INTRODUCTION

In the last decades, increasing consumption of electrical energy and damaging effect on environment and human’s health of fossil-fuels oblige the energy researchers to develop renewable energy alternatives.1,2 Therefore, among of different kinds of available renewable resources, wind power has become more attractive and promising source due to its advantages from a point of view of cost, efficiency, and reliability.3,4

Uncertain and unpredictable behavior of wind energy, affected by the daily and seasonal climate change, can have a negative impact on the performance and stability of the system.5 As a result, using Variable speed technologies of wind turbine allow to extract the maximum amount of wind energy by operating over a wide range of wind speeds.6

Thus, in the modern wind energy conversion systems (WECS), doubly fed induction generator (DFIG) have a crucial role in variable speed technology. This machine can offer many advantages: it can operate at variable speed (sub-synchronous or super-synchronous speed) by adjusting the phase and frequency of rotor voltages.7 The power converter can be significantly improved in terms of size. It can be designed to transfer only 30% of the DFIG’s rated power. This makes the wind turbine more efficient, lighter, and cheaper.8 Moreover, The DFIG allows the possibility to control separately the real and reactive power which makes this machine a competitive choice in terms of grid compatibility.9

The structure of the control system is very important not only for extracting the maximum wind power with the best performance, but also to prevent the quality degradation of...
electrical energy injected into the grid.\textsuperscript{10} The most frequent control methodology used in literature is vector control. The main objective of this technique is to separate the rotor currents into two components, one controls the torque and the other control the flux independently in order to emulate the simple regulation of a separately excited DC machine.\textsuperscript{11} Vector control based on conventional PI controllers are adopted for a long time, but this type of controllers remain limited and less effective for nonlinear applications.\textsuperscript{12} In the recent past, several works show that the fuzzy logic controllers (FLC) able to replace the conventional ones. The FLCs are more robust in terms of response tracking and less sensitive to nonlinearity, parametric variations, and disturbances compared with the PI controllers.\textsuperscript{6} Mahto and Mukherjee\textsuperscript{13} compared the performance of two FLC varieties for wind system and energy storage applications. Their optimal designs were carried out by adjusting their scaling factors. Civelek et al\textsuperscript{14} proposed a new fuzzy logic technique in order to reduce the moment tower and blades of wind turbine with maintaining the output power at a nominal value. This study sheds lights on fuzzy rules and membership functions (MSF). Sudheer et al\textsuperscript{15} evaluated the direct torque performance based on fuzzy logic approach. This technique is applied to control an induction motor to reduce the flux and torque ripples with the standard fuzzy logic controller parameters. Gupta and Garg\textsuperscript{16} examined the effectiveness of the fuzzy logic controller by modifying the shape of their MSF for a solar photovoltaic system connected to the grid. El Yaakoubi et al\textsuperscript{17} investigated the efficiency of the MPPT technique with fuzzy controllers. This technique is used to maximize the amount of power extracted by a wind system based on squirrel cage induction machine. Tir et al\textsuperscript{18} analyzed the effect of the field-oriented control with fuzzy logic controllers on the double star induction motor behavior. This study is carried out using the standard fuzzy logic parameters. Salleh et al\textsuperscript{19} improved the vector control technique by adopting an optimized FLC for induction motor drive systems. This optimization is accomplished by tuning the scaling factor of speed error and change of error and the position of the MSF. The work presented by Ismail and Bendary\textsuperscript{20} deals with the protection of the DFIG against symmetric and asymmetric faults using fuzzy logic technique. This study focuses on adapting the MSF to have satisfactory performances.

