Intelligent Variable Speed Wind Turbine Controller using the Type-2 Fuzzy Logic based on PID

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Abstract: An Intelligent and optimal Interval Type-2 Fuzzy Logic (IT2FL) based on Proportional, Integral, and Derivative controller (IT2FLC-PID) is designed in this paper for the robust control of a Wind Turbine System (WTS) to guarantee high and efficient stability of the system in different operating conditions. To improve the classical PID controller efficiency and robustness, we used the interval type-2 fuzzy logic controller (IT2FLC). However, the aim of using the IT2FLC is to overcome oscillations, imprecision, and uncertainty. This approach is applied in this study to adjust and optimize the gains of the PID controller. We have designed the proposed (IT2FLC-PID) to achieve considerable stability and to increase the performance of (VS-WT) system. Furthermore, for the purpose evaluate the effectiveness and the robustness of the proposed controllers (IT2FLC-PID), the simulation results attest that the (IT2FLC-PID) comparing with (IT1FLC-PID) and (PID) controller produces robust stability and better response for Wind Turbine systems.

1 INTRODUCTION

Wind energy has an important role and can be considered the most developed renewable energy source. The level of efficiency and profitability of a wind energy system (WES) depends very much on its control (Apata et Oyedokun, 2020). The most of wind energy system uses variable speed wind turbines (VS-WT). Due to their superiority compared to fixed-speed wind turbines (FS-WT). The characterization of variable speed wind turbine is the capacity to adapt the speed of the shaft in the case of changes in wind speed (Jabbariet al. 2016; Koumir et al. 2017).

Variable speed operation is primarily related to the type of generator that provides the mechanical-to-electrical conversion (Wang et al. 2018). Therefore, several research studies have been carried out on the use of wind turbine systems (WTS), whose purpose is the production of electricity. To achieve the performance and efficiency of the system based on the use of conventional controls such as the PID controller. There is no such thing as the perfect PID; it is all about compromise. Some applications will allow an overrun to improve the stabilization time, while others will not allow it, so it depends on the specifications. Each of the coefficients (KP, KI, KD) influences the response of the system. To decrease the static error, it is necessary to decreases KP and KI. The overshoot is reduced (ratio between the first peak and the setpoint) if KP or KI decreases or KD increases. The rise time decreases if KP or KI increases or KD decreases (Apata et Oyedokun, 2020). The stabilization time decreases as KP and KI increase. However, using this classical type of control (PID) causes many difficulties in guaranteeing robust performance; because there are many problems in the wind turbine system, such as the nonlinearity of the (WTS) systems, the uncertainties; the parameter variation, and unknown disturbances (Dib et al. 2019).

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The main objective of this work is to develop a new and intelligent approach (IT2FLC-PID); the purpose of this approach is the design of a robust and efficient controller. Most controllers existing in the literature use the traditional fuzzy logic system (IT1FLC). Furthermore, there is an alternative that uses the interval type-2 fuzzy logic controller (IT2FLC) (Miccio and Cosenza, 2014; Ben Meziane et al. 2019). Usually, Lotfi Zadeh has expressed a fuzzy logic by a set of linguistic rules called fuzzy rules, which are used to describe the dynamic behavior of an unknown or ill-defined system (Zadeh, 1965). Since fuzzy systems are built from the knowledge provided by the human expert, they are fraught with uncertainties. These uncertainties are injected at the level of the membership functions of the antecedent and consequent fuzzy sets, which will be uncertain. These fuzzy systems, called type-1 fuzzy systems, are unable to model these uncertainties because they use precise membership functions, which have a two-dimensional representation. Therefore, type-2 fuzzy sets, whose membership functions themselves are fuzzy, are the extension of type-1 fuzzy systems. Membership functions type-2 have a three-dimensional representation, the new (third) dimension of fuzzy sets provides an additional degree of freedom to accommodate uncertainties. The main advantage of type-2 fuzzy logic over type-1 fuzzy logic is its ability to take into account linguistic and numerical uncertainties (Mendel et al. 2006). IT2FLC; can be used in situations where there is uncertainty about the membership degrees themselves. For example, uncertainty in the form of the membership function or some of its parameters.

