

A Comparative Study between Fuzzy Logic and Fuzzy Sliding Mode Controller Applied to Wind Turbine Benchmark Model

Djillali MENOUEUR¹, Mohamed TADJINE¹, Abdelmadjid GOUICHICHE²

¹Laboratoire de commande de processus Ecole National Polytechnique ENP Alger-Algeria,

²Laboratoire de génie électrique et plasmas, University of Tiaret -Algeria.

E-mail: menouerdjillali1984@gmail.com

Abstract - Electricity generated from wind energy is increasing day by day globally; which requires us to give importance to the reliability of wind turbines so that the wind turbines continue to produce energy and keep the possibility of extracting the maximum power from the wind while ensuring the necessary operating performance. The work performed in this article presents a study of two types of FTC controller applied to wind turbine benchmark model. This work aims to investigate the effect of such a controller under a different scenario of sensors fault working in a full load zone. Moreover, a comparison analysis between the Fuzzy sliding mode controller FSM and the fuzzy logic FL controller in terms of fault tolerance is presented. The proposed control approach for the variable-speed wind turbines is presented using a wind turbine Benchmark model of a three-blade horizontal axis variable speed with a nominal power of 4.8 MW.

Keywords – Wind turbine; Benchmark model, fuzzy logic fuzzy logic sliding mode controller, sensors fault.

I. INTRODUCTION

Wind energy is an intermittent source of energy that is produced depending on the weather conditions and the power captured from this wind energy depends on the variable speed wind turbine conversion system. The fluctuating variations of the wind and the disturbances preventing from the outside force us to look for an adequate robust control approach.

The wind turbine system is driven by wind energy which is an uncontrolled complicated input and has nonlinear dynamics in which the conventional controller such as the PID controller might be not a suitable choice in terms of performance and fault tolerance capability [1].

The fuzzy logic sliding mode controller is known as an interesting alternative to the classical controller due to its robustness, disturbance rejection, and simple implementation by the mean of the power converter.

This paper presents fuzzy logic FL and fuzzy logic sliding mode FSM controller applied to the Benchmark model of a variable-speed wind turbine. the main objective is to develop a sliding mode controller that can handle efficiently the appearance of the sensor's fault. Therefore, a default scenario was considered to

evaluate the proposed control. In addition, a comparative study between the fuzzy logic controller and the fuzzy logic sliding mode controller is performed to demonstrate the effectiveness of our proposal.

The manuscript is organized as follows: the first part will be devoted to a description of the wind Benchmark model with the modeling of the various components of the wind conversion chain of the benchmark model; the second part presents the two control approaches followed by a simulation; The last part announces the simulation results with a comparison between the performances of tow controllers and finally, a general conclusion.

II. DESCRIPTION OF WIND TURBINE BENCHMARK MODEL

The main objective of the Benchmark model is dedicated to the diagnosis, its design is illustrated in Fig.1, the idée of this model uses the principle of frequency separation because the dynamics of the mechanical part are very slow in relation to the dynamics of the electrical part and as the inertia of the generator is included in the mechanical transmission model, in front of this given it is assimilated that the generator and the

converter has such a high frequency from the point of view of the control of the speed of the wind turbine that can be seen as a quasi-static function, This is why a first-order model with a high-frequency pole is used to approximate the parts of the generator and the power converter [2].

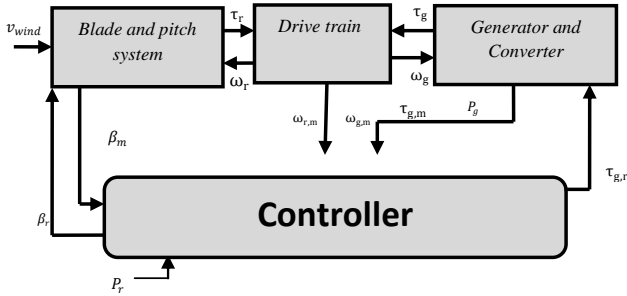


Fig.1. Benchmark model.

