DFIG stator reactive and active power control based fuzzy logic

W.Ayrir, M. Ourahou, and A.Haddi

Abstract— The stator reactive and active power control of a variable speed doubly fed induction generator (DFIG) based wind generation system is proposed in this paper. The proposed control aims to generate a suitable referential rotor voltage to control the rotor side converter. The generator mechanical speed is controlled using the MPPT based TSR technique, then the fuzzy logic control is used to control the rotor direct and quadratic currents so that they match their references gotten from the reactive and active power references respectively. The referential active power is gotten from the MPPT control, while the referential reactive power is set to 0 Vars in order to obtain a unit power factor at the stator terminals. The proposed control technique was simulated in MATLAB/SIMULINK. The results show the effectiveness of the fuzzy control strategy.

Keywords— DFIG, fuzzy logic, rotor currents control, TSR, wind turbine.

I. Introduction

Over the last decades, and with the industrial and population growth, energy consumption has increased significantly. Researchers' focus has recently been moved from conventional electricity sources to renewable and alternative energy solutions. Several renewable power generation sources have rapidly been developed in the last decades. Considered as a clean energy, wind energy is growing rapidly. Among all renewable energies, it is considered as a mature and most economical technology after hydroelectricity. It represents a significant source of renewable energy. Its share in the total world electricity production reached about 4% at the end of 2016 [1], [2]. Recently, in wind energy conversion systems (WECS), DFIG based wind turbines have been widely used due to the many advantages that they present. Many control techniques were investigated in the literature. The oriented vector control was widely applied to the rotor side converter (RSC) of the DFIG. Different orientations are used in the classical vector control. The stator flux oriented vector control is used to control directly the stator active and reactive powers of the machine, while the rotor flux oriented vector control is used to control the rotor flux and electromagnetic torque and consequently control the reactive and active power respectively. Many researchers have introduced intelligent control techniques to the classical vector control to get better results. In this paper, the stator active and reactive power control of a DFIG based WECS based on fuzzy stator flux oriented control is presented.

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The proposed control method is realized by aligning the stator flux with the d axis, and using fuzzy logic controllers (FLC) to control the resulting currents in order to control the generator stator active and reactive powers. The biggest advantage of the fuzzy logic control is that it is robust and simple to design, since the mathematical model of the system is not needed to design it [3]–[5].

II. Wind turbine modeling

The mechanical power extracted from the wind can be expressed as follows:

$$P_m = 0.5\rho\,\pi R^2 v^3 C_p(\lambda,\beta) \qquad (1)$$

ρ : The air density.
R : The blade radius.
v : The wind speed.
β : The pitch angle.
λ : The tip speed ratio, it is defined by:

$$\lambda = \frac{\Omega_t R}{v} \qquad (2)$$

C_p : The power coefficient, it is defined by:

$$C_p(\lambda,\beta) = c_1\left(\frac{c_2}{\lambda_i} - c_3\beta - c_4\right)e^{-\frac{c_5}{\lambda_i}} + c_6\lambda_i \qquad (3)$$

With:

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3+1} \qquad (4)$$

The aerodynamic torque is given by:

$$T_{aer} = \frac{1}{2}\rho\pi R^2 C_p v^3 \frac{1}{\Omega_{tur}} \qquad (5)$$

The Gearbox model:

$$T_m = \frac{T_{aer}}{G} \qquad (6)$$

$$\Omega_m = \Omega_t . G \qquad (7)$$

The dynamic equation of the wind turbine is given by:

$$J\frac{d\Omega_m}{dt} + f.\Omega_m = T_m - T_{em} \qquad (8)$$

Where:
J : The system total inertia.
T_m : The turbine's mechanical torque.
T_{em} : The generator's electromagnetic torque.
Ω_m : The generator's mechanical speed.
Ω_t : The wind turbine speed.