The (IT2FLC-PID) proposed controller is used in this study to achieve a high performance of control in terms of precision, variations, and external disturbances in the (WT) system; and facilitate the performance in damping oscillations, and increase the stability of the (WTS). We have using the IT2FL controller for adjusting the (Kp), (Ki), and (Kd) gains of the conventional PID controller to obtain the optimal parameters.

The paper is organized as follows: Section 2 presents the mathematical model of the wind turbine system, Section 3 shows the proposed controller, the simulation results are shown in Section 4, and the conclusion is given in Section 5.

2 MODELING WIND TURBINE SYSTEM (WTS)

Variable Speed Wind Turbines Systems are currently the most widely used in the industry. The term variable speed designates the fact that the speed of the turbine is independent of the frequency of the power system. The main advantage of operating the turbine at a variable speed is to maximize the capture of the energy available in the wind (Koumir et al. 2017).

The mathematical model of the aerodynamic power of the wind turbine (WT) is described by the following equation (Sid Ahmed et al. 2015):

$$P_v = \frac{1}{2}\rho A v^3 \quad (1)$$

The power captured by the rotor is given by the following equation (Hamedet al. 2016):

$$P_a = C_p(\lambda, \beta) P_v \quad (2)$$

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

Where $C_p$the coefficient of performance of power and λ presents the tip speed ratio given by:

$$\lambda = \frac{\omega_t R}{v} \quad (4)$$

ω_t Indicate the tangential speed of the tip of the blade; R design the radius of the area swept by the rotor. The expression of wind turbine power can be defined as follows (Lahlou et al. 2019):

$$P_a = \omega_t T_a \quad (5)$$

The aerodynamic power extracted Pa is a non-linear function of wind speed, rotor speed, and stall angle. Then, the aerodynamic torque is converted into mechanical power, which results in an aerodynamic torque Ta, we have the following equation:

$$T_a = \frac{1}{2\lambda}\rho \pi R^3 C_p(\lambda, \beta) v^2 \quad (6)$$

To describe the model of the wind turbine system, generally, a two-mass model is used, which is illustrated in Figure.1.

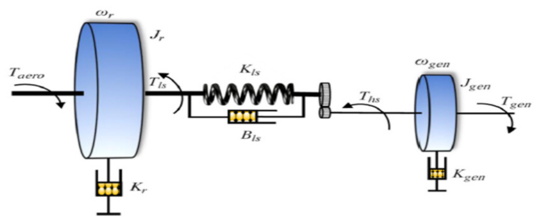

Figure 1: The model of a two-mass wind turbine system (Dib et al. 2019).

The main advantages of variable speed wind turbines compared to fixed speed ones are as follows (El Aimani et al. 2003):

• Increased operating range, especially for low wind speeds where maximum power can be easily converted.

• Simplicity of the blade orientation system.

• Reduction of mechanical efforts thanks to the adaptation of the speed of the turbine during variations in the wind.

• Noise reduction during low power operation because the speed is slow (Koumir et al. 2017).

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The rotor speed ω_t is given in the equation (7) (Hamed et al. 2016):

$$J_r \dot{\omega}_t = T_a - T_{ls} - K_r \omega_t \quad (7)$$

The torque of the low-speed shaft $T_{ls}$is given by equation (8):

$$T_{ls} = B_{ls}(\theta_t - \theta_{ls}) + K_{ls}(\omega_t - \omega_{ls}) \quad (8)$$

$$J_g \dot{\omega}_g = T_{hs} - K_g \omega_g - T_{em} \quad (9)$$

If an ideal gearbox with a ratio n_g is assumed, one has (Hamed et al. 2016):

$$n_g = \frac{T_{ls}}{T_{hs}} = \frac{\omega_g}{\omega_{ls}} = \frac{\theta_g}{\omega_{ls}} \quad (10)$$