The different variables between these four subsystems are defined as follows: v_w : is the wind speed acting on the turbine blades; τ_r : is the rotor torque; ω_r : is the rotational speed of the rotor; τ_g : is the generator torque; ω_g : is the rotational speed of the generator; β_r : is the reference to the pitch position; β_m : is the measured pitch position; $\omega_{r,m}$: is the measured rotational speed of the rotor, $\omega_{g,m}$: is the measured rotational speed of the generator; $\tau_{g,m}$: is the measured generator torque; $\tau_{g,r}$: is the torque reference to the generator; P_r : is the power reference to the wind turbine; and P_g : is the power produced by the generator.

A) Modeling of the main subsystems of the Wind Turbine benchmark model

The benchmark model contains four subparts see (oodgard 2009) [6] which are presented as follows:

A.1. Blade and Pitch Model

The blade pitch control adjusts the rotational speed and power generated by changing the pitch angle of the blades to keep the rotor speed within operating limits as the wind speed changes.

Blade feathering stops the rotor during emergency stops or when the wind speed exceeds the maximum rated speed. In gusty winds or when servicing wind turbines or to reduce unwanted torque.

Pitch control can be implemented via hydraulic or electric mechanisms. in our work we

have chosen hydraulic mechanisms because they have a longer life, faster response time due to higher driving force, and low maintenance spare spring [7].

The modeling of this system as being given as a closed-loop second-order transfer function servo-control between the measured pitch angle β_m and its reference β_{ref} as its identical reference for the three blades in the absence of a fault [7].

$$\ddot{\beta}(t) = 2\xi\omega_n\dot{\beta}(t) + \omega_n^2\beta(t) = \omega_n^2\beta_{ref}(t) \quad (1)$$

Where: $\zeta = 0.6$ is the damping factor and $\omega_n = 11.11$. is the natural frequency.

Therefore a torque given by the aerodynamic equation.02 wich it is result of the three torques applied to the blades.

$$\tau_r(t) = \sum_{i=1}^3 \frac{\rho\pi R^2 c_q(\lambda(t),\beta_i(t))v_{w,i}(t)^2}{6} \quad (2)$$

A.2. Drive Train Model

Drive train receives the rotational movement of the hub in order to drive the electric generator. Transmission: Also called multiplier or gearbox, it adapts the speed of rotation to the operation of the generator.

The equation (3) represents the state model of a drive train and the associated block is shown in Fig.2 .

$$\begin{bmatrix} \dot{\omega}_r(t) \\ \dot{\omega}_g(t) \\ \dot{\theta}_\Delta(t) \end{bmatrix} = A_{dat} \begin{bmatrix} \omega_r(t) \\ \omega_g(t) \\ \theta_\Delta(t) \end{bmatrix} + B_{dat} \begin{bmatrix} \tau_r(t) \\ \tau_g(t) \end{bmatrix} \quad (3)$$

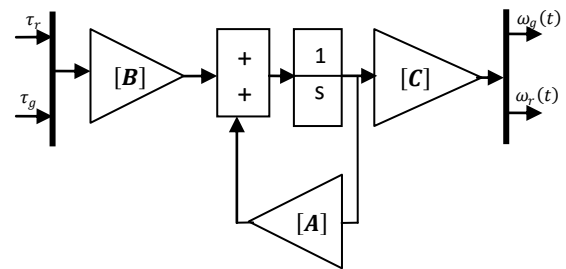


Fig. 2. Block diagram of the drive train.

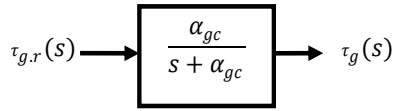
$$\text{Where : } A = \begin{bmatrix} \frac{-B_{dt}-B_r}{J_r} & \frac{B_{dt}}{N_g J_r} & \frac{-k_{dt}}{J_r} \\ \frac{\eta_{dt} B_{dt}}{N_g J_g} & \frac{-\eta_{dt} B_{dt} - B_g}{N_g^2} & \frac{\eta_{dt} k_{dt}}{N_g J_g} \\ 1 & -\frac{1}{N_g} & 0 \end{bmatrix}$$

$$B = \begin{bmatrix} \frac{1}{J_r} & 0 \\ 0 & \frac{-1}{J_g} \\ 0 & 0 \end{bmatrix}, C = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}.$$