The components of rotor currents can be related to the real and reactive powers. The real power reference can be determined by maximum power point tracking (MPPT) techniques in order to extract the maximum of wind power and produce electrical energy at the cheapest possible cost.\textsuperscript{21} The Optimal Power-MPPT (OP-MPPT) is one of the widely used algorithms in wind energy systems because of its simplicity, fastness and efficiency. Moreover, it doesn’t require the use of a wind speed sensor. This aim is attained by adjusting the mechanical speed and keeping the tip speed ratio (TSR) at its optimal value.\textsuperscript{22}

The main components of variable speed wind turbine are depicted in Figure 1. The turbine composed of three blades is coupled to the DFIG by means of the gear box to adapt the slow speed of the turbine shaft to the speed of the machine. The generator stator is directly connected to grid while the rotor is coupled thereto via power converter. Two levels of control part can be distinguished, the rotor side converter (RSC) allows controlling the flow of reactive and real power of the stator. This last one is delivered from the MPPT technique. The grid side converter (GSC) regulates the DC voltage link and the reactive power of the rotor.\textsuperscript{23}

In this study, indirect field-oriented control (IFOC) with fuzzy logic controllers is proposed to control the wind system based on DFIG in variable wind speed mode. Excellent controller performance can be achieved if the fuzzy logic controller parameters are adjusted properly. Previous works that use fuzzy logic approach have shown that the optimal design of a FL controller depends mainly on three parameters:

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{doubly-fed-induction-generator.jpg}
\caption{Doubly fed induction generator-based wind turbine configuration}
\end{figure}
scaling factors, MSF, and fuzzy rules. The main contribution of this work is to improve the controller performance by tuning all these parameters with the purpose of minimizing the difficulty related to the trial-and-error approach in the wind system based on DFIG. The initial parameter values are calculated based on the most frequent selections stated in the literature. The initial scaling factors are computed using the correlation between the conventional PI controller and the fuzzy controller. The initial MSF have the standard symmetrical shape and in the initial rules table, the symmetrical disposition of the fuzzy rules is employed. Thereafter, these parameters are adjusted in a learning process until satisfactory results are achieved.

The rest of this work is structured as follows: Section 2 is dedicated to the dynamic modeling of different part of the WECS. Section 3 presents the different strategies adopted to control the wind turbine. Only the control of RSC is concerned in this study. Section 4 detailed the different steps to reach the optimal design of the FLC. Finally, in Section 5, the obtained results under variable speed conditions are reported and discussed.

## 2 WIND SYSTEM MODELING

### 2.1 Modeling of aeromechanical part

The power extracted \( P_{\text{aer}} \) and torque developed by the turbine \( C_{\text{aer}} \) are expressed by:

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

\[
C_{\text{aer}} = \frac{P_{\text{aer}}}{\Omega_{\text{tur}}}
\]

where \( \rho \) is the air density, \( R \) is the turbine radius, \( v \) is the wind speed, and \( \Omega_{\text{tur}} \) is the mechanical angular velocity.

The power coefficient \( C_p \) presents the portion of wind power captured by the turbine. It depends on two parameters, namely tip speed ratio (TSR) \( \lambda \) and pitch angle of the blades \( \beta \) as shown in Figure 2. The first parameter presents the ratio between the blade tip speed and the wind speed. \( C_p \) and \( \lambda \) are given by:

\[
C_p(\lambda, \beta) = 0.5872 \left( \frac{116}{\lambda} - 0.4 \beta - 5 \right) e^{-2 \frac{1}{\lambda}} + 0.0085 \lambda
\]

\[
\lambda = \frac{\Omega_{\text{tur}} R}{v}
\]

### 2.2 Drive train modeling

The gearbox converts the slow turbine speed to high generator speed. It can be modeled by the following equations:

\[
C_g = \frac{1}{G} C_{\text{aer}}
\]

\[
\Omega_{\text{tur}} = \frac{1}{G} \Omega_{\text{mec}}
\]

where \( C_g \) is the generator torque, \( \Omega_{\text{mec}} \) is the generator speed and \( G \) is the gearbox ratio.

### 2.3 DFIG modeling

Under the matrix form, the mathematical model of the DFIG in PARK reference frame is the fifth order model. All the flux dynamics and the important interactions between variables are taken into account. To reduce the complicating features of the machine, some basic assumptions are considered. The air gap is assumed smooth with no slotting effect. The magnetic saturation is neglected and the machine windings are supposed sinusoidally distributed. The electrical magnitudes interactions are described by the following matrix:

\[
\frac{d}{dt} \begin{bmatrix} \Phi_{sd} \\ \Phi_{sq} \\ \Phi_{rd} \\ \Phi_{rq} \end{bmatrix} = \begin{bmatrix} -\frac{R_s}{\sigma L_s} & \frac{\sigma M}{\sigma L_s} & 0 & 0 \\ -\frac{R_g}{\sigma L_g} & -\frac{R_s}{\sigma L_s} & 0 & \frac{\sigma M}{\sigma L_s} \\ \frac{R_g}{\sigma L_g} & 0 & -\frac{R_s}{\sigma L_s} & 0 \\ 0 & 0 & -\frac{\sigma M}{\sigma L_s} & -\frac{R_s}{\sigma L_s} \end{bmatrix}\begin{bmatrix} \Phi_{sd} \\ \Phi_{sq} \\ \Phi_{rd} \\ \Phi_{rq} \end{bmatrix} + \begin{bmatrix} V_{sd} \\ V_{sq} \\ V_{rd} \\ V_{rq} \end{bmatrix}
\]

**FIGURE 2** \( C_p \) as a function of \( \lambda \) and \( \beta \)
where $\Phi_{sd,q}$ and $\Phi_{rd,q}$ are the stator and the rotor fluxes, respectively, $V_{sd,q}$ and $V_{rd,q}$ are the stator and rotor voltages, $R_s$ and $R_r$ are the stator and rotor resistances, $L_s$, $L_r$, and $M$ are the stator, rotor and magnetizing inductances, $\sigma$ is the leakage factor, $\omega_g$ and $\omega_m$ are the angular frequencies of the stator flux and the rotor shaft.

The electromagnetic torque ($C_{em}$) presents the link between mechanical and electrical part of the machine. It can be obtained in terms of fluxes $^{27}$:

$$C_{em} = \frac{3}{2} \rho \frac{M}{\sigma L_s L_r} (\Phi_{sq} \Phi_{rq} - \Phi_{sd} \Phi_{rd})$$  \hspace{1cm} (8)

The mechanical equation of DFIG can be expressed as follows:

$$J \frac{d\Omega_{mec}}{dt} = C_g - C_{em} - f_v \Omega_{mec}$$  \hspace{1cm} (9)

where $J$ is the system inertia and $f_v$ is the viscous friction.

In order to complete the model, the real and reactive power are necessary to be computed. They can be written as $^{28}$:

$$P_s = \frac{3}{2} (V_{sd} I_{sd} + V_{sq} I_{sq})$$  \hspace{1cm} (10)

$$Q_s = \frac{3}{2} (V_{sq} I_{sd} - V_{sd} I_{sq})$$  \hspace{1cm} (11)

### 2.4 Voltage converter modeling

The model of the two level converter with standard IGBTs is defined as $^{29}$:

$$\begin{bmatrix}
V_{an} \\
V_{bn} \\
V_{cn}
\end{bmatrix} = \frac{V_{dc}}{3} \begin{bmatrix}
2 & -1 & -1 \\
-1 & 2 & -1 \\
-1 & -1 & 2
\end{bmatrix} \begin{bmatrix}
S_a \\
S_b \\
S_c
\end{bmatrix}$$  \hspace{1cm} (12)

where $S_a$, $S_b$, and $S_c$ are the command signals, $V_{an}$, $V_{bn}$, and $V_{cn}$ are the output voltages and $V_{dc}$ is DC bus voltage.

### 3 CONTROL STRATEGIES FOR THE WECS

#### 3.1 Maximum power point tracking technique

The optimal-MPPT (OP-MPPT) is the most widely used MPPT technique in wind energy conversion system. $^{30}$ Its main objective is to extract the most amount of wind power as possible without wind speed measurements. This optimization strategy is applied when the wind speed is lower than its nominal value $v_n$ at which the wind system generates its nominal power ($v \leq v_n$) with maintaining the pitch angle value at zero.$^{22}$

As depicted in Figure 3, there is a specific turbine velocity that allows us to extract the maximum wind power at a given wind speed. Therefore, to increase the power conversion efficiency, the wind turbine should operate in variable speed mode.$^{21}$

From Equation (4), the wind speed can be determined in terms of $\lambda$ and $\Omega_{tur}$$^{31}$:

$$v = \frac{\Omega_{tur} R}{\lambda}$$  \hspace{1cm} (13)

