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New design of robust controller based on fuzzy 12 linguistic variables for wind power conversion system

***Abstract**. This paper proposes a strategy for robust control of the wind turbine using a double-fed induction machine (DFIM) controlled by the park transformation, which allows control commands to be applied to the generated power. By orienting the stator flux, the active and reactive powers generated by the DFIM can be decoupled. The proposed control utilises a combination of sliding mode control and fuzzy logic with 12 linguistic variables. This approach effectively addresses modelling uncertainties in both the generator and wind turbine, resulting in improved performance and production quality in this domain. Simulation results will demonstrate the advantages of this approach over the classic setting.*

***Streszczenie**. W artykule zaproponowano strategię niezawodnego sterowania turbiną wiatrową za pomocą maszyny indukcyjnej o podwójnym zasilaniu (DFIM), sterowanej transformacją parku, która pozwala na zastosowanie poleceń sterujących do generowanej mocy. Ukierunkowując strumień stojana, można oddzielić moc czynną i bierną generowaną przez DFIM. Proponowane sterowanie wykorzystuje kombinację sterowania w trybie przesuwnym i logiki rozmytej z 12 zmiennymi językowymi. Podejście to skutecznie eliminuje niepewności modelowania zarówno w generatorze, jak i turbinie wiatrowej, co skutkuje poprawą wydajności i jakości produkcji w tej dziedzinie. Wyniki symulacji wykażą przewagę tego podejścia nad klasycznym ustawieniem. (**Nowa konstrukcja solidnego sterownika opartego na 12 rozmytych zmiennych lingwistycznych dla systemu konwersji energii wiatru**)*

Keywords: Doubly fed induction generator, Wind power, Bidirectional converter, Sliding mode control, Fuzzy 12 linguistic variables.
Słowa kluczowe: Generator indukcyjny z podwójnym zasilaniem, Energia wiatru, Przetwornica dwukierunkowa, Sterowanie w trybie przesuwnym, Fuzzy 12 zmiennych językowych

1. Introduction

In recent years, wind power technology has significantly evolved because of the increasing number of exploitable regions and its cost-effectiveness [1]. Most wind turbines installed today use a doubly-fed induction machine due to its numerous advantages. These include variable speed generation across the speed of synchronism, decoupled control of active and reactive powers, reduced mechanical stresses and acoustic noise, improved power quality, and low cost [2, 3]. The DFIM enables the turbine to operate efficiently across a broad range of wind speeds, extracting maximum power from the wind at each speed. The generator's stator circuit is directly connected to the power grid, while its rotor circuit is connected to the grid through power converters. The use of converters is reduced compared to a variable speed wind turbine powered by the stator, due to the low power exchanged between the rotor and the grid. This generator is primarily used for high power production due to its capability to adjust the voltage at the connection point [4].

However, the Doubly Fed Induction Generator (DFIG) is subject to various constraints. These constraints include the effects of parametric uncertainties resulting from heating, saturation, and rate variation disturbances [1, 5]. Therefore, control measures should prioritize both robustness and performance to ensure optimal system functioning. Controlling this machine requires precise operation because of the motor's complex dynamics, which are influenced by changing parameters over time and a strong coupling between magnetic and mechanical behavior. Various control methods have been used, including vector control, input-output linearization techniques, and sliding mode control [6-8].

Sliding mode control is a type of variable structure controller that switches between different control laws. It is known for its high precision, rapid dynamic response, stability, simplicity of design, and robustness to various internal or external parameters. The control through sliding modes involves directing the machine's trajectories towards a predetermined sliding surface [9]. In practice, sliding mode control may induce high-frequency switching, which is known as chattering. These switchings can excite unwanted dynamics that risk destabilising, deteriorating, or even destroying the system under study. Several solutions have been proposed in the literature to address this issue. One of these solutions is the boundary layer approach, which involves modifying the signal characteristic by approximating it continuously in the sliding surface region. This can be achieved by using either a saturation or sigmoid characteristic. Another approach is to use higher-order sliding modes, which aim to reject discontinuities at the level of the system's higher derivatives. To reduce chattering, various strategies can be employed, such as neural sliding control and sliding-fuzzy control [10-13].

The theory of fuzzy logic serves as a bridge between the linguistic and digital domains. It simplifies complex systems by incorporating imprecise information and emulating the approximate reasoning mechanisms used by humans. A fuzzy controller can be viewed as a specialized expert system that aims to replace an operator's observation and judgement. This enables the handling of frequently uncertain human concepts. There is significant interest in utilising fuzzy controllers to regulate complex and non-linear processes [14].

