Modeling and Comparison of Fuzzy-PI and Genetic Control Algorithms for Active and Reactive Power Flow between the Stator (DFIG) and the Grid

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Abstract—This paper performs a comparison between Fuzzy-PI regulators and Genetic Algorithm (GA) for controlling an active and reactive Doubly-Fed Induction Generator (DFIG) for providing power to the electrical grid. Theoretical analysis, modeling, and simulation studies are provided. Control strategies were developed for both active and reactive forces in order to optimize energy production. The performance of the two control strategies was examined and compared using benchmarks for durability and reference traceability. This paper studied a system consisting of a wind turbine operating at variable wind speed and a two-feed asynchronous machine (DFIG) connected to the grid by the stator and fed by a transducer at the side of the rotor. The conductors were separately controlled for active and reactive power flow between the stator (DFIG) and the grid, which was achieved in this article using conventional PI and fuzzy logic controllers. The considered controllers generated reference voltages for the rotor to ensure that the active and reactive power reached the required reference values. This was done in order to ensure effective tracking of the optimum operating point and the maximum output of electrical power. System modeling and simulation were examined in Matlab/Simulink. Dynamic analysis of the system was performed under variable wind speed.

Keywords—Genetic Algorithm (GA); fuzzy logic controller (FC); Doubly Fed Induction Generator (DFIG); variable speed wind turbine; conventional PI controller; Maximum Power Point Tracking (MPPT)

I. INTRODUCTION

Globally, wind power has become the fastest growing renewable energy source. Wind turbine speed control is generally used to improve energy production. DFIG-based wind power transmission systems offer various advantages, including reducing stress on mechanical structures and acoustic noise with the ability to control active and reactive energy. Another feature of the DFIG system is that the connected AC/DC/AC PWM transformers between the grid and the rotating circuit of the induction generator are designed for only a portion of the generator power [1]. Wind power generation implementation was introduced on the basis of DFIG, a fuzzy PI gain scheduling developed for DFIG vector control units used in variable speed wind turbines [2]. Upon theoretical analysis of the wind turbine and DFIG processing, due to mathematical models of the system, a DFIG separation control was developed based on a fuzzy-PI controller in [3]. Wind power generation by DFIG can be connected directly to the grid via the stator, which is driven by a direct AC/DC inverter. The relative complexities (in size or structure) of the research space and the function to be improved lead to the use of radically different precision methods [4].

While the stochastic methods are the more efficient and effective, they use processes based on stochastic exploration of the space of possible solutions [5]. Among the latter, we find Genetic Algorithms (GAs) that represent a rich and interesting family of stochastic optimization algorithms. They are inspired by concepts of evolution and natural selection and the probabilistic research based on the mechanism of natural selection and genetics. GAs are highly effective and robust in a general set of problems. GAs maintain a set of encoded solutions and this group is geared towards the optimal solution [6]. In order to find an ideal solution to a problem in a complex space, it is necessary to find a compromise between two goals: to explore better solutions and to aggressively exploit the search space. Analytical studies have shown that GAs manage this trade-off optimally [7].

II. DFIG MODEL WITH STATOR FLUX ORIENTATION

The orientation of the voltage and the stator flux is shown in Figure 1.

The DFIG electrical state can be modeled using the Park transform, as follows [8]:

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The electromagnetic torque is expressed as:

\[ C_{em} = -pMq \phi_s I_{rq} \]  

(8)

The relationship of rotor voltage is given as:

\[ \begin{align*}
V_{rd} &= R_{r} I_{rd} - g \omega_s (I_{r} - \frac{M^2}{L_s}) I_{rq} \\
V_{rq} &= R_{r} I_{rq} + g \omega_s (I_{r} - \frac{M^2}{L_s}) I_{rd} + g \omega_s \frac{M q s}{L_s}
\end{align*} \]  

(9)

III. INDIRECT CLOSED LOOP FUZZY CONTROL

In this method, decoupling is performed at the level of the outputs of the rotor current regulators with system feedback. This allows the regulation of powers. One thus distinguishes a control by a loop in a cascade of the power and the rotor current for each axis, since this makes possible to separately control the currents \( I_d \) and \( I_q \) and the powers \( Q_r \) and \( P_r \) in a closed loop [10]. According to the reference torque delivered by the Maximum Power Point Tracking (MPPT) control, the rotor side converter guarantees a decoupled active and reactive stator power control, \( P_s \) and \( Q_s \) (MPPT). By holding the DC bus at a steady voltage level and imposing the reactive power \( Q_r \) at zero, the grid side converter controls the power flow exchange with the grid through the rotor [11]. The simplified diagram of this control assembly is illustrated in Figure 2.

