (1) [13]:

$$P_{a=}\frac{1}{2}\rho\pi R^2 C_p(\lambda,\beta)v(t)^3 \quad (1)$$

Where P_a is the wind power (W) , $\rho\,(kg.m^{-3})$ is the air density, $R(m)$ is rotor radius and $v(t)(m.s^{-1})$ denotes the wind speed [5, 19].

Wind turbines can extract only a part of wind energy. This quantity is described by a specific non-linear coefficient $C_p(\lambda,\beta)$ which depends on tip-speed ratio λ and blade pitch angle β (deg) . The relationship of tip speed ratio is given by (2):

$$\lambda = \frac{\omega_r}{v(t)}R \quad (2)$$

Where ω_r $(\mathrm{rad.s^{-1}})$ is the rotor speed.

The aerodynamic torque T_a (N.m) developed by a wind turbine is given by the following expressions[14]:

$$T_a = \frac{P_a}{\omega_r} = \frac{1}{2\lambda}\rho\pi R^2 C_p(\lambda,\beta)v(t)^2 \quad (3)$$

Controls Advanced Research Turbine (CART) power coefficient $C_p(\lambda,\beta)$ is shown in Fig. 2, it's given by a lookup table developed by NREL[15].

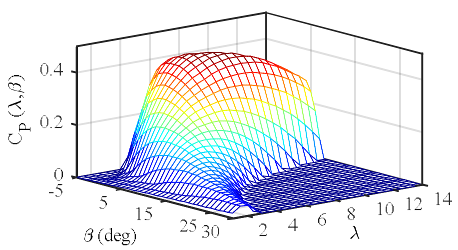

Fig. 2. $C_p(\lambda,\beta)$ for CART wind turbine

B. Wind turbine mechanics

The two-mass drivetrain model of wind turbine Figure 3-a can be described as follows:

$$J_r\dot{\omega}_r = T_a - T_{ls} - D_r\omega_r \quad (4)$$

$$J_g\dot{\omega}_g = T_{hs} - T_e - D_g\omega_g \quad (5)$$

$J_r\,(kg.m^2)$ and $J_g\,(kg.m^2)$ denote the rotor and the generator inertia $\omega_r\,(rad.s^{-1})$ and $\omega_g\,(rad.s^{-1})$ are the rotor and generator speed. $D_r\,(N.m.rad^{-1}.s^{-1})$ and $D_g\,(N.m.rad^{-1}.s^{-1})$ represent the rotor and the generator external damping respectively. $T_e\,(N.m)$ denotes the generator torque. $T_{hs}\,(N.m)$ is the high speed shaft torque.

The low speed shaft torque $T_{ls}\,(N.m)$ can be expressed as follows:

$$T_{ls} = k_{ls}(\theta_r - \theta_{ls}) + D_{ls}(\omega_r - \omega_{ls}) \quad (6)$$

Where $k_{ls}\,(N.m.rad^{-1})$ denotes the low shaft speed stiffness. $D_{ls}\,(N.m.rad^{-1}.s^{-1})$ is the low speed shaft damping. $\theta_r\,(rad)$ and $\theta_{ls}\,(rad)$ represent the rotor side angular deviation and the gearbox side angular deviation , respectively. The relationship between ω_{ls} and ω_g is defined by the gearbox ratio described as follows:

$$n_g = \frac{\omega_g}{\omega_{ls}} = \frac{T_{ls}}{T_{hs}} = \frac{\theta_g}{\theta_{ls}} \quad (7)$$

By using (4) and (7) the following one mass model illustrated in Figure 3-b is mathematically expressed as follows:

$$.J_t\dot{\omega}_r = T_a - D_t\omega_r - T_g\,. \quad (8)$$

Where $J_t\,(kg.m^2), D_t\,(N.m.rad^{-1}.s^{-1})$ and $T_g\,(N.m)$ denote the turbine total inertia, turbine total external damping and generator torque in the rotor side, respectively; which are expressed as follows:

$$\begin{aligned} J_t &= J_r + n_g{}^2 J_g \\ D_t &= D_r + n_g{}^2 D_g \\ T_g &= T_e n_g \end{aligned} \quad (9)$$

Where: n_g described the gearbox ratio.