The aim of this article is to conduct fundamental and applied research on wind energy and enhance the efficiency and productivity of electric energy through optimal control methods. To achieve this, we utilized the sliding-fuzzy control method with 12 linguistic variables.

2. Wind energy conversion system

The wind energy conversion chain used in our system involves two converters on the rotor side, as shown in Figure 1 [4, 13].

The following matrix form describes the dynamic model of the Doubly Fed Induction Generator in the (d, q) reference frame, encompassing both electrical and mechanical dynamics [9, 15].

(1) $\dot{X} = AX + BU$

Where:
$X = [\varphi_{sd} \quad \varphi_{sq} \quad I_{rd} \quad I_{rq}]^T$; $U = [V_{sd} \quad V_{sq} \quad V_{rd} \quad V_{rq}]^T$;

$$[A]=\begin{bmatrix}-\frac{1}{T_s} & \omega_s & \frac{M}{T_s} & 0\\ -\omega_s & -\frac{1}{T_s} & 0 & \frac{M}{T_s}\\ \alpha & -\beta\omega & -\delta & (\omega_s-\omega)\\ \beta\omega & \alpha & -(\omega_s-\omega) & -\delta\end{bmatrix};\qquad [B]=\begin{bmatrix}1 & 0 & 0 & 0\\ 0 & 1 & 0 & 0\\ -\frac{M}{\sigma L_s L_r} & 0 & \frac{1}{\sigma L_r} & 0\\ 0 & -\frac{M}{\sigma L_s L_r} & 0 & \frac{1}{\sigma L_r}\end{bmatrix}$$

With: $\sigma=1-\frac{M^2}{L_r L_s}$; $T_r=\frac{L_r}{R_r}$; $T_s=\frac{L_s}{R_s}$; $\alpha=\frac{M}{\sigma L_r L_s T_s}$; $\beta=\frac{M}{\sigma L_r L_s}$; $\delta=\frac{1}{\sigma}\left(\frac{1}{T_r}+\frac{M^2}{L_s T_s L_r}\right)$

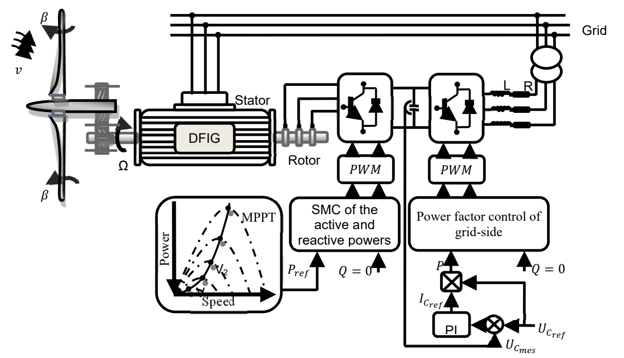

Fig.1. Block diagram of the wind energy conversion system.

The equations for mechanics and electromagnetism are as follows:

(2) $J\frac{d\Omega}{dt}=C_{em}-C_r-f\Omega$

(3) $C_{em}=P\frac{M}{L_s}\left(\varphi_{sq}I_{rd}-\varphi_{sd}I_{rq}\right)$

In order to regulate the power production of the wind turbine, it is essential to have an objective control of the energetic and reactive powers. This can be achieved by establishing equations that connect the values of the rotor voltages to the energetic and reactive stator powers [2, 14].

By selecting a (d,q) reference frame associated with the rotating stator region and aligning the stator flux vector with the d -axis, the following results are obtained: $\varphi_{sd}=\varphi_s$ and $\varphi_{sq}=0$. Assuming a stable electric community and negligible stator resistance, the equation yields $V_{sd}=0$, $V_{sq}=V_s$ and $V_{sq}=V_s/\omega_s$.