![Indirect closed loop fuzzy control diagram](image)

**Table I.** Rule table of the fuzzy controller

| \( AU \) | \( E \) |
|----|----|
| NG | NG | NG | NG | NM | NM | NM | NM | NF | EZ | PP | PP | PM | PG |
| NG | NG | NG | NG | NM | NM | NM | NM | NP | EZ | PP | PP | PM | PG |
| NP | NG | NM | NM | NP | NP | EZ | PP | PP | PM | PG | PM | PM | PG |
| EZ | NG | NM | NP | EZ | PP | PP | PM | PM | PG | PM | PM | PM | PG |
| PP | NM | NP | EZ | PP | PP | PM | PM | PM | PG | PM | PM | PM | PG |
| PM | NP | EZ | PP | PM | PM | PM | PM | PM | PG | PM | PM | PM | PG |
| PG | EZ | PP | PP | PM | PM | PG | PG | PG | PG | PG | PG | PG | PG |

The linguistic variables are noted as follows: NG for large negative, NP for small negative, EZ for approximately zero, PP for small positive, PG for large positive, NM for mean negative, and PM for mean positive. \( E \) is the error, \( \Delta e \) is the
error variation, and $\Delta U$ the controller output. The table gives forty-nine rules. For example:

R1 : IF $E = \text{NG}$ AND $\Delta e = \text{NG}$ THEN $\Delta U = \text{NG}$.

V. DESCRIPTION AND DEVELOPMENT OF THE FUZZY CONTROLLER

Our goal is to control the rotor currents of a dual-power DFIG. The developed controller uses the scheme proposed by [13]. This diagram is represented by Figure 3. The output of the regulator is given by:

$$V_{rd}^v = V_{rd}(k - 1) + du(k) \quad (10)$$

The triangular and trapezoidal membership functions. This choice is done due to the simplicity of implementation.

- A universe of standardized discourses.
- The universe of discourses is divided into seven fuzzy sets (fine tuning) for the input and output variables. A very fine subdivision of this universe on more than seven fuzzy sets does not generally bring any improvement in the dynamic behavior of the system to be regulated.
- Mamdani’s [13] implication for inference.
- The center of gravity method for defuzzification.

For every gene that mutates, we take numbers $\tau$ and $r$. The first can take the values $+1$ for an effective alternate and $-1$ for a negative trade. The second is a randomly generated range within the variety $(0, 1)$. It determines the value of the trade. Under those conditions, the $C_i^e$ gene, which replaces the mutated gene, is calculated from one of the following relationships [15]:

$$C_i^e = C_i + (C_{\text{max}} - C_i) \left( 1 - r \left( \frac{1}{\pi} \right)^{\tau} \right) \quad \text{if } \tau = +1$$

$$C_i^e = C_i - (C_i - C_{\text{min}}) \left( 1 - r \left( \frac{1}{\pi} \right)^{\tau} \right) \quad \text{if } \tau = -1$$

(11)

where $C_{\text{max}}$ and $C_{\text{min}}$ denote, respectively, the lower and higher limits of the price of the parameter $C_i$, and $G_F \leq G_T$ represents the era for which the amplitude of the mutation cancels out.

The procedure for optimizing the parameters of the regulators can be summarized by the following steps [16]:

- Randomly generate an initial population.
- Evaluate this population.
- Apply genetic operators (selection, crossing, mutation).
- Evaluate the new population created by the genetic operators.

In the following, we will apply this procedure to the two regulators, classical PI and fuzzy PI. Hybridization method: simplex. The complete control diagram is shown in Figure 5.

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A fuzzy regulator for the transient regime and
a PI regulator for the steady state.

The major drawback of fuzzy regulators is the matching of gains, ensuring system stability. In addition, the order is calculated only from two values: the error and its variation [19].

VII. SIMULATION RESULTS

The results of the wind energy system simulation (turbine + DFIG) are controlled by fuzzy logic and GA. This paper displays the results of the different curves obtained by controlling the energetic and reactive forces generated at the stator level of the DFIG. This allows separating the expressions of the active and reactive powers of the generator or bears those of the flow and torque. The system first starts up without load. Then, an active reference force is applied:

Active power:
- Between t = 0s and t=0.2s (P_{ref} = 0 VAR).
- Between t = 0.2s and t = 0.6s negative scale (P_{ref} = -5000W).
- Between t = 0.6s and t = 1s (P_{ref} = 0W).

Reactive power:
- Between t = 0s and t=0.2s (Q_{ref} = 0 VAR).
- Between t = 0.2s and t = 0.6s negative scale (Q_{ref} = -5000 VAR).
- Between t = 0.6s and t = 1s (Q_{ref} = 0 VAR).

The simulation results will allow the analysis of the behavior of DFIG magnitudes for the stator flow direction with reactive force control and rotational speed adjustment in order to maximize the active energy provided by the stator windings. For this, Matlab-Simulink was used. Figures 6 and 7 show the simulation results of the active and reactive stator forces. According to these Figures, the measured stator forces follow their active references. It is noted that this difference affects the direct rotor current, I_{rd}, and does not affect the rotor current I_{rq}, which explains why there is a separation between the active power and the I_{rd} current.

Figures 8 and 9 show the simulation results of rotating currents along the d and q axes. Figures 10 and 11 show the simulation results of the stator currents along the d and q axes.
VIII. DISCUSSION AND COMPARISON WITH OTHER WORKS

The novelty of this work is the application of GA to DFIG and its comparison with the traditional PI regulator and fuzzy logic, where in previously published works the comparison between the traditional and fuzzy regulators was made only in addition to the improvement in the obtained results. Good results were obtained compared to previously published works.