In order to extract the maximum power, it is necessary to maintain the TSR at its optimum value $\lambda_{opt}$. By replacing the above equation in Equation (1). The expression of the mechanical power which corresponds to every optimal conversion point can be written as $^{32}$:

$$P_{aer,ref} = \frac{1}{2\lambda_{opt}^3} C_{p,\max} \rho \pi R^5 \Omega_{tur}^3$$  \hspace{1cm} (14)

During this control process, the controlled power is the real power of the stator $P_s$. Thus, to determine $P_{s,ref}$ we can subtract the estimated real power of the rotor generator $P_r$ from $P_{aer,ref}$ $^{33}$.
Figure 4 represents the block diagram of OP-MPPT.

3.2 Rotor side converter control

3.2.1 Indirect field-oriented control structure

Vector control still the most used control technique for the DFIG-based wind turbine. In this strategy, the rotor current vector is separated into two elements using synchronously rotating (dq) reference frame. The direct rotor current is responsible for the control of reactive power and the quadrature current is related to the real power. In this way, the DFIG can closely match the structure of DC machine, which magnitudes controlling the torque and the flux are naturally decoupled.

For an AC machine, this simple vector control performance is not directly possible to be obtained. There are two options to achieve this. The first one is to align to $d$-axis with the stator flux. The second one is to orient the $q$-axis along the stator voltage and delay the $d$-axis by 90° because the two vectors are shifted by 90°. The first option is the widely proposed for wind power generation using DFIG and is the classical method used in the literature.

Loop control of rotor currents

The relationship between the flux and currents, under stator flux vector orientation, can be expressed as:

$$L_s I_{sd} + M L_s I_{rd} = Φ_{sd} = Φ_s$$

$$L_s I_{sq} + M L_s I_{rq} = 0$$

From Equations (16) and (17), the relationship between the stator and rotor currents can be derived:

$$I_{sd} = \frac{Φ_s}{L_s} - \frac{M}{L_s} I_{rd}$$

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

By replacing Equations (18) and (19) in rotor flux expressions, they can be written in terms of rotor currents as follows:

$$Φ_{rd} = \left( L_r - \frac{M^2}{L_s} \right) I_{rd} + \frac{M}{L_s} Φ_s$$

$$Φ_{rq} = \left( L_r - \frac{M^2}{L_s} \right) I_{rq}$$

Finally, the relationship between the rotor voltages and the rotor currents can be established by substituting Equations (20) and (21) into $V_{rd}$ and $V_{rq}$ expressions:

$$V_{rd} = R_r I_{rd} + \left( L_r - \frac{M^2}{L_s} \right) \frac{dΦ_{rd}}{dt} - \left( L_r - \frac{M^2}{L_s} \right) (ω_s - ω_m) I_{rq} + \frac{M}{L_s} \frac{dΦ_s}{dt}$$

$$V_{rq} = R_r I_{rq} + \left( L_r - \frac{M^2}{L_s} \right) \frac{dΦ_{rq}}{dt} - \left( L_r - \frac{M^2}{L_s} \right) (ω_s - ω_m) I_{rd} + \frac{M}{L_s} (ω_s - ω_m) Φ_s$$

Generation of the current references

To determine the current references, a few assumptions are made. First, the small drop in the stator resistance is neglected. This is more realistic in large scale of wind turbines. Second, we can assume that the DFIG is connected to a stable grid so, $Φ_s$ is held constant.

The stator voltage equations can be simplified as follows:

$$V_{sd} = 0$$

$$V_{sq} = V_s = ω_s Φ_s$$

By substituting the Equations (18), (19), (24) and (25) into Equations (10) and (11), the real and reactive power can be rewritten in terms of rotor currents as follows:

$$P_s = -\frac{3}{2} V_s I_{rq}$$

$$Q_s = \frac{3}{2} Φ_s V_s - \frac{3}{2} \frac{M}{L_s} V_s I_{rd}$$
Figure 5 represents the general structure of the IFOC. The rotor current references can be estimated from the desired powers. Then, the control loops are utilized to ensure that these references are followed by the measured currents.\textsuperscript{36}