By using (7)–(10), we can model the (WTS) by equations (11):

$$\begin{bmatrix} \dot{\omega}_t \\ \dot{\omega}_g \\ \dot{T}_{ls} \end{bmatrix} = \begin{bmatrix} c_{11} & c_{12} & c_{13} \\ c_{21} & c_{22} & c_{23} \\ c_{31} & c_{32} & c_{33} \end{bmatrix} \begin{bmatrix} \omega_t \\ \omega_g \\ T_{ls} \end{bmatrix} + \begin{bmatrix} b_{11} \\ b_{21} \\ b_{31} \end{bmatrix} T_a + \begin{bmatrix} b_{12} \\ b_{22} \\ b_{32} \end{bmatrix} T_{em} \quad (11)$$

We define $x_1 = \omega_t, x_2 = \dot{\omega}_t, x_3 = \omega_g$, and $u = T_{em}$, the state space of the system is described by equations (12) (Lahlou et al. 2019):

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = f(x) + g(x).u + \xi(x,t) \\ \dot{x}_3 = c_{22}x_3 + \frac{c_{23}}{c_{13}}(x_2 - c_{11}x_1 - b_{11}T_a) + b_{22}u(x,t) \\ y = x_1 \end{cases} \quad (12)$$

The two-mass model becomes a non-linear system. With two inputs: Tem which is a controllable input, and v, which is a non-controllable input, and at one output, it is the rotor speed ω_t .To maximize the energy captured by the wind, the variables λ and β must be kept at their optimal values to ensure the maximum value of Cp. Thus, the pitch angle of the blade is fixed at its optimum value βopt. The rotor speed ωt must be adjusted by Tem to follow the optimal reference ω_{topt}.

The nonlinearity of this system comes from the aerodynamic torque, which depends on ωt and on the wind speed, which is a non-controllable, random, and fluctuating input (Koumir et al. 2017).

3 INTERVAL TYPE-2 FUZZY LOGIC BASED ON PID CONTROLLER

3.1 Interval Type-2 Fuzzy Logic System

In recent years, the classical fuzzy logic called type-1 fuzzy logic has been developed to a new generation called type-2 fuzzy logic. Mendel and his team contributed a lot to its development (Mendel et al. 2006). The type reducer block is given between the inference engine and the defuzzification block. The basic structure of the IT2FLC system, which is represented by Figure 2, is essentially composed of three elements namely: the fuzzification interface, the inference mechanism, and the output processing module(El-Nagar et al. 2014).

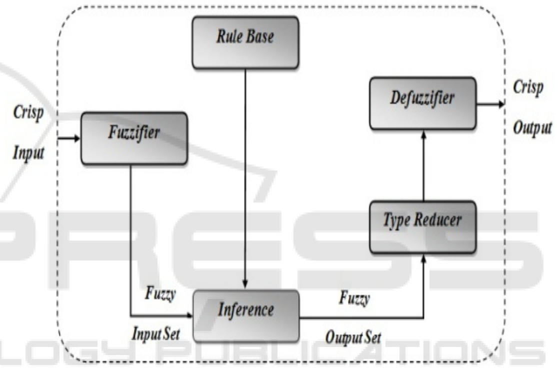

Figure2: Structure described the IT2FLC.

- **Fuzzification:** Unlike the type-1 membership function, the type-2 membership function gives multiple membership degrees (or dimensions) for each input. Therefore, the uncertainty will be better represented.

- **Rule bases:** The difference between type-1 and type-2 lies only like the membership functions; therefore, the structure of the rules in the case of type-2 remains the same (Mendel et al. 2002).

- **Inference Mechanism:** The inference system in a type-2 fuzzy system uses the fuzzy rule base to relate the input vector to the scalar output.

- **The type-reducer**: is used to convert output sets of type-2 fuzzy into sets of type-1 fuzzy to give finally a crisp output (Lahlou et al. 2019). The type-reducer takes into account more information about the uncertainties of the rules than the defuzzified value (a number). However, this operation requires intensive calculations, except for interval type 2 where there is a simple procedure for implementing type reduction. The choice of (IT1FL) may not present the correct and the optimal solution to all types of control problems, while a possible alternative is to use controllers based on type-2 fuzzy logic.