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III. Speed control

To maximize the use of wind energy, the maximum power point tracking (MPPT) control is indispensable for optimizing the conversion of energy. This method consists in constantly determining the maximum operating point allowing to assign a maximum power. Many techniques are used for the MPPT, one of the most used is the tip speed ratio (TSR) based MPPT. This method aims to keep λ at an optimum value λ_{opt} so that the captured power will be maximum because C_p is maximum at this wind speed [6]–[8]. So according to equation (2), the referential speed is given by:

$$\Omega_{t\_ref} = \frac{\lambda_{opt}\, v}{R} \tag{9}$$

The diagram block of the TSR based MPPT is shown in the following Fig.1:

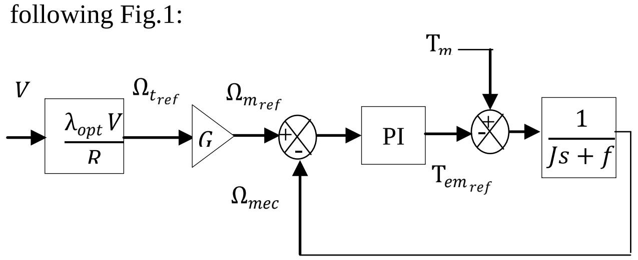

Fig.1 the speed control scheme

The scheme of the proportional integral (PI) speed controller is given in Fig.2:

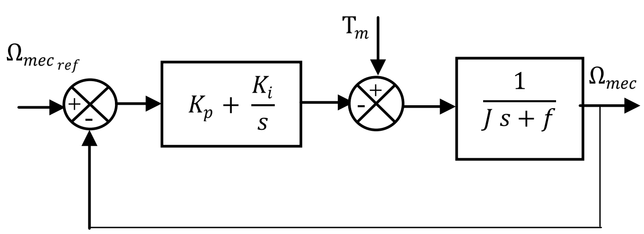

Fig. 2 the speed controller

The proportional gain and the integral gain of the PI controller expressions are gotten by determining the closed-loop transfer function of the system above as follows:

$$F(s) = \frac{\left(K_p + \frac{K_i}{s}\right)\frac{1}{Js+f}}{1 + (K_p + \frac{K_i}{s})\ \frac{1}{Js+f}} \tag{10}$$

F(s) is rewritten as a second order transfer function:

$$F(s) = \frac{K_p s + K_i}{Js^2 + \left(f + K_p\right)s + K_i} \tag{11}$$

Then by using the pole compensation method, we get:

$$K_i = J\omega_n^2 \tag{12}$$

$$K_P = 2\zeta J\omega_n - f \tag{13}$$

ω_n The undamped natural frequency.

ζ The damping coefficient.

IV. Modeling of the DFIG

The general model of the DFIG is resumed as follows:

The equations of the stator and rotor voltages in the d-q frame respectively are given by:

$$\begin{aligned} V_{ds} &= R_s I_{ds} + \frac{d}{dt}\Psi_{ds} - \omega_s \Psi_{qs} \\ V_{qs} &= R_s I_{qs} + \frac{d}{dt}\Psi_{qs} + \omega_s \Psi_{ds} \\ V_{dr} &= R_r I_{dr} + \frac{d}{dt}\Psi_{dr} - \omega_r \Psi_{qr} \\ V_{qr} &= R_r I_{qr} + \frac{d}{dt}\Psi_{qr} + \omega_r \Psi_{dr} \end{aligned} \tag{14}$$

The stator and rotor flux linkage equations in the d-q frame respectively are given by:

$$\begin{aligned} \Psi_{ds} &= L_s I_{ds} + M I_{dr} \\ \Psi_{qs} &= L_s I_{qs} + M I_{qr} \\ \Psi_{dr} &= L_r I_{dr} + M I_{ds} \\ \Psi_{qr} &= L_r I_{qr} + M I_{qs} \end{aligned} \tag{15}$$

The electromagnetic torque generated by the DFIG is given by:

$$T_{em} = \frac{pM}{L_s}\left(\Psi_{ds} I_{qr} - \Psi_{qs} I_{dr}\right) \tag{16}$$

R_s , R_r : stator and rotor phase resistances.

L_s , L_r : stator and rotor phase inductances.

M : the mutual inductance.

p : poles pair number of the machine.

