Fuzzy control of a doubly fed induction generator based wind power system

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Abstract: - This paper deals with the vector control based on fuzzy logic of active and reactive power of a doubly fed induction generator (DFIG) integrated in a wind turbine system. The power transfer between the stator and the grid is achieved by acting on the rotor signals via a bidirectional converter. For a comparative study, the independent control of active and reactive power is ensured in the first step by conventional controllers (PI) and the second step by the fuzzy controller. The performance and robustness are analysed and compared by simulation based on Matlab / Simulink environment.

Key-Words: - Doubly fed induction generator, fuzzy logic, Proportional Integral, Vector control, wind energy.

1 Introduction
During the last years, there was a strong development of wind energy. Renewable and clean, this energy of the future has a major role to play in meeting the current and future climate challenges. DFIG is considered one of the most adequate solution to integrate it into a wind system. It offers many advantages, such as reduction of inverter cost.

In this paper, we focus on the control strategy of the doubly fed induction generator (DFIG) based wind power system. At first, the modeling of the turbine and the DFIG will be presented. Then, the vector control of active and reactive power is achieved by adjusting the rotor magnitudes, while applying the PI and fuzzy controllers.

Finally, to validate the proposed controls, we will conduct a series of numerical simulations using Matlab Simulink software.

2 Modeling of wind turbine
Fig.1 shows the conversion chain based DFIG connected to the electrical power grid. The turbine converts the kinetic energy of wind into electrical energy. This processing depends on the air density, the area swept by the rotor and wind speed [1]. The aerodynamic power appearing at the rotor of the turbine is written [2] [3]:

\[ P_{\text{aer}} = \frac{1}{2} \rho S C_p(\lambda, \beta) v^3 \] (1)

Where: \( \rho \) – air density, \( S \) – turbine area, \( v \) – wind speed, \( C_p(\lambda, \beta) \) – power coefficient.

The speed ratio is defined by:

\[ \lambda = \frac{\Omega_t R}{v} \] (2)

Where \( \Omega_t \) represents the rotational speed of turbine.

In our study, the expression of the power coefficient is given by [4]:

\[ C_p(\lambda, \beta) = c_1 \left( \frac{c_2}{\lambda^4} - c_3 \beta - c_4 \right) \exp \left( \frac{c_5}{\lambda^2} \right) + c_6 \lambda \] (3)

With:

\[ \frac{1}{\lambda_1} = 0.035 \beta^3 + 1 \quad , \quad \frac{1}{\lambda_2} = 0.08 \beta \quad , \quad \lambda_1 = 0.5176 \]

\[ c_1 = 116 \quad , \quad c_2 = 0.4 \quad , \quad c_3 = 5 \quad , \quad c_4 = 21 \quad , \quad c_6 = 0.0068 \]

Knowing the speed of the turbine, the aerodynamic torque is therefore determined by [5]:

\[ T_{\text{aer}} = \frac{P_{\text{aer}}}{\Omega_t} = \frac{1}{2 \Omega_t} C_p(\lambda, \beta) \rho Sv^3 \] (4)
The multiplier is modeled by the following equations:

\[ \Omega_m = G \Omega_i \]  
\[ T_{accr} = GT_g \]  

The Model proposed considers that the total inertia \( J \) is given by:

\[ J = J_t + J_g \]  

By applying the fundamental law of dynamics, the relationship between the rotation speed and torques is expressed by:

\[ J \frac{d\Omega_m}{dt} = T_{accr} - T_e - f\Omega_m \]  

Where: \( T_{em} \) – electromagnetic torque, \( T_g \) – torque derived from multiplier, \( f \) – Coefficient of viscous friction.

3 Mathematical model of the DFIG

The generator chosen for the wind power system is the DFIG. In addition, the DFIG controlled by inverters through its rotor operates over a range of \( \pm 30\% \) variation around the synchronous speed. This choice allows the converters dimensioned to transit 30\% of nominal power. Therefore, it will be economic [6]. The model of the DFIG is expressed in the (dq) reference frame by the following equations [7] [8] [9].