- **Defuzzification:** The defuzzifier in a type-2 fuzzy system can then defuzzify the reduced set to obtain an ordinary non-fuzzy output.

The variation in the wind and the change in the operating point introduce some unpredictable values into the information collected. All the uncertainties are reflected at the level of the base of the fuzzy rules by functions belonging to the premises and uncertain consequences. We will illustrate how to use the IT2FLC to minimize the effect of these uncertainties.

3.2 Proposed Interval Type-2 Fuzzy Logic based on PID Controller (IT2FL-PID)

The new proposed control used in this study is obtained as:

$$\hat{U}_{IT2FLC-PID} = \hat{K}_P e(t) + \hat{K}_I \int e(t)dt + \hat{K}_D \frac{de(t)}{dt} \quad (13)$$

With $\hat{K}_P$, $\hat{K}_I$, $\hat{K}_D$ represent respectively the corrected values of proportional, integral, and derivative gains, which, are tuned by using the IT2FLC. We have Exposed the structure of the new control law based on the IT2FLC-PID controller in Figure 3.

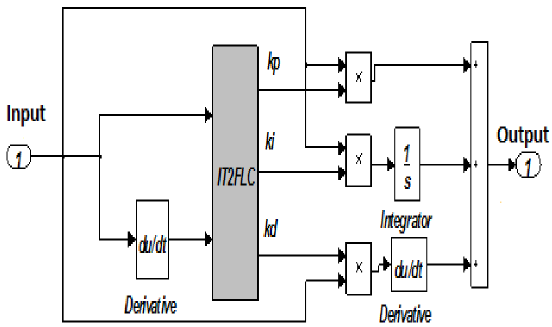

Figure 3: Structure of IT2FL- PID controllers.

The type-2 interval fuzzy system (IT2FL) is designed using the MATLAB / Toolbox (Castillo, 2007). The type-2 Gaussian membership function is chosen for the two inputs and the outputs. We have chosen seven membership functions for each input and output. These membership functions have different ranges in the universe of discourse.

The interval of outputs gains KP, KI, KD of the two-area are from:

$$\hat{K}_P = [0,20];\ \hat{K}_I = [0,60];\ \hat{K}_D = [0,15]$$

In this paper, Figure 4 describes the type-2 membership functions (MF). We have used the symmetrical and Gaussian (MF).

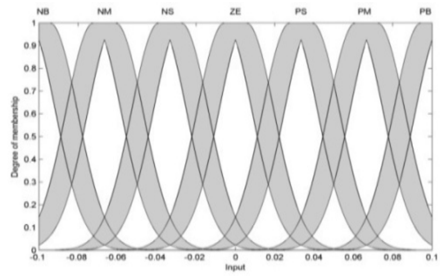

Figure 4: Gaussian type-2 membership functions.

After the fuzzification of the input and output variables, we proceed to the design of the inference engine. We have designed 49 rule bases in the form of a matrix.

Finally, we can get the (IT2FLC-PID), our proposed controller, which is presented by the equations (14):

$$\hat{u} = \hat{u}_{eq} + \hat{u}_{IT2FL-PID} \quad (14)$$

4 SIMULATION RESULTS

This paper selects one type of the two-mass model of the wind turbine. We have proposed to test Simulation in MATLAB Software to validate the validity and the robustness of the developed and suggested control device (IT2FLC-PID). The parameters of the wind turbine are taken from (Orlando et al. 2010).

Simulation Scenario 1: The wind speed profile applied in the first scenario with more minor variations. The result of the simulation is illustrated in Figures:

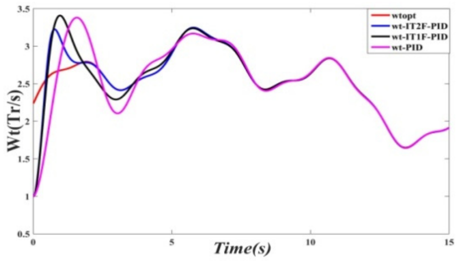

Figure 5: The Rotor Speed response.