and $\omega_r(t)$: is the speed of the rotor, J_r : is the moment of inertia of the low-speed shaft, τ_r : is the torque applied to the rotor $\tau_g(t)$: is the torque applied to the generator, k_{dt} : is the torsion stiffness of the drive train, $\omega_g(t)$: is the speed of generator, B_{dt} is the torsion damping coefficient of the drive train, B_r : is the viscous friction of the low-speed shaft, B_g : is the viscous friction of the high-speed shaft, J_g : is the moment of inertia of the high-speed shaft, η_{dt} : is the efficiency of the drive train, $\theta_{\Delta}(t)$: is the torsion angle of the drive train, N_g : is the gear ratio.

A.3. Generator and Converter Model

In the benchmark model the generator and the converter were modeled as being a 1st order system since the electrical part is very fast.



Where α_{gc} is the generator and converter model parameter.

The power produced by the generator is given by (4).

$$P_g(t) = \eta_g \omega_g(t) \tau_g(t) \quad (4)$$

where η_g is the efficiency of the generator.

A.4. Controllers

The purpose of the control system is to follow the power reference in the event that the wind speed is high, i.e. after the start-up zone of the turbine (zone 1), we enter the zone where the wind is very low (Zone 2) also called the optimization range, in this range the pitch angle is about 0 degrees and the tip speed ratio is constant at its optimal value λ_{opt} to capture the maximum energy.

this optimal value of λ_{opt} corresponds to $(\beta r [n] = 0)$ and the converter reference torque $\tau_{g,r}$ given as follows in equation (05).[3] but when the wind exceeds a certain value, the controller will do its part to maintain the energy extracted from the wind around its nominal value (Zone 3), Finally, after zone III, the wind turbine stops and goes into security at the time of the violent wind, and

the Fig.3, Indicates the zones of operation of a wind turbine. In our work, we propose the method of control of the pitch angle by one of the robust approaches opposite Violent wind disturbances, and changes are tested with the Benchmark wind turbine conversion chain model.

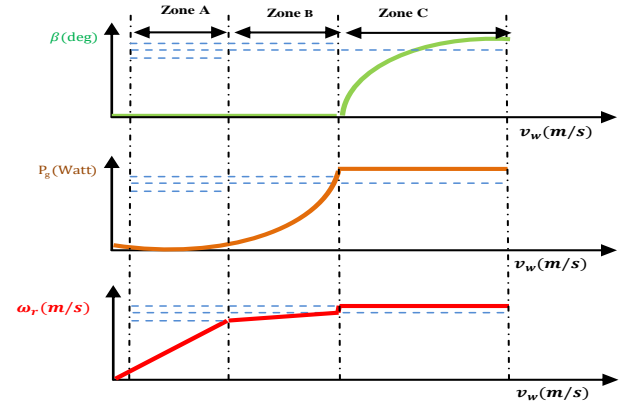


Fig. 3. Main operating zones of a wind turbine.

$$\tau_{g,r}(k) = K_{opt} \left(\frac{\omega_g(k)}{N_g} \right)^2 \quad (5)$$

Where:

$$K_{opt} = \frac{1}{2} \rho A R^3 \frac{C_p \max}{\lambda_{opt}^2} \quad (6)$$

And A : is the area covered by the blades and λ_{opt} is the point which corresponds to the optimal coefficient, $\left(\frac{\omega_g(k)}{N_g} \right)^2$ ρ : the air density and $C_{p \max}$: the maximum value of the power coefficient, in this area $\omega_g < \omega_n - \Delta\omega$

$\Delta\omega$: is a small offset used to prevent more than two switching between control modes at the same time.

In three zone, the action will be on the angle β via the controller to maintain the speed of the generator at its nominal value, then the controller will start if $P_g > P_r$ and $\omega_g > \omega_n$.

B) Wind Model

The wind sequence used in our simulation is the one used in the benchmark model (for details on the wind model and the implementation method).

$$V_{equivalent}(t) = V_H(t) + V_{shear \text{ component}}(t) + V_{tower \text{ shadow}}(t) \quad (7)$$

where V_H is the wind speed at hub height, V_{eqws} is the wind shear component which it results from wind energy lost at the earth's surface,

causing wind speed to increase as distance to the earth's surface increases, V_{eqts} is the tower shadow component.

The latter two components can be represented as [4]:

$$V_{eqws,i}(t) = \frac{2V_H}{3R^2} \left[\frac{\alpha R^3}{3H} \cos(\theta_i(t)) + \frac{\alpha(\alpha-1)R^4}{8H^2} \cos(\theta_i(t))^2 + \frac{\alpha(\alpha-1)(\alpha-2)R^5}{30H^3} \cos(\theta_i(t))^3 \right] \quad (8)$$

$$V_{eqts,i}(t) = m \frac{\left(\theta_i(t) + \frac{(i-1)2\pi}{3} - \text{floor} \left(\frac{\theta_i(t) + \frac{(i-1)2\pi}{3}}{2\pi} \right) 2\pi \right)}{3r_o^2} (F_1 + F_2)$$

where:

$$F_1 = 2a^2 \frac{R^2 - r^2}{(R^2 + r^2) \sin \left(\theta(t) + \frac{(i-1)2\pi}{3} - \text{floor} \left(\frac{\theta(t) + \frac{(i-1)2\pi}{3}}{2\pi} \right) 2\pi \right)^2 + K^2},$$

and,

$$F_2 = \frac{2a^2 K^2 \left(r^2 \sin \left(\theta(t) + \frac{(i-1)2\pi}{3} - \text{floor} \left(\frac{\theta(t) + \frac{(i-1)2\pi}{3}}{2\pi} \right) 2\pi \right)^2 + K^2 \right)}{R^2 \sin \left(\theta(t) + \frac{(i-1)2\pi}{3} - \text{floor} \left(\frac{\theta(t) + \frac{(i-1)2\pi}{3}}{2\pi} \right) 2\pi \right)^2 + K^2}$$

Where α is the empirical wind shear exponent, r : is the radius of the blade hub, K is an aerodynamic parameter is the elevation of rotor hub (m), a is the tower radius (m), x is the distance from the blade origin to the tower midline (m), and, $m = 1 + \left[\frac{\alpha(\alpha-1)}{8} \right] \left(\frac{R}{H} \right)^2$ is a coefficient of the wind turbine, $i = 1, 2$ or 3 , and θ is the angular position of the three blades.

For the wind component $V_H(t)$, a wind sequence is obtained by processing a set of measured wind data with a low pass filter. The stochastic part of the wind model is modeled by Kaimal filters with its Simulink implementation model can be found in the Simulink of Benchmark model.[5].

An implementation of this model can be found in the Simulink implementation of this reference model [6].

Thus according to the sequence of the wind speed simulated in the benchmark model taking into account the components of the wind to be as close as possible to the reality of the real wind. we can see that the wind speed is always in a range of 05 to 20 m/s, with some peaks at 25 m/s, this type of wind says nice breeze, according to the simulation of the wind band shown in Fig. 4,

and this is considered good coverage of normal wind turbine operation.

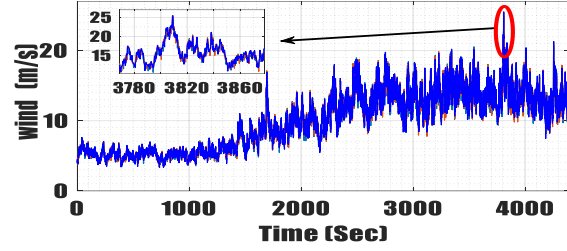


Fig. 4. Sequence of the wind turbine benchmark model

Where the numerical values of the various parameters used in the benchmark model are indicated below in table I [3].

TABLE 1. Numerical Values of Parameter of Benchmark Model

WIND MODEL	
$\alpha = 0.1$, $H = 81$ m, $r = 1.5$ m, $a = 2.2$ m, $k=4.7$	
BLADE AND PITCH MODEL	
$R = 57.5$ m, $\rho = 1.225 \frac{kg}{m^3}$, $\zeta = 0.6$, $\omega_n = 11.11 \frac{rad}{s}$	
DRIVE TRAIN MODEL	
$B_{dt} = 775.49 \frac{Nm}{rad}$, $J_r = 55.10^6$ kg.m ² , $N_g = 95$ $k_{dt} = 2.7.10^9 \frac{Nm}{rad}$, $\eta_{dt} = 0.97$, $J_g = 390$ kg.m ² $B_r = 7.11 \frac{Nm}{rad}$, $B_g = 45.6 \frac{Nm}{rad}$	
GENERATOR AND CONVERTER	
$\alpha_{gc} = 50 \frac{rad}{s}$, $\eta_{gc} = 0.98$	

C) Different types of fault to be simulated

The frequent faults to be treated must be chosen according to their frequency of appearance and their severity, for this we choose three types of faults as shown in the Fig.5, the faults of the sensors, of the actuators and the faults of the System and their values (Odgaard & Stoustrup, 2009). are mentioned in the table 2.

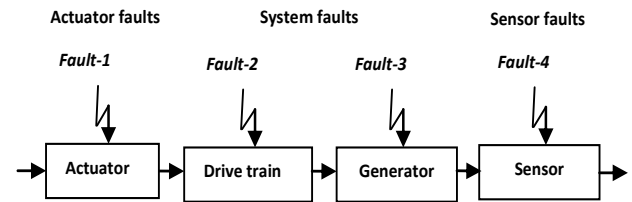


Fig. 5. Different types of faults.

Where the fault 7 is the change in the dynamics due to Hydraulic leakage on pitch actuator 3. The fault is slowly introduced during 30 s with a constant rate; afterward the fault is active during 40 s, and again decreases during 30 s. The fault begins at 3400 s and ends at 3500 s.

TABLE 2. Faults Occurrence Scenario.

Faults	Fault design	Fault description	Type	Values of second scenario	Time (sec)
Sensor Faults	Default_1	Change in pitch 1 sensor	Fixed value	$\beta_{1,m1} = 24^\circ$	2000-2100
	Default_2	Change in pitch 2 sensor	Gain factor	$\beta_{2,m2} = 10 \beta_{2,m2}$	2300-2400
	Default_3	Change in pitch 3 sensor	Fixed value	$\beta_{3,m1} = 20^\circ$	2600-2700
	Default_4	Change in rotor speed sensor	Fixed value	$W_{r,m1} = 3.5 \text{ rad/s}$	1500-1600
	Default_5	Change in rotor speed sensor	Gain factor	$W_{r,m2} = 3 W_{r,m2}$	1000-1100
		Change in generator speed sensor	Gain factor	$W_{g,m2} = 5 W_{g,m2}$	
Default_6	Change in generator speed sensor	Fixed value	$W_{g,m1} = 95 \text{ rads}$	1300-1400	
Actuator Faults	Default_7	Parameter slowly change in pitch 3 (Hydraulic leakage)	Changed dynamic	$\zeta_3 = 0.95$ $W_{n3} = 1.42$	1800-1900
	Default_08	Parameter change in pitch 3 (Pump wear)	Changed dynamic	$\zeta_4 = 0.76$ $W_{n4} = 7.30$	3100-3200
	Default_09	Parameter abrupt change in pitch 2 (High air content in oil)	Changed dynamic	$\zeta_2 = 0.25$ $W_{n2} = 8.73$	4000-4200
System Faults	Default_10	Converter torque	Add a fixed value	$\tau_{gc} = -500 \text{ Nm}$	3800-3900
	Default_11	Change of the value in the friction in the drive train (eta_{d12})	Fixed value	0.5	4100-4300

III. CONTROLLERS BENCHMARK MODEL

In what follows we will present the two approaches that will intervene in the part of full load followed by simulations on matlab.2013.