Estimator block
This block calculates the stator flux angle required to align the stator flux with the \( d \)-axis and compute \( \Phi_{sd} \) and \( d\Phi_{sd} \) needed to compensate the perturbation terms. They can be described by the following equations:\textsuperscript{7}

\[
\frac{d}{dt} \Phi_{sd} + \frac{R_s}{L_s} \Phi_{sd} = v_{sd} + \frac{M}{L_s} R_s I_{rd} \tag{28}
\]

\[
\omega_{\Phi_s} = \frac{v_{sq}}{\Phi_{sd}} + \frac{M}{L_s} R_s I_{rq} \tag{29}
\]

3.2.2 | Fuzzy logic controller design
Fuzzy logic controller is a powerful tool and has become popular in the few recent years. It allows the control of the complex processes whose parameters are unknown, imprecise or have high degree of non-linearity.\textsuperscript{13,14,41} Figure 6 represents the schematic block of a FLC. It consists of three blocks:\textsuperscript{18,42}:

- **Fuzzification**: This block converts the normalized input variables to fuzzy ones. Each fuzzy variables is defined by linguistic sets such as NB, NM, NS...where each is represented by a membership function.
- **Inference**: The main function of this process is to settle and determine the behavior of the controller based on compilation of conditional fuzzy statements stated as a set of IF-THEN rules in order to calculate the optimal control action.
- **Defuzzification**: During this mathematical procedure, the fuzzy outputs are converted into crisp values.

To design a FLC, it is necessary to follow the procedure as mentioned below:\textsuperscript{16,43}

- Choose the control variables. In this study, current error and change of current error are selected.
- Some standard parameters should be determined. These include scaling factors, number and form of MSF, fuzzy inference method, and the defuzzification technique. For reducing the simulation time, with accurate results, “prod-mean” fuzzy inference and “centroid” defuzzification techniques are chosen in this study.
- Attach labels to MSF of the input and output variables.
- Define the fuzzy rules.
- Tune manually the scaling factors, membership function and the fuzzy rules until the desired performance is obtained. This step is the most significant in the controller design to ensure a better control behavior.
Scaling factors tuning

The scaling factors are used to normalize the physical variables within range of −1 to +1. In literature, they are considered as the most important variables due to their significant impact on FLC behavior.

The most common technique to determine the initial values of input scaling factors $K_e$ and $K_{de}$ is the correlation between the PI controller gains and FLC scaling factors. The relationships between those parameters are expressed by Equations (30) and (31):

$$G_e = \frac{K_i T_s}{G_u} \quad (30)$$

$$G_{de} = \frac{K_p G_u}{G_u} \quad (31)$$

where $K_p$ and $K_i$ are the proportional and integral coefficient, respectively, $T_s$ is the sampling time and $G_u$ is the output scaling factor.

$G_u$ has less influence than $G_e$ and $G_{de}$ on the system performance. In literature, it takes a value between 1 and 3. $G_u = 3$ is used in this study.

Then, these factors are retuned manually to achieve the desired performance.

Membership functions tuning

The triangular membership functions are chosen for each variable. The number of MSFs is arbitrary and using five to nine fuzzy sets is commonly adopted in fuzzy control. In this study, the number is limited to seven MSFs labeled as: BN (Big Negative), MN (Medium Negative), SN (Small Negative), Z (Zero), SP (Small Positive), MP (Medium Positive), BP (Big Positive).

Changing the width and moving the peak position of the MSF of the current error and error change can enhance the fuzzy control performances in terms of settling time and accuracy. According to Figure 7, a large control action is obtained when the MSFs for current error are tuned toward zero and the MSFs for change of error are tuned away from zero.

The controller behavior is less sensitive to the output MSF. Therefore, they will keep their initial positions.

Rules tuning

The rules base is shown in Table 1. The rows represent the error and the columns represent the change of error. The output level $d_u$ is determined by the pair $(e, de)$. The performance characteristics are affected in specific zone in the rule table.

The rules of zone 1 are fired when the controlled variables are in the steady-state region and can also affect the settling time and the overshoot. In zone 2 and 3, the rules are fired during the transient cycle. The other zones have less impact on controller performances by the reason of their lower firing frequency.