The above equations can be adapted to the simplifying assumptions as follows:

(4) $$\begin{cases}I_{sd}=\frac{\varphi_s}{L_s}-\frac{M}{L_s}I_{rd}\\ I_{sq}=-\frac{M}{L_s}I_{rq}\end{cases}$$

(5) $$\begin{cases}P_s=-\frac{V_s M}{L_s}I_{rq}\\ Q_s=\frac{V_s^2}{\omega_s L_s}-\frac{V_s.M}{L_s}I_{rd}\end{cases}$$

(6) $$\begin{cases}\varphi_{rd}=\left(L_r-\frac{M^2}{L_s}\right)I_{rd}+\frac{V_s M}{\omega_s L_s}\\ \varphi_{rq}=\left(L_r-\frac{M^2}{L_s}\right)I_{rd}\end{cases}$$

(7) $$\begin{cases}V_{rd}=R_r I_{rd}+\left(L_r-\frac{M^2}{L_s}\right)\dot{I}_{rd}-\mathrm{g}\omega_s\left(L_r-\frac{M^2}{L_s}\right)I_{rq}\\ V_{rq}=R_r I_{rq}+\left(L_r-\frac{M^2}{L_s}\right)\dot{I}_{rq}+\mathrm{g}\omega_s\left(L_r-\frac{M^2}{L_s}\right)I_{rd}+\mathrm{g}\frac{V_s M}{L_s}\end{cases}$$

The method used in electricity control involves disregarding coupling phrases and installing an impartial regulator on each axis. This allows for independent control of active and reactive power. This method is referred to as the direct approach, as the electricity regulators directly control rotor voltages [1].

3. Sliding mode control

The primary concept of SMC is to confine the states of the machine within a predetermined region and then devise a control regulation that will consistently maintain the machine within that region [9, 16]. SMC is comprised of three parts:

- Choice of switching surface : the sliding surface is determined by the trendy equation proposed by J.J. Slotine:

(8) $$S(X)=\left(\frac{d}{dt}+\lambda\right)^{n-1}e \qquad e=X^d-X$$

Where: λ : positive coefficient; e : error on the signal to be adjusted; n : system order.

- The convergence condition is described using the Lyapunov equation [17], which ensures that the region is both attractive and invariant.

(9) $$S(X)\dot{S}(X)<0$$

- Control calculation: the rules for the control set are described using the relation:

(10) $$u=u^{eq}+u^n$$

Where:
u^{eq} is the control vector that is equal and can be obtained by considering the sliding regime.
u^n : represents the switching part of the control, which acts as a correction factor, $u^n=k\,sign\big(S(X)\big)$.

3.1 Active power control

The sliding surface's expression is:

(11) $$s(P)=\left(I_{rq}^{ref}-I_{rq}\right) \qquad \dot{s}(P)=\left(\dot{I}_{rq}^{ref}-\dot{I}_{rq}\right)$$

By substituting the expressions given in equations (5) and (7) for the current derivatives, we obtain:

(12) $$\dot{s}(P)=\left(-\frac{L_s}{MV_s}\dot{P}_s^{ref}-\frac{1}{L_r\sigma}V_{rq}-\frac{1}{L_r\sigma}\left(-R_r I_{rq}-\mathrm{g}\omega_s L_r\sigma I_{rd}-\mathrm{g}\frac{MV_s}{L_s}\right)\right)$$

The control voltage V_{rq} is defined by: $V_{rq}=V_{rq}^{eq}+V_{rq}^{n}$.
Where : $s(P)=0$, $\dot{s}(P)=0$ and $V_{rq}^{n}=0$.

(13) $$V_{rq}^{eq}=-\frac{L_s L_r\sigma}{MV_s}\dot{P}_s^{ref}+R_r I_{rq}+\mathrm{g}\omega_s L_r\sigma I_{rd}+\mathrm{g}\frac{MV_s}{L_s}$$

During the convergence mode, the condition $s(P)\dot{s}(P)<0$ must be verified with:

(14) $$V_{rq}^{n}=L_r\sigma k_1 sign\big(s(P)\big)$$

Where: $k_1>0$.

3.2 Reactive power control

The expression of the sliding surface becomes:

(15) $$s(Q)=\left(I_{rd}^{ref}-I_{rd}\right)\Rightarrow \dot{s}(Q)=\left(\dot{I}_{rd}^{ref}-\dot{I}_{rd}\right)$$

By replacing $\dot{I}_{rd}^{ref}$ and $\dot{I}_{rd}$ by their expressions given by equations (5) and (7), we obtain:

(16) $\dot{s}(Q) = \left(\left(\frac{V_s}{\omega_s M} - \frac{L_s}{V_s M}\dot{Q}_s^{ref}\right) - \frac{1}{L_r\sigma}V_{rd} - \frac{1}{L_r\sigma}\left(-R_r I_{rd} + g\omega_s L_r \sigma I_{rq}\right)\right)$

The control voltage V_{rd} is defined by: $V_{rd} = V_{rd}^{eq} + V_{rd}^{n}$.

(17) $V_{rd}^{eq} = L_r\sigma\left(\frac{V_s}{\omega_s M} - \frac{L_s}{V_s M}\dot{Q}_s^{ref}\right) + R_r I_{rd} - g\omega_s L_r \sigma I_{rq}$

During the convergence mode, the condition $s(Q)\dot{s}(Q) < 0$ must be verified with:

(18) $V_{rd}^{n} = L_r\sigma k_2 sign\big(s(Q)\big)$

Where: k_2 positive constant.

4. Fuzzy sliding mode control

The primary drawback of sliding mode control is its high switching frequency, also known as chattering. This phenomenon is undesirable because it can excite unmodelled high-frequency modes within the controlled system.

To address this issue, a control method that can predict performance even when the system model is not well-known is required. This control method must also be able to adapt to changes in parameters or external disturbances. These controls are often called 'intelligent controls' and are based on the principles of fuzzy logic and genetic algorithms.

4.1 Principle of fuzzy logic

Conventional set theory dictates that an element either belongs to a set or it does not. However, the theory of fuzzy sets allows for degrees of membership, where an element can partially belong to a set with a membership degree between 0 and 1 [14]. A fuzzy logic regulator comprises four parts: the rule base, fuzzification, inference engine, and defuzzification.

4.2 Fuzzy regulator for the DFIG

Figure 2 shows the proposed control, which suggests replacing the active and reactive power regulators with a sliding-fuzzy mode regulator to achieve robust high-performance regulation. The control comprises an equivalent sliding mode control (SMC) and a fuzzy logic control (FLC), as represented by the following equation.

(19) $u_{FSMC} = u_{eq} + u_f$

Where:

(20) $u_f = k_f \Delta u$

The previous section provides the mathematical development of the u_f fuzzy control (attractive), which is designed to meet the robustness requirement.

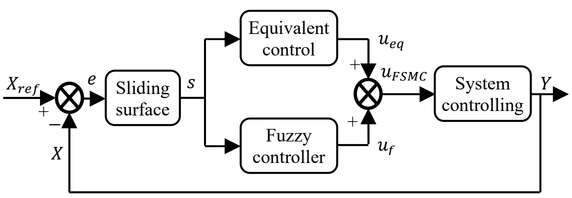

Fig.2. Schematic of hybrid control slidnig-fuzzy.

The figure below shows the fuzzy controller developed in this work:

The figure above shows the proposed fuzzy controller, which consists of a normalization factor k_i associated with the error (e) and k_f associated with the variation of the control Δu, a fuzzification block of the error, fuzzy control rules that determine the control gains k_i based on the current operating state of the controlled system, and a defuzzification block used to convert the fuzzy control variation to a digital value. In the proposed controller, which is a fuzzy logic system of the Mamdani type, it is important to choose the values of k_i and k_f. Fuzzy rules can be written as shown in Table 1.

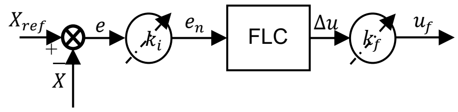

Fig.3. Block diagram of a fuzzy controller.

Table 1. The basic rules of the FSMC.

e	NV	NL	NB	NM	NS	ZR-	ZR+	PS	PM	PB	PL	PV
u_f	PV	PL	PB	PM	PS	ZR+	ZR-	NS	NM	NB	NL	NV

Figure 4 shows the membership functions for the input and output.

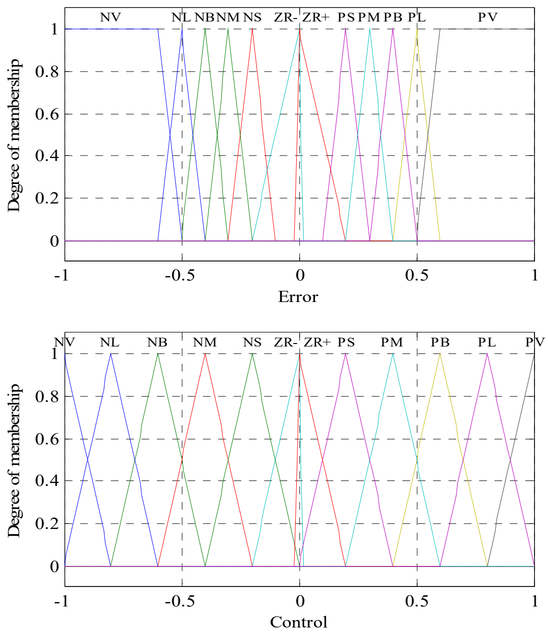

Fig.4. Membership functions of input (e) and output (u_f).