III.1.The FL controller Benchmark Model

The FL is the fuzzy logic control used for the benchmark model shows in the Fig.6, is applies fuzzy logic to process control using error $e(n)$ and change in error $e(n - 1)$

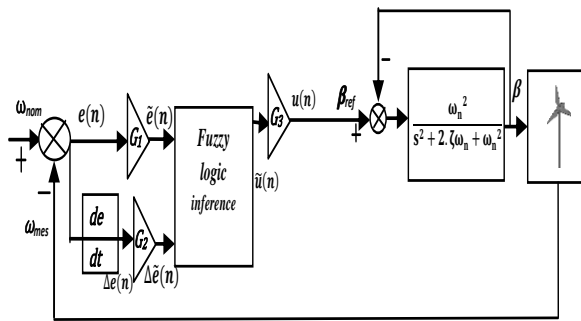


Fig. 6. Bloc of fuzzy controller.

The fuzzy control action equation is given by $u(n) = f(e(n), \Delta e(n))$ (7)

The normalized error and change in error are: $\Delta \tilde{e}(n) = G_2 \Delta e(n)$ and $\tilde{e}(n) = G_1 e(n)$ and the gains of denormalize increment are given by : $G_1 = 0.1, G_2 = 0.5$ and the gain of normalize is $G_3 = 0.7$.

Where f is a non linear function representing the inference fuzzy system and $u(n) = G_3 \tilde{u}(n)$ $e(k) = w(n)_{mes} - w(n)_{nom}$ and $\Delta e(n) = e(n) - e(n - 1)$.

The linguistic variables of both input and output are expressed in Fig.7, (A,B,C) and the inference used is that of Mamdani, the first input of is the error and the output is the control action which present five fuzzy sets, namely: NB, Negative Big; NM, Negative Medium; Z, Zero, Positive Medium; PM, Positive Big; PB, while the second input is the change in error and presents three fuzzy sets : Negative; N, Zero; Z, positive ; P , the rules applied of the fuzzy logic controller are expressed as follows in Table:

	E	NB	NM	Z	PM	PB
ΔE						
NB		NB	NM	PB	PM	PB
NM		NB	NM	PB	PM	PB
Z		NB	NM	Z	PM	PB
PM		NB	NM	NB	PM	PB
PB		NB	NM	NB	PM	PB

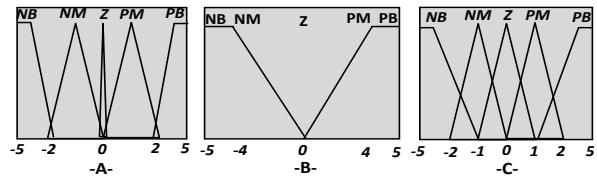
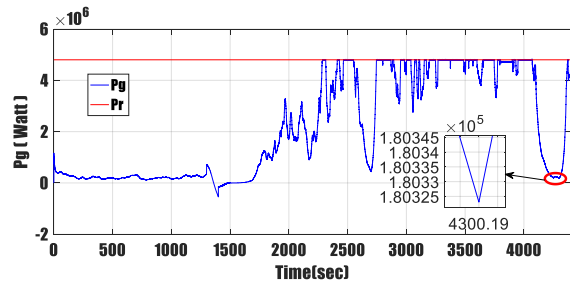


Fig. 7. A-Membership function of inputs (error); B-Membership function of the second input (change in error); C-Membership function of the output.

A) FL control simulation results

The FL control simulation results with the wind turbine benchmark model are shown in Fig. 8, We can see that this control mode worked well in the full load zone where the power is always fluctuated around the nominal power in a tolerant way to disturbances and or faults generated.



(D)

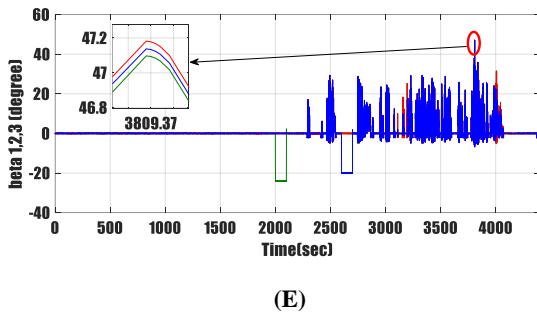


Fig. 8. (D) the power generated by the wind turbine and (E) the angle of the blade pitch system obtained from the simulation of the FL controller of wind turbine benchmark model.