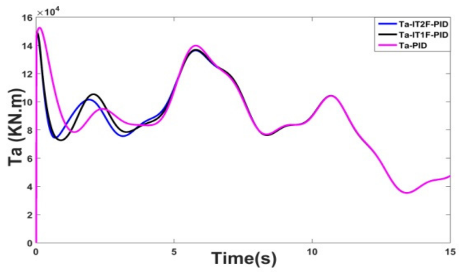

Figure 6: The aerodynamic torque.

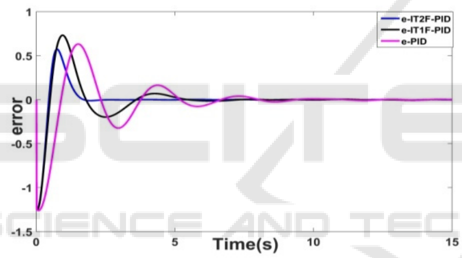

Figure 7: Comparison of tracking errors.

From this simulation results; it can therefore be deduced from this case of simulation the efficiency and the robustness of the proposed controller device (IT2FLC-PID). The results confirm that this intelligent controller is capable of eliminating the oscillations and minimizing the tracking errors. Comparing with the other controllers and intelligently controlling the speed of the rotor of a wind turbine in different wind profiles and offers a better result and response time.

Simulation Scenario2: The wind speed profile used in this scenario with high variation:

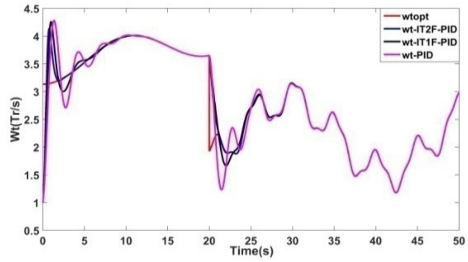

Figure 8: The Rotor Speed response.

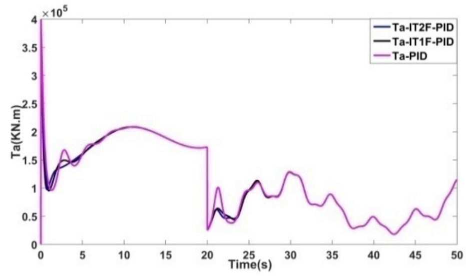

Figure 9: The aerodynamic torque.

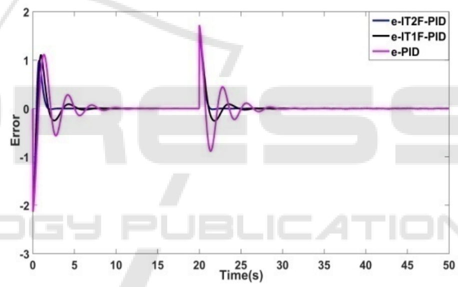

Figure 10: Comparison of tracking errors.

From all these results, we can deduce that all the output response of (IT2FLC-PID) converges to de the required values rapidly compared to other controllers (IT1FLC-PID) and (PID). Consequently, the result of the simulations shows that the suggested approach makes it possible to minimize the response time with good convergence despite the variations in wind speed.

The proposed controller shows good performance in terms of eliminating disturbances as well as in terms of pursuing the desired rotational speed. We notice that the proposed controller quickly converges to the optimal state with less oscillation even when changing the wind profile.

5 CONCLUSIONS

In this paper, the intelligent and optimal (IT2FLC-PID) controller for a Variable Speed Wind Turbine (VS-WT) System is introduced to ameliorate the stability of the (WT) system. We have optimized the gains of the (PID) controller by using the (IT2FLC) approach to eliminate and overcome the significant parametric variations, imprecision, and system nonlinearities, this method strategy is used. We can also show that the control device we have proposed (IT2FLC-PID) in this work can ensure the good performances of tracking which leads to the overall stability of variable speed wind turbine systems in various conditions of operating.

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