4 | RESULTS AND DISCUSSION

With the aim to verify the performance of the proposed control strategy, a simulation test is carried out in MATLAB/SIMULINK environment using wind turbine based on
2 MW DFIG model. The system parameters are listed in Table 2. Three tests have been performed for 10 seconds simulation time. In the first one, a comparative study between the FLC with initial parameters and the FLC with the optimal parameters is conducted to check the efficiency of the proposed FLC design in terms of rapidity, accuracy, and stability. Along this test, the aeromechanical part and the MPPT block are removed from the model, only the DFIG and the control blocks are needed. In the same test, the decoupling axes methods are investigated by applying different times. In the second one, the whole system model is taken into consideration and a step change of wind speed from 5 to 10 m/s at \( t = 5 \) seconds allowing the transition from the sub to super-synchronous mode operation is applied. The purpose of this test is to examine the effectiveness of the MPPT technique. In the last test, the dynamic of the system is analyzed using variable wind speed profile. Along with this simulation, the reactive power reference of stator machine is settled to zero, \( Q_s,ref = 0 \), to have a unity power factor. Finally, the obtained responses for electrical and mechanical magnitudes are examined to draw the respective conclusions.

Figure 8 depicts the stator real power response before and after optimizing the scaling factors. The optimal scaling factors of the power error and change of error \( (K_e = 1.16 \times 10^{-7}, K_{de} = 9.3 \times 10^{-4}) \) are obtained by increasing the initial ones \( (K_e = 5.26 \times 10^{-8}, K_{de} = 3.89 \times 10^{-6}) \) which are calculated from the PI controller gains. It is obvious that the optimized FLC keep a better settling time than the standard one. This time was enhanced from 170 to 25 ms without overshoot. In the steady state, the power response track reasonably well its reference with a zero value of static error and without compromising the DFIG stability. The effect of changing the width and the peak value of the membership functions is illustrated in Figure 9. The machine behavior is improved by moving the peak position of the error MSFs toward the zero and tuning the peak position of the change of error MSFs away from zero as depicted in Figure 7. Settling time of the estimated stator power is significantly decreased from 170 to 20 ms with negligible excess of 0.8%. The three dimensional surface represented in the same figure reveals the non-linear behavior of the optimal controller around the set point. The stability is also guaranteed with a steady-state error equal to zero. As regards the rules table, changing the rules in specific zones (Zone 1, 2, and 3) leads to fast power response as demonstrated in Figure 10. The settling time is reduced from 170 to 50 ms with an overshoot of 2.1% and no static error. In addition, the optimized controller can maintain the system stability even for sudden change of power references.

Figures 11 and 12 depict the positive impact of the decoupling method on the system stability. The fuzzy controllers are directly supplied with step power references at different times. When the axes are decoupled, \( Q_s \) is not affected by the change of \( P_s \) and vice versa. Furthermore, the measured magnitudes exhibit a negligible overshoot denoting that they are critically damped. However, without decoupling of axis, the system stability is highly degraded with a significant overshoot before reaching the reference value and remarkable static error.

Under second test, Figure 13 shows the capability of the system to track the maximum power point. The net power is adjusted to follow the MPPT curve after starting below it at the point A. The jumping of mechanical power from 5 to 10 m/s power curve can be explained by the instantaneous transition of wind speed, which emulates the gust of wind. When the system attains the synchronous speed \( (\omega_{mec} = 1500 \text{ rpm}) \), the stator power becomes lower than the
net power and the rotor power has switched from negative to positive value. This means that the rotor is supplied from the grid in sub-synchronous mode operation and produces the electrical power in super-synchronous mode. In the last mode, the machine can produce 2.2 MW while it is rated only for 2 MW. Moreover, the figure shows a small difference between mechanical and net powers at point B which represent the copper losses in the stator and rotor. So, the best performance in tracking the optimal power is clearly demonstrated.