B) Fuzzy Sliding Mode Controller Benchmark Model

In this part we associate two types of control: the first is the sliding mode controller and the second one is the fuzzy logic. This combination is designed for the control of the pitch angle. The structure of the closed-loop fuzzy sliding mode control system is shown in Fig. 9. This method of fuzzy control and sliding mode control is different from conventional control theory because each of these controls has its own advantages and disadvantages. For example, the fuzzy command does not need a precise mathematical model to create objects and has good robustness. However, once the control rule and the coefficient are defined, the fuzzy control may not adapt well to the change in condition.

Sliding mode control has the advantage of a fast response characteristic and is insensitive to variable parameters and rapid wind changes. In the traditional SMC, the structure of the controller is determined by the switching function, it is sensitive to external disturbances during the approach process, and it is easy to cause vibration. The combination of the fuzzy control with the sliding mode control can attenuate or eliminate the vibrations caused by the sliding mode control.

Given the control objective of maintaining the output power at a nominal value, the output error and its change are defined as:

$$\dot{e}(n) = e(n) - e(n-1) \quad (8)$$

Choosing the error as follows:

$$e(n) = \omega_g(n) - \omega_{nom} \quad (9)$$

The switching function of sliding mode is given as follows:

$$s = c \cdot e(n) + \dot{e}(n) \quad (10)$$

$$\dot{S}(n) = S(n) - S(n-1) \quad (11)$$

The control output $u(n)$ is given as follows:

$$u(n) = \Delta u(n) + u(n-1)$$

The rules applied of the fuzzy logic are expressed as follows:

1. If (S is PB) then (CONTROL is PB)
2. If (S is NB) then (CONTROL is NB)
3. If (S is NM) then (CONTROL is NM)
4. If (S is PM) then (CONTROL is PM)
5. If (S is Z) and (\dot{S} is NA) then (CONTROL is PB)
6. If (S is Z) and (\dot{S} is PA) then (CONTROL is NB)
7. If (S is Z) then (CONTROL is Z)

The block diagram of the FSM control is shown in Fig. 9.

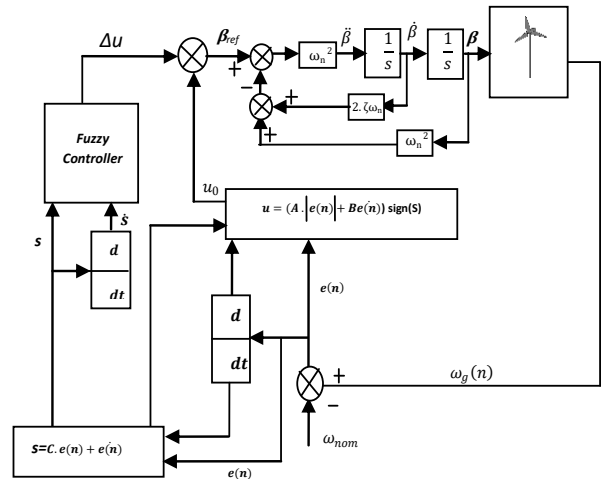
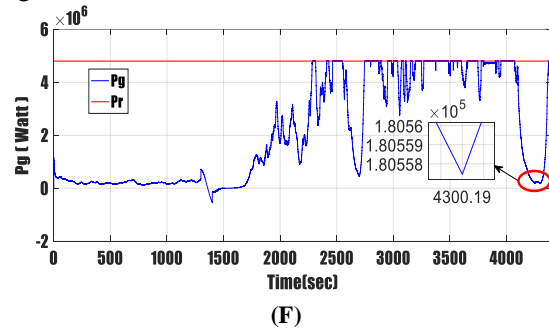


Fig. 9. FSM Controller Benchmark Model

The FSM control simulation results with the wind turbine benchmark model are shown in Fig. 10.



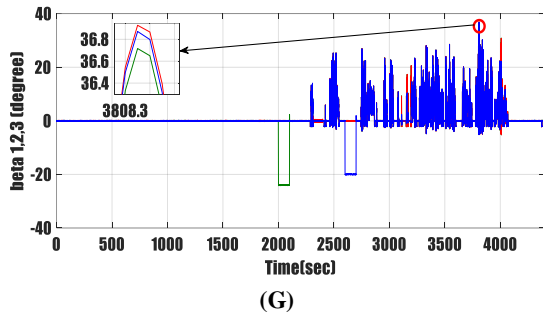


Fig. 10. (F) the power generated by the wind turbine and (G) the angle of the blade pitch system obtained from the simulation of the FSM controller of wind turbine benchmark model.

IV. DISCUSSIONS

The simulation results illustrated in the previous figures show the difference between the two approaches and this is clear to observe in terms of the power generated and the pitch angle for the different simulated approaches where it has been observed that each approach improves performance. by contribution to the other. and means have been used to monitor the performance of the different approaches and these are:

$ITAE = \int_0^{t_f} t \cdot |e(t)| dt$ is the integral of time multiplied by the absolute value of the error, is used as numerical measure of tracking performance for the entire error curve.

$ISV = \int_0^{t_f} u(t)^2 dt$ is the integral of the square value of the control input, is the energy consumption.

Table 3 reflects the different results observed during the simultaneous.

TABLE 3. Comparison Between Multiple Controllers.

The Fuzzy Logic Controller	The Fuzzy Sliding Mode Controller
* $ITAE = 3.67210^8$	* $ITAE = 3.672 \times 10^8$
* $ISV = 1.374 \times 10^5$	* $ISV = 01.286 \times 10^5$
* all the peaks are around 29° except one peak around 47°	* All peak are around 28 ° with except one peak around 36.8°
* $P_{min} = 1.80325 \times 10^5 w.$	* $P_{min} = 1.80558 \times 10^5 w.$

V. CONCLUSIONS

In this paper, a comparison between **FL** control and **FSM** control for blade pitch angel of

wind turbine reference model simulations were validated in Matlab/Simulink environment.

1- Regarding the pitch angle

Figures 8 and 10 illustrate the pitch angle for both controllers, or in the case of the FL controller the pitch angle varies around 29 degrees with a peak value of 47 degrees. While with the FSM controller, only one peak reached 36.8 degrees and the others vary around 28 degrees, which informs us that the control effort is less in the FSM controller compared to the FL controller.

2-Regarding the power generated

The power generated with the FSM controller remains in a less band compared to the FL control see figures 8.10 (F,D) which translates that the FSM presents less oscillation compared to the FL controller and this comes down to the capacity of the controller FSM to deal with the non-linearization of systems and robustness to disturbances with respect to the FL.

The simulation results showed that the FSM controller improved the performance of the system, in terms of energy consumption and fault tolerance with respect to this type of fault, due to their ability to manage the non-linearities of the system.

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REFERENCES

- [1] Odgaard, P. F., Stoustrup, J., & Kinnaert, M. (2009). Fault tolerant control of wind turbines—a benchmark model. IFAC Proceedings Volumes, 42(8), 155-160.
- [2] Odgaard, P. F., & Johnson, K. E. (2013, June). Wind turbine fault detection and fault tolerant control-an enhanced benchmark challenge. In 2013 American Control Conference (pp. 4447-4452). IEEE.
- [3] Odgaard, P. F., Stoustrup, J., & Kinnaert, M. (2013). Fault-tolerant control of wind turbines: A benchmark model. IEEE Transactions on control systems Technology, 21(4),
- [4] Tan, J., Hu, W., Wang, X., & Chen, Z. (2013). Effect of tower shadow and wind shear in a wind farm on AC tie-line power oscillations of interconnected power systems. Energies, 6(12), 6352-6372.

- [5] Odgaard, P. F. (2014). Wind turbine benchmark model for fault detection, isolation and accommodation.
- [6] Tan, J., Hu, W., Wang, X., & Chen, Z. (2013). Effect of tower shadow and wind shear in a wind farm on AC tie-line power oscillations of interconnected power systems. *Energies*, 6(12), 6352-6372.
- [7] Rebiai, S. E., & Lehouche, H. (2021). Commande par mode glissant adaptative appliquée sur un système éolien (Doctoral dissertation, Université Abderrahmane Mira-Bejaia).