V. Vector control strategy

Hasse and Blaschke developed this technique by inspiring from DC motor drives. This method allows to separate the control of flux and torque [9]. Nowadays, the vector control is widely applied to DFIG due to its ability of controlling more efficiently. For the proposed strategy, the stator flux is aligned with the d axis:

$$\begin{cases} \varphi_{sd} = \varphi_s \\ \varphi_{sq} = 0 \end{cases} \tag{17}$$

So according to equation (16), the electromagnetic torque is given by:

$$T_{em} = -p\frac{M}{L_s}\varphi_{sd} I_{rq} \tag{18}$$

The expressions of the direct and quadratic stator currents respectively:

$$I_{sd} = -\frac{M}{L_s} I_{rd} + \frac{\varphi_s}{L_s} \tag{19}$$

$$I_{sq} = \frac{-M}{L_s} I_{rq} \tag{20}$$

Assuming that the grid is constant and the voltage drop of the stator resistance Rs is neglected [10], [11]:

$$V_{sd} = 0 \tag{21}$$

$$V_{sq} = V_s = \omega_s \varphi_s \tag{22}$$

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Thus, by orienting the direct axis with the stator flux, the voltage is aligned with the axis in quadrature. The stator active and reactive powers can then be written as follows:

$$P_s = V_s I_{sq} \tag{23}$$

$$Q_s = V_s I_{sd} \tag{24}$$

To obtain the expressions of the powers as a function of the rotor currents, the currents in the two previous equations are replaced by their expressions in equations (19) and (20):

$$P_s = -V_s \frac{M}{L_s} I_{rq} \tag{25}$$

$$Q_s = -V_s \frac{M}{L_s} I_{rd} + \frac{V_s^2}{L_s \omega_s} \tag{26}$$

The last equations show that the active and reactive powers could be controlled via rotor currents. The active power can be controlled by the current on the quadratic axis, while the reactive power can be controlled by the current on the direct axis.

Thus, the rotor voltages in the d-q axis can be written as follows:

$$V_{rd} = \left(\frac{R_r L_s + \sigma L_s L_r s}{M V_s}\right)\left(Q_s - \frac{V_s^2}{\omega_s L_s}\right) - \omega_r L_r \sigma I_{rq} \tag{27}$$

$$V_{rq} = \left(\frac{R_r L_s + \sigma L_s L_r s}{M V_s}\right) P_s + \omega_r L_r \sigma I_{rd} + \omega_r \frac{M V_s}{\omega_s L_s} \tag{28}$$

σ : the leakage coefficient, it is given by :

$$\sigma = 1 - \frac{M^2}{L_s L_r} \tag{29}$$

The system transfer function is defined by neglecting the coupling terms $-\omega_r L_r \sigma I_{rq}$ and $\omega_r L_r \sigma I_{rd} + \omega_r \frac{M V_s}{\omega_s L_s}$. Then adding these terms to the output.

VI. Fuzzy power control of the DFIG

Fuzzy logic is an extension of classical logic that allows approaching the human reasoning that makes use of the tolerance, uncertainty, imprecision and flexibility in the decision-making process [12]. It was introduced by L.Zadeh in the mids of 60s. In recent years, the number and variety of applications of fuzzy logic have increased significantly.

In order to design a fuzzy logic controller, the following steps must be performed:

- Fuzzification: It is the first step to be considered in the structure of the fuzzy logic control. It consists of transforming the inputs and outputs of the system to fuzzy sets using fuzzy linguistic terms and membership functions (MFs). A membership function is a function that allows defining the degree of belonging of a numeric variable to a linguistic variable.
- Fuzzy rules: Once the input and output variables and MFs are defined, we will be able to design the rule-base composed of <If condition, then conclusion> rules based on the knowledge of the system behavior. These rules transform the input variables to an output that will indicate the risk of operational problems [13], [14].
- Defuzzification: After developing the rules in the second step, the defuzzification consist of merging these rules and transform the resulting fuzzy sets into numerical variables.