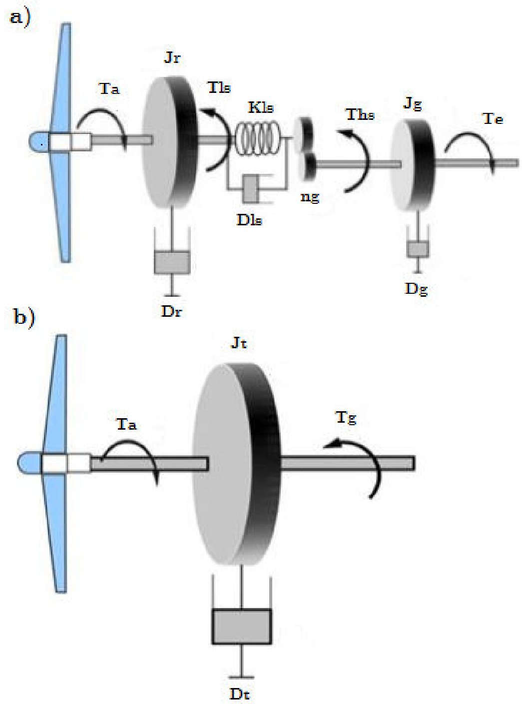

Fig. 3. Schematic of drive-train models: a) two mass drive-train model, b) one mass drive-train model [16]

III. Torque control based on Tip-Speed Ratio method

In order to maximize the energies' production, tip-speed ratio (TSR) method consists in imposing the reference magnetic torque by fixing the rotor speed at its reference value, To achieve this objective, the turbine TSR must be maintained in the neighborhood of its optimal value [17].

A. PI torque controller

The PI controller is traditionally applied to maintain the rotor speed at its rated value. and to reduce electromagnetic torque disturbances [3]. Fig. 4 presents the control law structure.

The used PI controller is mathematically expressed by (10) as follows:

$$T_{em} = K_P(\omega_{r_{ref}} - \omega_r) + K_I \int (\omega_{r_{ref}} - \omega_r)\, dt \qquad (10)$$

Where K_P and K_I are the optimal controller gains to be determined.

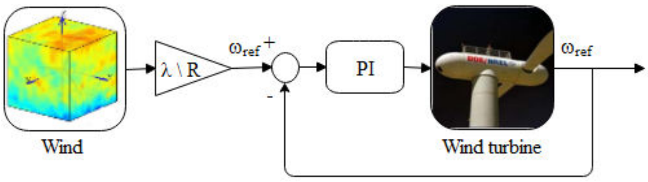

Fig. 4. Conventional PI control scheme

B. Fuzzy gain scheduling PI (FGSPI) controller

This study aims to improve the performance of the rotor speed control system. To achieve the drawn objective, we propose a real time adaptation of proportional and integral gains of PI controller using Mamdani fuzzy logic system.

The main challenge is the implementation of the online interpolation strategy through which gains are tuned based on measured error and its first derivative. The proposed controller performs as a set of local controllers, acting each one around a specific operating point. Fig. 5 shows the block diagram of the proposed technique where the inputs are: e_ω, $\dot{e}_\omega$ and the output are optimal K_p and K_i.

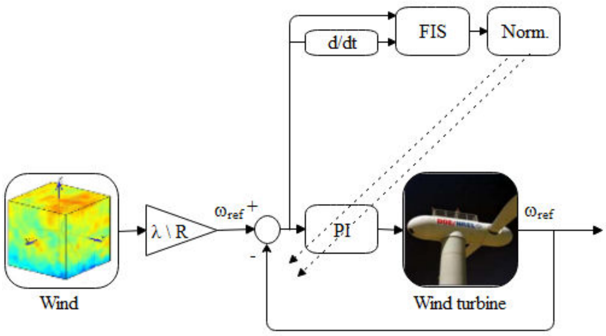

Fig. 5. Fuzzy gain scheduling PI (FGSPI) control schemes.

To design a Mamdani fuzzy inference system, the following steps must be done:

1) Fuzzification

Each input is fuzzified using 5 triangular membership functions (MFs) and one S-shaped MFs and one Z-shaped MFs, while S-shaped MFs and Z-shaped MFs are used for each output, as shown in Fig.6-7.