- The base table of the mysterious console was a 7×7 table, while in previously published works it was applied to a 5×5 table.
- The number of iterations increased in order to obtain more precise and better results in terms of error compared to previously published works. For a smaller number of iterations, the results were less precise. Figure 12 shows the improvement of the objective function applied to these results.

![Fig. 11. The quadrature current of the stator (A).](image)

IX. MATLAB SIMULATION CODE

```matlab
KP_p=kp_pmin+(kp_pmax-kp_pmin)*kp_pde/Gmax
KP_i=kp_imin+(kp_imax-kp_imin)*kp_ide/Gmax
KI_p=ki_pmin+(ki_pmax-ki_pmin)*ki_pde/Gmax
KI_i=ki_imin+(ki_imax-ki_imin)*ki_ide/Gmax

%%%%%%%%%%%%%%%%%%%%%%%
SELECTION AND CROSSING
%%%%%%%%%%%%%%%%%%%%%%%
[fun,index]=fate(fan);
for i1=1:NC/2
paron(i1,:)=POP(index(i1),:);
end
Lu=randsrc(1,1,[1:NB-1]);
child (1:NC/4,)=paron(1:NC/4,1:Lu)
paron(NC/4+1:NC/2,Lu+1:NB));
child (NC/4+1:NC/2,)=paron(NC/4+1:NC/2,1:Lu)
paron(1:NC/4,Lu+1:NB));
POP=[paron ; child];
%%%%%%%%%%%%%%%%%%%%%
MUTATION
%%%%%%%%%%%%%%%%%%%%%
Mu=rand(NC,NB);
for i=1:NC
for j=1:NB
if Mu(i,j)<=pm
if POP(i,j)==1
POP(i,j)=0;
else
POP(i,j)=1;
end
end
end
i9=i9+1;
fanf(i9)=Val;
end
figure
stud (funf,'-o')
title('Function optimization objective')
xlabel ('Itération')
ylabel('Function')
grid
```

X. CONTROL LAW

This law is a function of the error and its variation \( u = f(e, \Delta e) \). It is given by:

\[
    u_{k+1} = u_k + G_{\Delta e} \Delta u_{k+1} \quad (12)
\]

where \( G_{\Delta e} \) is the gain associated with the order \( u_{k+1} \) and \( \Delta u_{k+1} \) is the variation of the order. Error \( e \) and the variation of the error \( \Delta e \) are normalized as follows:

\[
\begin{align*}
    & \frac{e}{e^\prime}, \\
    & \frac{\Delta e}{\Delta e^\prime}
\end{align*}
\]

where \( G_e \) and \( G_{\Delta e} \) are the scaling (normalization) factors. We vary these factors until we can have a transient phenomenon of suitable adjustment. Indeed, it is the latter, which will determine the performance of the command.

XI. CONCLUSION

In this paper, a fuzzy logic controller and an active and interacting GA connected to a stator network (DFIG) are considered. The fuzzy controller's effectiveness test against GA and conventional PI control under different operating conditions showed the optimum and effective performance of fuzzy controller in terms of changing rotor resistance, insensitivity to torque disturbance, low response time, accuracy, and overtaking speed, as well as faster dynamics with little error in steady state under all dynamic operating...
conditions. The simulation results showed good control behavior directed towards better performance of the fuzzy controller. Its superiority is particularly evident compared to the performance of the traditional control system and the GA. However, we can observe the appearance of a small error in the response of the system controlled by this type of control. The reason for this error is that the adaptation law is not fast enough to detect sudden changes in wind speed. This drawback can be limited by short sampling time. However, this choice can increase calculation time. In practice, good continuity of control allows saves energy (increases energy efficiency), increases component service life, and system performance, with more efficiency and stability.

APPENDIX

PARAMETERS OF 1.5 MW DFIG

| Symbol | Parameter | Value |
|--------|-----------|-------|
| $P_t$  | Rated power | 1.5MW |
| $V_s$  | Stator voltage | 300V |
| $f_s$  | Stator frequency | 50Hz |
| $R_s$  | Stator resistance | 0.01Ω |
| $L_s$  | Stator leakage inductance | 0.02Ω |
| $R_r$  | Rotor resistance | 0.02Ω |
| $L_r$  | Rotor leakage inductance | 0.02Ω |
| $M$    | Mutual inductance | 0.0169H |
| $P$    | Pairs of poles number | 2 |
| $J$    | Rotor inertia | 1000Kg.m$^2$ |

PARAMETERS OF THE TURBINE

| Symbol | Parameters | Value |
|--------|------------|-------|
| $R$    | Blade radius | 35.25m |
| $N$    | Number of blades | 3 |
| $G$    | Gearbox ratio | 90 |
| $J$    | Moment of inertia | 1000Kg.m$^2$ |
| $f_t$  | Viscous friction coefficient | 0.0024N.m.s$^{-1}$ |
| $V_n$  | Nominal wind speed | 16m/s |
| $V_d$  | Cut-in wind speed | 4m/s |
| $V_m$  | Cut-out wind speed | 25m/s |

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