Figure 14 represents the wind speed profile taken into account in the last test. Figure 15 traces the generator speed. From these figures, the slow dynamic of the system is remarkable due to wind turbine inertia. Notice that this parameter is reduced to have a reasonable simulation time.
The change of power generated explains the change of stator current magnitudes. Figure 16 that the stator current can attain 1.78 kA equivalent to 1.26 kA (rms) knowing that the rated current stator is 1.76 kA (rms). Furthermore, the stator current and stator are shifted by 180° indicating that only the real power is injected into the grid (maintaining the unity power factor).

Figures 17 and 18 illustrate the spectrum analysis of the stator current with and without optimization of the FLC parameters. It is clear that the Total Harmonic Distortion is
mitigated from 1.55% to 0.85%. This confirms the effectiveness of the proposed design of FLC with fewer ripples and less harmonic noises in the output magnitudes.

Figure 19 shows the “a” phase generated rotor voltage and its reference (phase to neutral). The order commands adopted for the back-to-back two level converter is the PWM (pulse width modulation) with injection of the third harmonic and the switching frequency of the RSC is set to 10 kHz.

Figures 20 and 21 depict the waveforms of the rotor voltages and rotors currents. It is clear that the frequency of those magnitudes approach to zero around the synchronous speed. Furthermore, we can expect the change of phases order from “abc” to “acb” in the transition between the two mode operations.

The estimator performance is analyzed in Figure 22. It can be seen that the closed loop control produces a very stable estimation of the grid angular speed. This means that the
machine magnitudes remain synchronized with the grid frequency and angular position.

The behavior of the whole model of wind system is inspected with and without the optimized scaling factor, width and peak position of the MSFs and rules table. Figure 23 compares the dynamic responses of stator power using initial and tuned FLC parameters under variable wind speed conditions. It is obviously shown that the FLC gives satisfactory performances in terms of rapidity, stability, and robustness with a negligible error and no overshoot.

Table 3 represents a comparative study between the proposed design and other control techniques existing in literature, which are based on fuzzy logic approach. As shown, the optimized FLC adopted in this work presents the faster response with less overshoot percentage and best current THD.

5 | CONCLUSION

The present study focuses on the design of an optimal fuzzy logic controller based on indirect field-oriented control for
wind turbine application. The different parts of the variable speed wind turbine based on 2 MW DFIG have been described and modeled. The OP-MPPT technique was used to extract the maximum amount of wind energy. The significant parameters of the FLC are optimally tuned to improve the system performance. After testing the system using MATLAB/SIMULINK under variable wind speed conditions, the key findings of this work are as follows:

- OP-MPPT assured a better aerodynamic efficiency by capturing more energy under rapid wind variation.
- The decoupling of the rotor currents axed enhanced the performance of the system in terms of stability and accuracy.
The turbine can operate under sub or super-synchronous mode operation of generator. It produces a higher power than its rated one by operating in the second mode operation.

The obtained parameters of FLC, which are scaling factor rules base and membership functions, provided a good dynamic behavior of wind system in terms of rapidity and robustness, with no overshoot.

**NOMENCLATURE**

- $C_a$: wind turbine torque
- $C_em$: electromagnetic torque
- $C_g$: generator torque
- $C_p$: coefficient of performance
- $G_{de}$: change of error scaling factor
- $G_e$: error scaling factor
- $G$: gearbox ratio
- $G_u$: output scaling factor
- $J$: system inertia
- $K_i$: integral gain of PI controller
- $K_p$: proportional gain of PI controller
- $L_r$: rotor inductance
- $L_s$: stator inductance
- $M$: magnetizing inductance
- $P_{aer}$: wind turbine power
- $P_r$: real power of the rotor
- $P_s$: real power of the stator
- $Q_s$: reactive power of the stator
- $V_{rd,q}$: rotor voltage components in PARK reference frame
- $V_{sd,q}$: stator voltage components in PARK reference frame
- $v$: wind speed
- $\lambda$: tip speed ratio
- $\sigma$: leakage factor
- $\Phi_{rd,q}$: rotor flux components in PARK reference frame
- $\Phi_{sd,q}$: stator flux components in PARK reference frame
- $\omega_g$: angular frequency of the stator flux
- $\omega_m$: angular frequency of the rotor shaft
- $\Omega_{mec}$: generator shaft angular velocity
- $\Omega_{tur}$: mechanical angular velocity

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