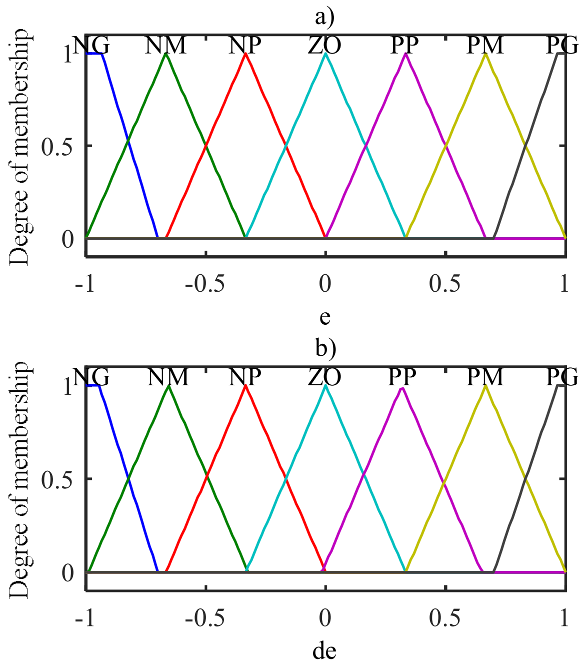

Fig. 6. Inputs MFs: a)Error MFs, b) error derivative MFs

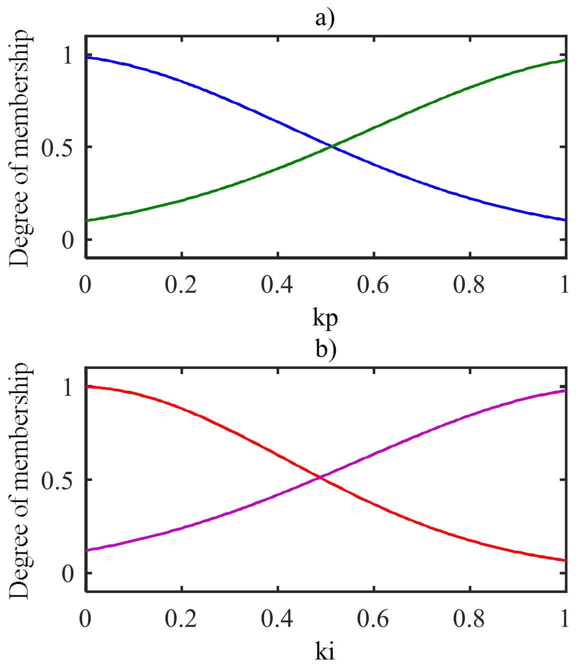

Fig. 7. Outputs MFs: a) K_p MFs, b) K_I MFs

The linguistic variables used for the MFs are:

- For each of the two inputs there are seven MFs; namely: Negative Big (NB), Negative Medium (NM), Negative Small (NS), Zero (ZO), Positive Small (PS), Positive Medium (PM) and Positive Big (PB).
- For each of the two outputs: Small (S) and Big (B).

2) Fuzzy rules

The appropriate linguistic rule-base of IF-THEN type should be implemented in order to manage the output based on human expertise. the proposed FGSPI controller has 49 significant rules given in Table 1:

TABLE I. FUZZY RULES

e_ω		KP							KI						
		NB	NM	NS	ZO	PS	PM	PB	NB	NM	NS	ZO	PS	PM	**PB**
$\dot{e}_\omega$	**NB**	B	B	B	B	B	B	B	B	B	B	B	B	B	**B**
	NM	S	B	B	B	B	B	S	B	B	S	S	S	B	**B**
	NS	S	S	B	B	B	S	S	B	B	B	S	B	B	**B**
	ZO	S	S	S	B	S	S	S	B	B	B	S	B	B	**B**
	PS	S	S	B	B	B	S	S	B	B	B	S	B	B	**B**
	PM	S	B	B	B	B	B	S	B	B	S	S	S	B	**B**
	PB	B	B	B	B	B	B	B	B	B	B	B	B	B	**B**

3) Defuzzification

To get the output of the proposed system, the centroid defuzzification method with a maximal aggregation is used.