For the proposed control strategy, the referential direct rotor current and quadratic rotor current gotten from the referential reactive and active powers respectively are compared with their measured values. The differences are introduced to the fuzzy logic controllers. The proposed control scheme is shown in the following figure:

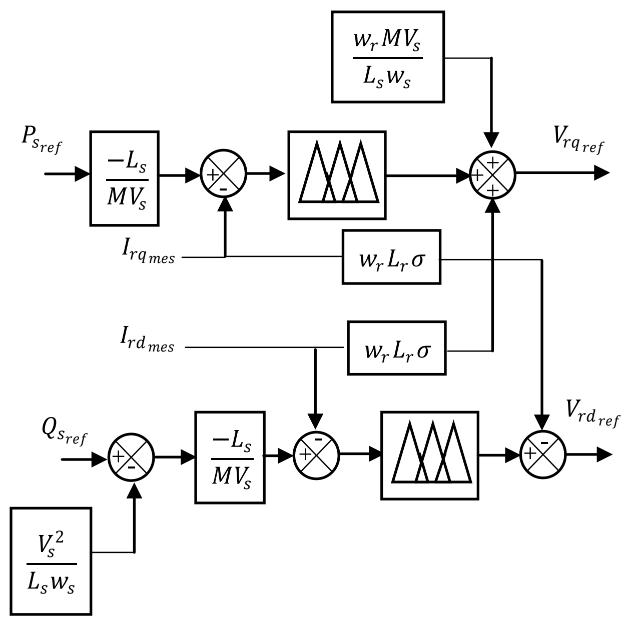

Fig. 3 the proposed control scheme

The structure of the fuzzy controller is shown in figure 4. It has two inputs: the error between the referential and the measured rotor current e (k), and the discrete derivative of this error de(k). The output of the controller is the derivative referential rotor voltage dU that will be integrated to get the referential voltage U to be applied to the rotor side converter.

All the inputs and output of the controller are normalized by multiplying them by the scaling factors K_e, K_{de} and K_{du} respectively.

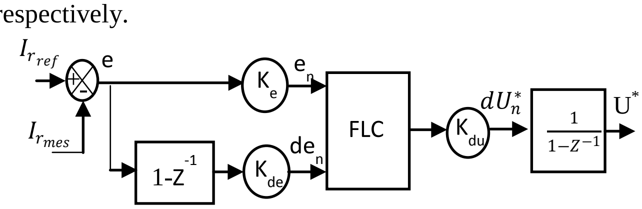

Fig.4 proposed fuzzy current controller

e: the error, it's defined by:

$$e(k) = I_r^*(k) - I_r(k) \tag{30}$$

de: the error derivative, it is given by :

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$$de(k) = e(k) - e(k-1) \quad (31)$$

$e(k)$: The actual error.
$e(k-1)$: The previous error.
$de(k)$ could be expressed as:

$$de(k) = I_r(k) - I_r(k-1) \quad (32)$$

A. Fuzzification:

The inputs are fuzzified to three linguistic variables:

- P: Positive
- Z:Zero
- N: Negative

The output is fuzzified to five linguistic variables:

- P: Positive
- PB: Positive big
- Z:Zero
- N: Negative
- NB: Negative big

The MFs for the inputs and output are given in the following Fig. 5 and Fig.6 respectively.

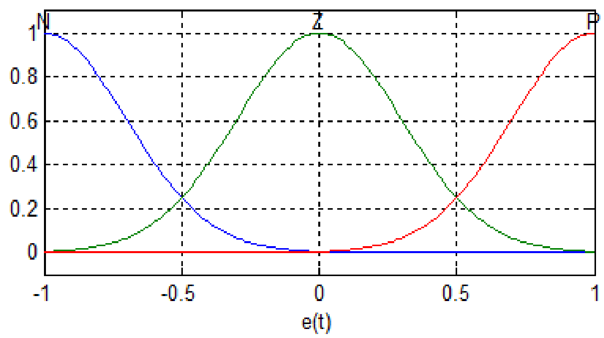

Fig. 5 the inputs' membership functions

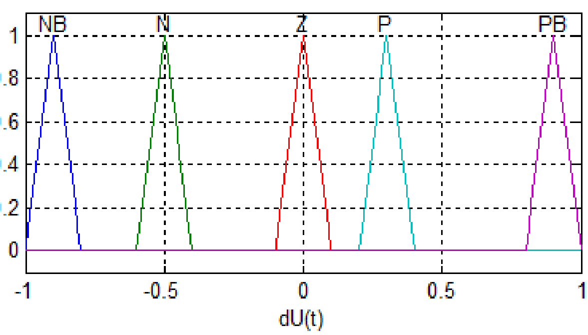

Fig.6 the output's membership functions

B. The fuzzy rules:

The following steps explain the elaboration of the fuzzy rules:

Step 1: Apply Fuzzy Operator:

After the inputs are fuzzified, each control rule can be described using the input variables which are the current error and its derivative, and the output variable dU which is the rotor voltage derivative as [15]:

If (e is A) AND (de is B) THEN (dU is C)

Where A, B and C are the fuzzy sets used for the inputs and output. The AND method used is product.
Example of rules:

- IF e is P, which means that the referential rotor current is bigger than the measured one. AND de is N, which means that the actual measured current is smaller than the previous one. Then the control system should hold previous action.

- IF e is Z, which means that the referential rotor current is equal to the measured one. AND de is Z, which means that the actual measured current is equal to the previous one. THEN the control system should cancel action.

Each of the two inputs of the fuzzy controller has three fuzzy sets, which gives a set of nine rules. These rules could be represented by the following inference matrix:

Table 1: Rule base of the fuzzy controller

de \ e	P	EZ	N
P	Z	N	NB
EZ	PB	Z	NB
N	PB	P	Z

Step 2: Apply implication method:

The implication is the process of specifying how a fuzzy logic controller scales the MFs of an output linguistic variable based on the rule weight of the corresponding rule. After proper weighting has been assigned to each rule, the implication method is implemented. For the proposed controller: the weight of each rule is 1 and the implication method used is the product.

Step 3: Aggregate All Outputs:

Aggregation is the process by which the fuzzy sets that represent the output of each rule are combined into a single fuzzy set. "Each rule whose antecedent has a non-zero matching degree will contribute an output with an activation value equal to the matching degree of the antecedent" [16]. A rule will generate a fuzzy membership value μ_e coming from the error and a membership value μ_{de} coming from the derivative of the error. The aggregation is their combination: μ_e and μ_{de}. The aggregation method used for the proposed fuzzy controller is the maximum.

C. Defuzzification:

The center of gravity defuzzification method is used to defuzzify the output. This technique was developed by Sugeno in 1985 [13]. It consists of calculating the position of the center of gravity of the resulting MF using equation (33). Therefore, the abscissa of this point becomes the output of the controller.

$$COG = \frac{\int_s \mu(x).x.dx}{\int_s \mu(x).dx} \quad (33)$$

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VII. SIMULATION AND RESULTS

The simulation has been performed in MATLAB Sim Power Systems toolbox. The parameters used for the simulation are given in the table below [17]:

Table 2: The DFIG and wind turbine parameters

R_s	$0.455\ \Omega$
R_r	$0.62\ \Omega$
L_s	0.084 H
L_r	0.081 H
M	0.078 H
J	$0.3125\ \mathrm{Kg.m^2}$
F	$6.73e^{-3}$ Nm. s. rad
c_1	0.5176
c_2	116
c_3	0.4
c_4	5
c_5	21
c_6	0.0068
$C_{p\,max}$	0.5

The system was simulated for a variable wind speed for 10s as it is shown in Fig.7.
Fig.8 shows the mechanical speed, it tracks perfectly its reference . Moreover the response time is very fast, about 0.15s. Fig.9 shows the performance coefficient. It is obviously seen that it is at the maximum (0.5), which proves the efficiency of the MPPT technique.
Fig.10 and Fig.11 show the active and reactive stator powers respectively. The referential stator active power is gotten from the MPPT bloc, while the stator reactive power is set to 0 Vars. It is clearly seen that both powers track closely their references.
Finally, Fig.12 shows the power coefficient, it is almost a unit power factor which is due to the reactive power that was set to 0 Vars. The negative sign is in the fact due to the negative generated active power.
The obtained results show that the proposed control gives good performance: the well tracking of references and the fast response time. Which proves the perfect adaptation of the fuzzy logic control to the stator flux oriented vector control.

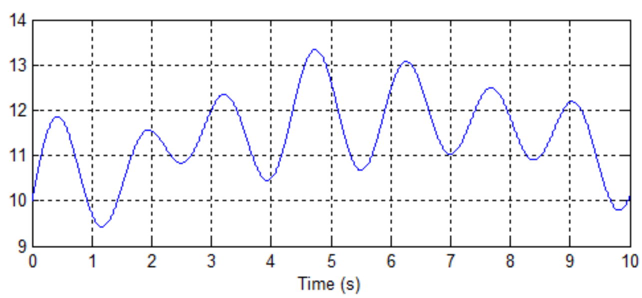

Fig.7 the wind speed (m/s)

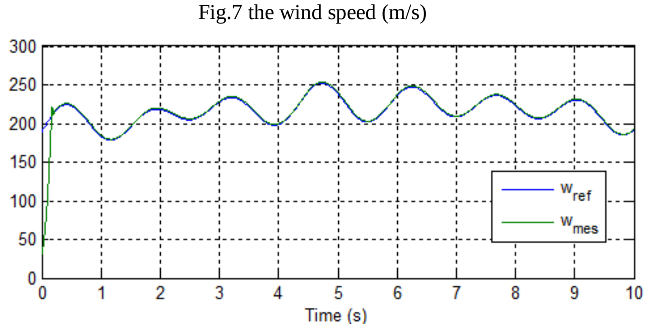

Fig.8 the mechanical speed (rad/s)

Fig. 9 the performance coefficient C_p

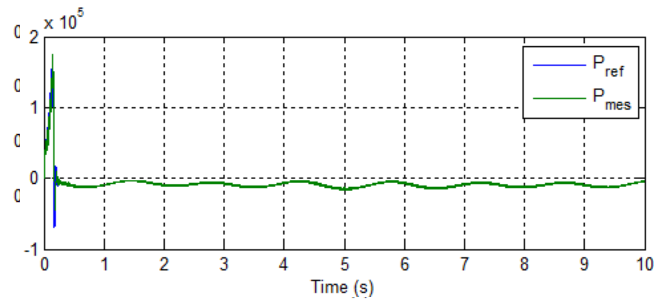

Fig.10 the stator active power (Watt)

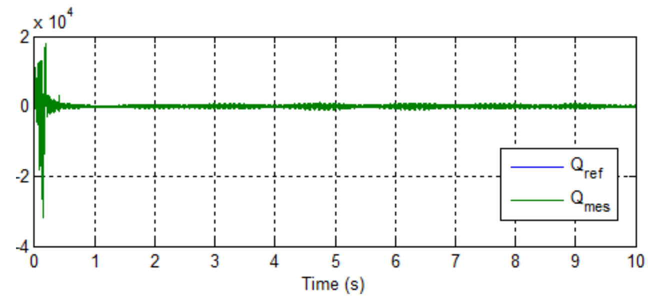

Fig.11 the stator reactive power (Vars)

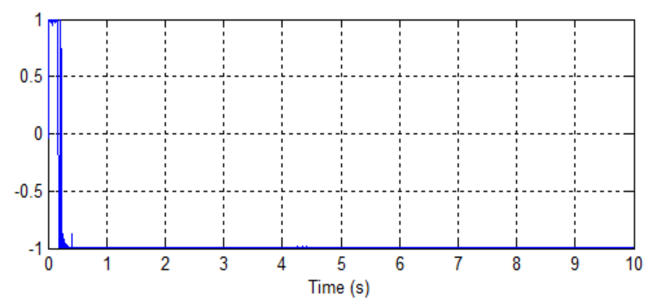

Fig.12 the stator power factor

VIII. CONCLUSION

The stator reactive and active power control of a variable speed DFIG based wind generation system was presented in this paper. The obtained results show the effectiveness of the proposed control strategy in tracking the references. Generally the design of a fuzzy logic controller is quite simple as it doesn't need the mathematic model of the system. The previous knowledge of the system action and behavior is the key issue to design it. Furthermore, finding the optimal scaling factors would give the best results.

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