\[
\begin{align*}
V_{sd} &= R_s I_{sd} + \frac{d\varphi_{sd}}{dt} - \omega_s \varphi_{sq} \\
V_{sq} &= R_s I_{sq} + \frac{d\varphi_{sq}}{dt} + \omega_s \varphi_{sd} \\
V_{rd} &= R_r I_{rd} + \frac{d\varphi_{rd}}{dt} - \omega_r \varphi_{rq} \\
V_{rq} &= R_r I_{rq} + \frac{d\varphi_{rq}}{dt} + \omega_r \varphi_{rd} \\
\varphi_{sd} &= L_s I_{sd} + L_m I_{rd} \\
\varphi_{sq} &= L_s I_{sq} + L_m I_{rq} \\
\varphi_{rd} &= L_r I_{rd} + L_m I_{sd} \\
\varphi_{rq} &= L_r I_{rq} + L_m I_{sq} \\
T_{em} &= p(\varphi_{sd} I_{sq} - \varphi_{sq} I_{sd}) \\
\omega_s &= \omega_s - p\Omega_m
\end{align*}
\]

Where: \( s / r \) are stator/rotor subscript, \( V / I \) voltage/current, \( R_s / R_r \) rotor/stator resistance, \( L_s / L_r \) rotor/stator leakage inductance, \( L_m \) mutual inductance, \( p \) number of pairs of poles of the DFIG, \( \omega_s / \omega_r \) rotor/pulsation, \( \varphi \) flux, \( T_{em} \) electromagnetic torque, \( \Omega_m \) mechanical speed of DFIG.

4 Control strategy

To be able to control the DFIG easily, we will achieve independent control of active and reactive power by the stator flux orientation. The principle is to align the stator flux along the axis (d) of the rotating frame; this can be written in the form of equations as follows:

\[ \varphi_{sd} = \varphi_s, \varphi_{sq} = 0 \]  

The stator is assumed supply by a stable grid. Moreover, the stator resistance can be neglected since it is a realistic assumption for high power machines used for wind power [10], these simplifying assumptions allows us to write the following equations:

\[ V_{sd} = 0, V_{sq} = V_s \]  

The stator active and reactive powers are written [11]:

\[ P_s = V_{sd} I_{sd} + V_{sq} I_{sq} \]  
\[ Q_s = V_{sd} I_{sq} - V_{sq} I_{sd} \]  

Considering the simplifications mentioned above, expressions of power becomes:

\[ P_s = -V_s \frac{L_m}{L_s} I_{rq} \]  
\[ Q_s = -L_r V_s I_{rd} + \frac{V_s^2}{\omega_s L_s} \]

Thereafter, we establish the equations showing the relationship between the rotor voltages and rotor currents:

\[ V_{rd} = R_r I_{rd} + \sigma L_r \frac{dI_{rd}}{dt} - g\sigma L_r \omega_r I_{rq} \]  
\[ V_{rq} = R_r I_{rq} + \sigma L_r \frac{dI_{rq}}{dt} + g\sigma L_r \omega_r I_{rd} + \frac{g L_m V_s}{L_s} \]

Where: \( g \) – Slip of the DFIG, \( \sigma = 1 - \frac{L_m^2}{L_r L_s} \) – the dispersion coefficient of the DFIG.
Equations (17), (18), (19) and (20) allow us to establish the electrical system of the block diagram of the DFIG to regulate (Fig.2).

\[ g \frac{L_{qi} V_{qi}}{L_s} \]
\[ \frac{1}{R_{qi} + s L_{qi}} \]
\[ g \omega_s \sigma L_{qi} \]
\[ I_{qi} \]
\[ g \omega_s \sigma L_{rd} \]
\[ I_{rd} \]
\[ \frac{1}{R_{rd} + s L_{rd}} \]
\[ g \frac{V_{qi}^2}{\sigma L_{qi}} \]
\[ P_s \]
\[ Q_s \]

Fig.2 Structure of a wind energy system based on DFIG

5 PI control of the DFIG

The currents and voltages are related by a first order transfer function. Since the slip value is weak, we will set up a control loop on each power with an independent regulator (PI) while compensating the disturbance terms (Fig.3).

\[ P_s \]
\[ I_{qi} \]
\[ g \omega_s \sigma L_{qi} \]
\[ I_{rd} \]
\[ g \omega_s \sigma L_{rd} \]
\[ Q_s \]

Fig.3 Diagram of control of the DFIG by PI regulators

The Proportional Integral controller (PI) is still the most commonly used for controlling the DFIG [12], as well as in many industrial control systems. It is easy and quick to implement while providing acceptable performance [13]. Regulators each axis role is to eliminate the gap between the active and reactive power references and the measured active and reactive power. The synthesis of PI controllers is presented in [14].