The block diagram of FSMC of a DFIG is illustrated by the figure below:

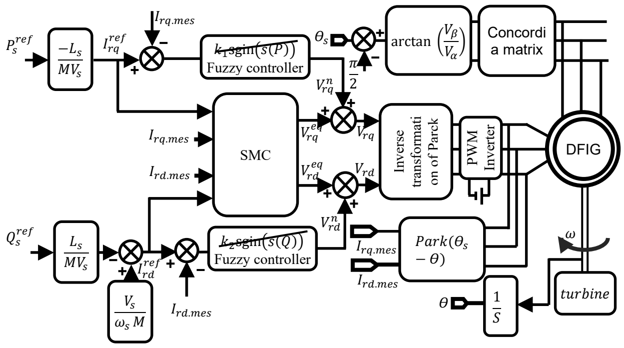

Fig.5. Block diagram of the hybrid sliding-fuzzy control of a DFIG.

5. Results obtained

To demonstrate the performance and robustness of the proposed FSMC, a series of tests were conducted. These tests involved carrying out steps of active and reactive power. During the simulation period of the sliding-fuzzy mode control, the Doubly Fed Induction Generator (DFIG) is powered by a wind turbine. The simulation results demonstrate improved performance and robustness of this control method. A perfect decoupling between the two components of the active and reactive stator power is observed, and the chattering problem is negligible.

The simulation results clearly represent that the new control technique allows perfect decoupling between the two components of the stator power (active and reactive) and manages to maintain the active and reactive powers at their desired values, the remarkable improvement in the results obtained are : a rapid response for the transient regime and for the change of instructions, maximum minimization of error between the setpoint values and those measured et a significant reduction in power oscillations.

Parameters of the DFIG are equal [15]: $P_n = 4\,KW$, $I_n = 15/8.6\,A$, $\Omega_n = 1440\,rpm$, $P = 2$, $R_s = 1.2\,\Omega$, $R_r = 1.8\,\Omega$, $L_s = 0.1554\,H$, $L_r = 0.1568\,H$, $M = 0.15\,H$, $J = 0.2\,Kg.m^2$, $f = 0.001\,IS$.

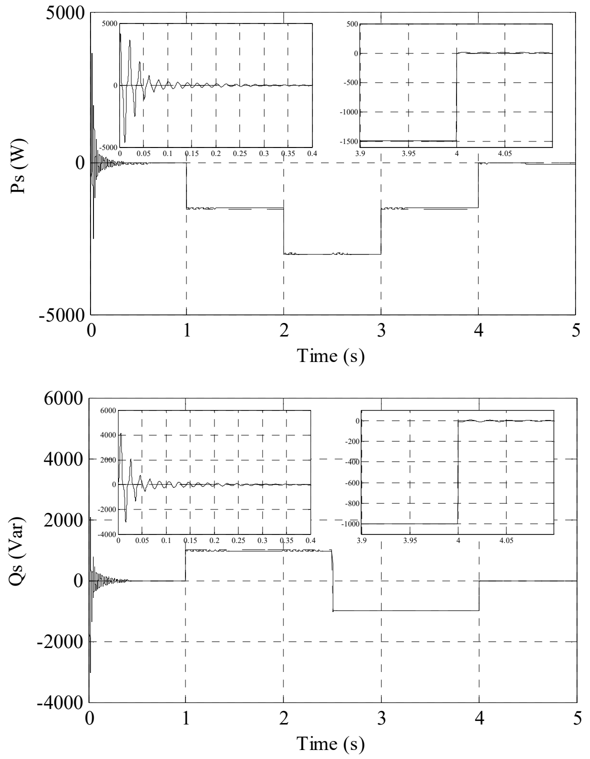

Fig.7. Simulation result of active power (Ps) and reactive power (Qs).

6. Conclusion

This article presents a wind power conversion system equipped with a double-fed induction generator. The system was modelled, and two controllers were developed: one for active power and the other for reactive power, using fuzzy sliding mode control with 12 linguistic variables.

The results obtained are relevant for the application of wind energy to ensure the robustness and quality of the energy produced. The control algorithm is simple, robust, and easy to implement on a computer.

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