The output gains are expressed as follows [14]:

$$K_p^{'} = \frac{K_p - K_{p\,min}}{K_{p\,max} - K_{p\,min}} \tag{11}$$

$$K_i^{'} = \frac{K_i - K_{i\,min}}{K_{i\,max} - K_{i\,min}} \tag{12}$$

IV. RESULTS AND DISCUSSIONS

Fatigue, Aerodynamics, Structures, and Turbulence (FAST) is an aeroelastic simulator used either by scientists and industrials providing extreme and fatigue loads simulation and predictions of two- and three-bladed wind turbines[18] It operates with Simulink using S-function, which facilitates the implementation and the test of control laws [19]. The proposed torque controller is validated by FAST simulator using the parameters of the CART located at the National Renewable Energy Laboratory (NREL). The characteristics of CART wind turbine are given in Table 2. In this present study, 6 degrees of freedom (DOFs) are considered as First flapwise blade mode, Second flapwise blade mode, First edgewise blade mode, Rotor-teeter, Drivetrain rotational-flexibility and Generator DOF.

TABLE II. CART WIND TURBINE CHARACTERISTICS

Turbine Type	Horizontal axis, upwind rotor, teetering hub
Rotor diameter	43.3 m
gearbox ratio	43.165
Hub height	36.6 m
Generator system electrical power	600 kW
Maximum rotor torque	162 kN.m

The applied input wind speed profile was developed by using Turbsim which is developed by NREL [20]. The test wind speed shown in Figure 8 consists of 10 min dataset that was generated using the Kaimal turbulence spectra. It has the mean value of 7 m/s at the hub height, turbulence intensity of 20% and time step of 0.01 s.

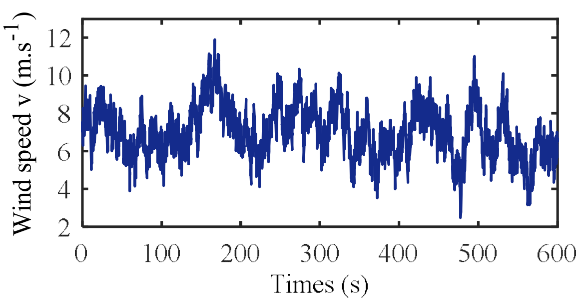

Fig. 8. Wind speed

In order to compare the conventional and the proposed control strategy, all simulations were done under the followings conditions [21]:

- Filtering the generator torque T_g in order to smooth the control action.
- Filtering the measured and reference rotor speed.
- In presence of additive measurement noise on ω_r ω_r with an SNR around 7 dB.
- In presence of a constant additive control input disturbance 5000 N.m in the generator torque T_g .

The objective of the control in the second zone is to improve electrical efficiency while mitigating mechanical loads. As such, the reduced oscillation of the drivetrain and the smoothness of the control torque are evaluated by the standard deviation (*STD*) and its maximum.

For the purpose of maximizing the generated power, the electrical efficiency is calculated as follows:

$$\eta_{elec}(\%) = \frac{\int_{t_{ini}}^{t_{fin}} P_e dt}{\int_{t_{ini}}^{t_{fin}} P_{a_{opt}} dt} \tag{13}$$

where Pa_{opt} is the optimal aerodynamic power given in (14):

$$P_{a_{opt}} = 0.5\rho\pi R^2 Cp_{opt} \tag{14}$$

The detailed statistical analysis is summarized in Table 3. Thus, we require an intelligent system which, based on the fuzzy reasoning, providing the optimal PI gains for each wind speed in a wind speed profile; and therefore, Mamdani fuzzy logic controller is used. The structure of conventional PI method is shown in Figure 5. In this method, the rotor speed is regulated by a conventional PI controller. The gains of the PI controller are adjusted roughly without taking into account the interdependence of the gains. Simulations were performed by varying *Kp* until the value leading to the best tracking of the reference was obtained while Ki is maintained at zero. Once we found the best *Kp*= 1900 we used the same method to adjust *Ki* and reduce the static error. The optimal value of *Ki* is 2.

The second method, which is referred too as the common method in this paper is described in Section 3.2, with its structure being shown in Figure 5. The proposed strategy determines the optimal values of gains Figure 9, taking into account the rapid variation in wind profile.

As one can see in Figure 10 the rotor and generator speed obtained by FGSPI is kept near to its optimal value and has better performances, in terms of rise time, transient error and steady-state error. It is important to note that the conventional method of determining optimal PI gains is not suitable for variable wind speeds because for each operating point there is a unique gain pair. However, a pair of gains that is optimal for one specific wind speed is not optimal for another.

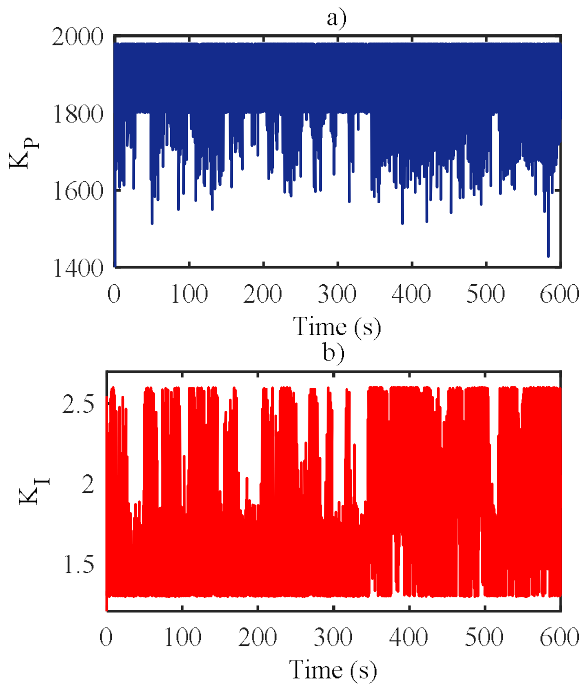

Fig. 9. Optimal FGSPI gains: a) Optimal proportional gain K_P) Optimal integral gain K_I

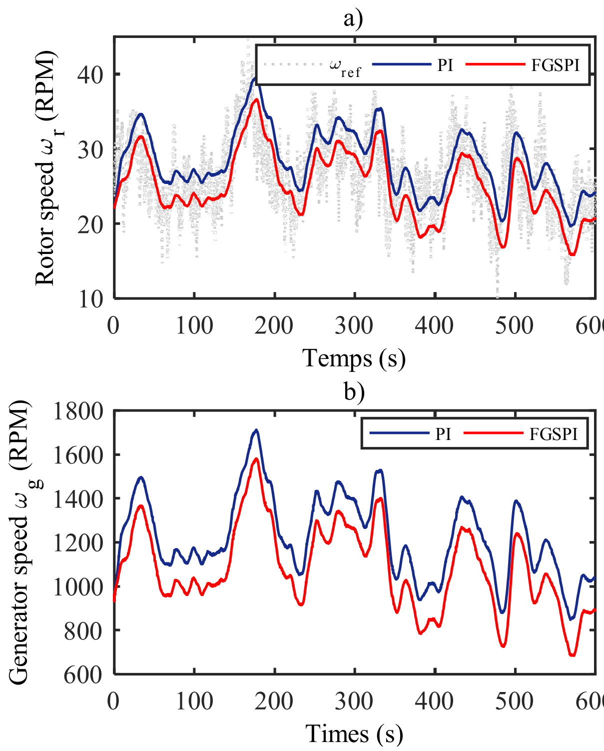

Fig. 10. Wind turbine speed: a) rotor speed, b). generator speed

As one can see in Figure 11 the proposed controller is able to provide an appropriate torque T_g with an STD of 0.21 against 0.25 for the conventional PI and a maximal T_g exceeding 63 kN.m, while it's about 58 kN.m for PI controller. In this way, the rotor speed is decreased and brought back to its optimal value. Low speed shaft torque T_{ls} is too close to T_g, but it's much more fluctuant due to the fact that the flexibility of the slow shaft is taken into account, which gives an idea of the influence of the control force on the machine components.

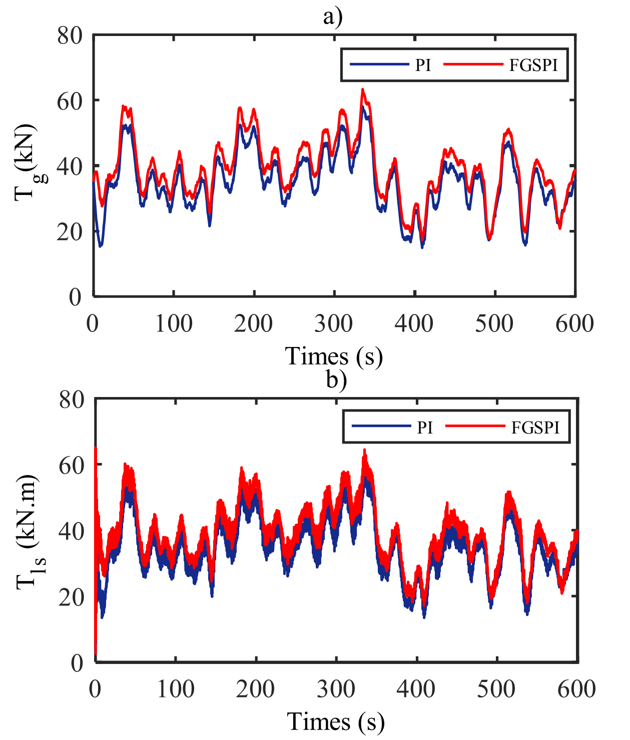

Fig. 11. Wind turbine Torque: a) generator torque, b) low speed shaft torque

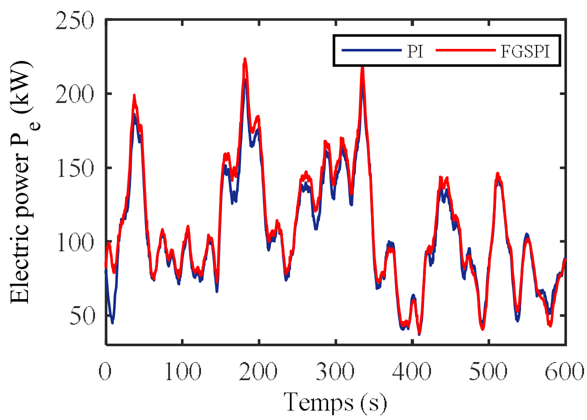

Fig. 12. Electric power

TABLE III. COMPARISON OF DIFFERENT CONTROL STRATEGY USING FAST SIMULATOR

Control strategy	PI	FGSPI
η_{elec} %	64	66
$STD\,T_{ls}$ $(kN.\mathrm{m})$	8.55	8.94
T_{ls} Max $(kN.\mathrm{m})$	64.70	65.10
STD T_g $(kN.\mathrm{m})$	0.21	0.25
$T_g\,max(kN.m)$	58.10	63.28

As we can see a mitigation of fatigue loading is observed. $STD\,T_{ls}$ for FGSPI is about 8.55 with a maximal value of 64.70. While the measured $STD\,T_{ls}$ for PI controller is 8.94 kN.m with maximum of 65.10 kN.m.

Electric power is shown in Fig. 12; the proposed controller shows a good improvement of the produced electric power with an efficiency of 66% while the measured electric efficiency of PI controller is 64%.

V. CONCLUSION

In order to deal with the fluctuating nature of wind which requires calibration of PI gains for each specific point, a fuzzy system based on expertise is proposed in this paper. A new FGSPI controller has been developed and compared to the conventional PI control traditionally applied to wind turbines.

The proposed FGSPI controller's detailed design procedure has been presented and validated by the FAST aero-elastic simulator using the parameters of the CART wind turbine with 6 DOFs, the obtained results show that the proposed FGSPI controller has a good response and better performance as compared to the PI controller.

Besides its ability to reject disturbances, the proposed FGSPI controller has intrinsic rules which give it the ability to maximize electrical energy efficiency, deal with the nonlinearity of wind and smooth the output power and drive-train torque fluctuations in presence of an additive measurement noise for wind turbine. In addition, it can be implemented in field large wind turbines and operates with a potentially high performance.

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