6 Fuzzy control of the DFIG

The fuzzy control approaches to some extent the flexibility of human reasoning; he manages to offer satisfactory performance without the need of the mathematical model of the system, just by incorporating experts’ knowledge [15].

As presented in Fig.4, the fuzzy control based on Mamdani model. This mechanism is divided into three part. First, using input membership functions, the inputs are fuzzified and then based on rule bases and inference system, outputs are produced and finally the fuzzy outputs are defuzzified and applied to the system. Error and the error change rate are selected as inputs.

Fig.4 Block diagram of fuzzy control

Fig.5 shows the block diagram where fuzzy controllers are integrated into the vector control block of DFIG. The active and reactive powers are controlled independently, each with its own fuzzy controller.

Fig.5 Fuzzy control of DFIG

The design of the fuzzy controller is shown in the block diagram of fig.6. The gains $G_x$, $G_{xx}$, and $G_{xo}$ are scaling factors (normalization). We vary these factors until we can get a proper control. Indeed, it is they who will decide the performance of control.

Fig.6 Design of a fuzzy controller

Generally, the design of a fuzzy controller for the control of electric drives requires the choice of the
following parameters: linguistic variables, membership functions, inference method, and defuzzification strategy [16]. Fuzzy controller inputs are the error and its derivative, while the output is the command itself. Triangular and trapezoidal membership functions are used on a universe of discourse normalized in the range [-1; 1] for each variable as shown in Fig.7 and Fig.8 respectively for the inputs (error, error variation) and output (input process).

Fig.9 shows the surface generated by the fuzzy system.

Fig.7 Membership functions of error and change of error

Fig.8 Membership functions of output

The subsets fuzzy membership were noted as follows: BN: Big-Negative; SN: Small-Negative; AZ: About-Zero; SP: Small-Positive; BP: Big-Positive.

The fuzzy rules, for determining output variable of the controller as a function of input variables are grouped in the Table 1.

Table 1. Inference matrix

<table>
<thead>
<tr>
<th>( \Delta u )</th>
<th>e</th>
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<tbody>
<tr>
<td>BN</td>
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<td>SP</td>
<td>BN</td>
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<td>BP</td>
<td>AZ</td>
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7 Simulation results

The simulation of the control of the DFIG associated with wind system was made with the Matlab / Simulink environment (Fig.10).

Fig.10 Block diagram of the control in Matlab/Simulink

The results plotted in the following figures show powers generated when the reference signals are applied. Fig.11 displays the results of PI and fuzzy controllers using the targets in the form of echelons. Fig.12 shows the results with variable targets of powers. The test of robustness is presented in fig.13.
It is clear that the active and reactive power of the system follow perfectly the reference levels. Static error is almost equal to zero. In transient state, the time response of the fuzzy controller is much faster than the PI controller (Fig. 11).

Fig.11 Responses with fuzzy and PI controllers

Fig.12 shows that the two controllers follow their references, but the fuzzy present better performance than the PI in terms of response time and static error.

Fig.12 Responses with fuzzy and PI controllers for variables powers

Fig.12 shows that the two controllers follow their references, but the fuzzy present better performance than the PI in terms of response time and static error.

Fig.13 Responses with fuzzy and PI controllers for variables powers

The comparison between the two controllers shows that the fuzzy controller has good performance. By cons, for the PI controller, its performance is lost.

8 Conclusion

The control of a wind energy system equipped with a doubly fed induction generator has been described in this paper. At first, a model of the turbine and the generator are proposed. Then, a control strategy based on fuzzy logic and PI controllers allowing independent control of power has been presented. Through the response characteristics obtained by the simulation results, the good performance is observed even in the presence of variations of targets. Moreover, by comparing the controller PI and fuzzy, it’s clear that the fuzzy control is robust against parametric variations of the machine, provides fast convergence, not affected by noise and spurious signals, and easy to implement it in a calculator.

Appendix

Parameters of the wind power system.

DFIG nominal parameters

\[ V_s = 230\text{V}, \quad f = 50\text{ Hz}, \quad p = 2, \quad R_s = 0.455\Omega, \]
\[ R_r = 0.19\Omega, \quad L_s = 0.07H, \quad L_r = 0.0213H. \]
Turbine nominal parameters

- Number of blades = 3
- Diameter = 60 m
- Gearbox = 70

DFIG + Turbine parameters

- \( J = 32 \text{Kg.m}^2 \), \( f = 0.046 \text{N.m.d / rad} \)

References:


