New grid synchronization and power control scheme of doubly-fed induction generator based wind turbine system using fuzzy logic control

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\textbf{A B S T R A C T}

This paper deals with the analysis, modeling and control of a doubly-fed induction generator in variable speed wind turbine systems. The start-up procedure of the wind turbine including the grid synchronization has been established. New sensorless control schemes were developed, the first one is designed for standalone mode and grid synchronization named direct voltage control, the second one is designed for grid-connected mode named direct power control. To improve the robustness of the controlled system performance in case of machine parameters variations, a fuzzy logic controller was introduced. Various operation modes have been tested including accelerating and braking of the wind turbine, limited power and speed operation mode, power maximization mode, standalone operation mode with supplying a variable load. Simulation of the full start-up procedure was performed using Matlab/SimPowerSystems. The simulation results for several transient conditions demonstrated the effectiveness of the proposed control strategy.

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1. Introduction

Doubly-fed induction generators (DFIGs) based wind turbine systems (WTSs) have certainly emerged as one of the main technologies in wind turbines (WTs) industry, proving that it is an efficient, reliable and cost-effective solution. Another advantage of the DFIGs is that their power electronic system (mostly Scherbius structure) is sized only for a fraction of the machine rated power, so an extra cost reduction has been achieved compared to AC generators with full rated converters. DFIG is similar to the standard squirrel cage based induction generator in many ways. However, it needs its own deep analysis to reach sufficient comprehension [1].

DFIGs need more complex start-up procedure than other AC generators, due to the limited AC voltage offered by the reduced size power converters used to supply the rotor windings. The extra complexity comes from the natural behavior of the DFIG itself [1]. Thus, in case of reduced size back-to-back converter supplying the rotor, the DFIG has to be controlled in a range of rotor speed close to synchronism (less than ±30% of the synchronous speed). Therefore, it is essential to use an external acceleration mechanism for starting-up if the rotational speed is near to zero [2].

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At first, the stator terminals of the machine and the grid are disconnected from each other by a mechanical switch (Fig. 1). The blade pitch angle control system is used to accelerate the WT by the wind power itself which is the longest step due to the heavy inertia of the large scale WTS [2]. Then, when the rotor speed reaches the controllability range, proper grid connection procedure is carried out before closing the stator side switch, and move on to the grid connection mode which aims to generate as much as possible of electrical energy from the wind [1].

Grid connection of the WTS is an important procedure; it has to be fast, smooth and safe with minimum influence on the stability of both WTS and grid [3]. Moreover, this process is very important when a grid fault arises which leads to the disconnection of the generators from the grid. For instance, when the voltage dip exceeds the time defined by the grid code requirements [2], this causes the tripping of protection relays (PR). A smooth start-up allows reclosing of the system immediately when the grid fault is over, in order to provide voltage and frequency support to the grid. Actually, during the grid disconnection period, the WTS can stay in a temporary standalone operation mode and supply any local load connected to it [4]. However, and despite the number of published papers related to the DFIG control in literature, the majority of papers have treated only the grid-connected mode, and only few studies have described clearly the start-up and the grid connection process [5].

Various proven grid synchronization schemes have been documented in literature during the last decade. In [2], the steps taken through start-up procedure have been listed however the problems of zero encoder position detection and Proportional–Integral (PI) controller gains tuning method have not been discussed. In [6], the authors explained explicitly the problem of initial rotor position error and how to use a PI controller to compensate the phase difference between stator and grid voltages. The phase difference is obtained by controlling the $d$ component of stator voltage to be zero, and adding the controller output to the calculated slip angle, however, the authors did not show the gains tuning process of the PI controller. Paper [7] has summarized the synchronization process step by step, and has used the same method used in [6], and [8] for position error correction. Another method proposed in [1,9], where the phase difference is detected by using a model reference adaptive system observer. The phase difference between the estimated stator and rotor fluxes was minimized using an integral controller, and the output of the integral controller was exactly the phase difference between stator and grid voltages. In [10], a simpler way that uses four-quadrant inverse tangent (arctan) function on $d$ and $q$ components of stator voltage to compute the phase difference has been used. Then, a sample-and-hold function updates the slip angle and eliminates the phase difference. All the mentioned papers have used the same field-oriented control method and PI controllers in the rotor current control loop.

Faulty operating conditions have been discussed in [3,11], a Direct Voltage Control (DVC) method using an integral variable structure control (IVSC) theory was used to synchronize the DFIG to the grid, parametric variations and grid disturbances were carefully involved into the design of the control law, and good experimental results were presented. A second-order sliding mode control scheme for both grid synchronization and power control of a DFIG has been presented in [12], the experimental results show a good tracking accuracy and high robustness. The authors in [5] proposed a new sensorless predictive direct virtual torque control (PDVT) scheme of the DFIG, with excellent performance in steady and transient states, also fast and smooth grid synchronization and power regulation were achieved. In [13,14], a sensorless DVC was experimentally validated for standalone and grid synchronization operation modes after the grid fault occurred; this DVC is based on the direct control of amplitude and angle of stator voltage.

For grid-connected mode only of the DFIG, various control strategies have been developed and reported during the last twenty years, maybe the stator active and reactive powers based field-oriented control scheme have been the most discussed [10]. Direct Power Control (DPC) based look-up table (LUT) [15], sliding mode [16,17], fuzzy logic [18], and predictive [19] concepts are also widely investigated.
Controlling industrial systems needs a faster response and better accuracy. Besides, the environmental conditions of the systems create significant constraints such as external disturbances or variations of the system parameters due to aging. Also, it is often difficult to find a simple mathematical model of the controlled process [20]. Proportional–Integral–Derivative (PID) controllers commonly used in industry, proved efficient and reliable, but they need a good tuning of their three gains in order to find the best compromise between accuracy and speediness. The previously mentioned constraints can lead to the failure of the PI control method. Therefore, the use of Fuzzy Logic Controller (FLC) which is based on the expertise of a human operator looks an interesting solution [20]. FLC doesn’t have much better performance in time response than PID control, but its advantage is that it can deal with nonlinear and uncertain systems [21].

The remaining of this paper is organized as follows: The operating stages changing mechanism is described in Section 2. The modeling and the pitch control of the WTS are presented in Section 3. The PI-like fuzzy logic control design is described in Section 4. In Section 5, the proposed DVC and DPC schemes of the DFIG through the rotor side converter (RSC) are designed. Then, Section 6 illustrates the simulation results and the performance discussion. Finally, a global conclusion is provided in Section 7.

2. Operating stages

Four operating regions of the variable speed WTS are shown in Fig. 2, where \( V_{\text{cut-in}} \) and \( V_{\text{cut-out}} \) are respectively the minimum and maximum boundaries of the allowed wind velocities [1].

Under the cut-in wind speed the WTS cannot cover its own losses, so in this region the turbine is kept in quasi-steady situation using a mechanical brake. Start-up of the WTS takes place at the cut-in wind speed, where the WTS is controlled to extract the maximum energy from the wind with pitch angle equal to zero, it is known as the maximum power point tracking (MPPT) region. Between the rated and the cut-out wind speeds, the rated power of the WT is already being produced, however the wind speed is still increasing and offering extra power, so the additional power is shed by turning the blades around their axis. Beyond the cut-out wind speed, the wind power became very strong and insecure for the mechanical structure; hence the system is stopped totally by the pitch system and mechanical brakes. The operation mode of the WTS is decided in the superior control level and four operation goals were considered such as startup, power generation, braking and stopping as presented in Fig. 3.

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**Fig. 2.** Operating regions of the variable speed WTS.

**Fig. 3.** Supervision of the operating stages in the WTS.
3. Modeling and control of WTS

The WT is the prime mover of the WTS that allows the conversion of the kinetic energy of wind \(E_w\) into mechanical power \(P_m\) and finally into electrical power \(P_{r1}+P_{r2}\) [22].

\[
P_m = \frac{\partial E_w}{\partial t} C_p = \frac{1}{2} \rho A \omega^2 C_p(\lambda, \beta).
\]  

(1)

where \(V_w\) is the air speed at the center of the rotor (m/s), \(\rho\) is the air density (kg/m\(^3\)), \(A = \pi R^2\) is the frontal surface of the WT (m\(^2\)) and \(R\) is the rotor radius (m). \(\lambda\) (Tip Speed Ratio) is the ratio of the linear speed of blade tip and wind speed:

\[
\lambda = \frac{\omega_R R}{V_w}
\]

(2)

Efficiency coefficient \(C_p\) is a function of the blade angle called the pitch angle which is denoted by \(\beta\), and the TSR, this triple relationship is presented in Fig. 4, and it is approximated using a nonlinear function given by Eq. (3) [22]:

\[
C_p(\lambda, \beta) = 0.22 \left( \frac{116}{\lambda_i} - 0.4 \beta - 5 \right) e^{\frac{12.3}{\lambda_i}} \text{ where } \frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08 \beta - \frac{0.035}{\beta^3 + 1}}.
\]

(3)

From Fig. 4, we can extract the maximum power by driving the WTS at a particular speed that corresponds to wind speed in such a way that the TSR remains constant (for \(\lambda \approx 9.95\) and \(\beta = 0\)deg we get: \(C_{p_{\text{max}}} = 0.5\)). The optimal rotational speed of the induction machine which has to be taken as a control reference is given by Eq. (4):

\[
\omega_{m_{\text{opt}}} = \frac{N_g \omega_{r_{\text{opt}}}}{N_g} = \frac{\lambda_{\text{opt}} V_w}{R}
\]

(4)

Where: \(\omega_t\): turbine speed, \(\omega_{m}\): generator speed, \(N_g\): gearbox ratio, \(\lambda_{\text{opt}}\): optimal TSR

TSR based MPPT method seeks to force the WTS to remain at the optimal point by comparing optimal and actual rotor speeds and feed this difference to a controller. Optimal TSR is determined either experimentally or theoretically, while the wind speed is continuously measured. When the wind speed became high, the pitch control system is activated, and the mechanical speed \(\omega_m\) and power \(P_m\) are controlled to stay around their rated values (1.2pu and 1pu respectively). The pitch control system is presented in Fig. 5 where the mechanical power is given by: \(P_m \approx P_s + P_r = (1-s)P_s\) where \(s\) here is the slip, \(P_s\) and \(P_r\) are the stator and rotor active powers respectively.

4. Fuzzy logic control design

In this paper, a PI-like FLC has been used to accelerate the WT by the calculation of the appropriate reference of pitch angle. As the FLC does not need any mathematical model of the WT aerodynamic system, it has the ability to control systems with significant non-linearities, such as the un-stationary wind with large turbulence.

The PI-like FLC is driven by a set of control rules rather than constant PI gains [23]. Unlike the PD (Proportional and Derivative)-like FLC where the input signals are the error and its change in the discrete form, the PI-like FLC uses as inputs the error and the error increment instead, which create a problem with the formulation of the rules table. So, the solution is to move the increment from the input side to the output side of the FLC, then we may have the error and its change as inputs and we still have the soul of the original PI-like FLC. The conventional PI controller output is given by:

\[
u(t) = K_p e(t) + K_i \int e(t) dt
\]

(5)
If we take the derivative of the controller output, it becomes:

$$\frac{du(t)}{dt} = K_p \frac{de(t)}{dt} + K_i e(t) \quad \text{(in discrete form: } \Delta u(k) = K_p \Delta e(k) + K_i e(k))$$

where the index $k$ represents the current state of the discrete system.

Eq. (6) gives the form of the PI-like FLC which has two inputs and one output which is the change of the command instead of the command itself, so the diagram of the employed PI-like FLC is shown in Fig. 6 [23], where the inputs are the error and its change (similar to PD-like FLC) of the rotor speed ($\omega_m$ and $\Delta \omega_m$), and the output is the change in pitch angle ($\Delta \beta$), an increment of the output is added to get the actual command. A triggering mechanism is designed to activate or deactivate the acceleration process according to the wind intensity.

Actually, the scaling factors of the inputs $K_i$ and $K_p$ are called $K_e$ and $K_{\Delta e}$ respectively, so by using those factors the input signals are transferred from the actual universe of discourse into the interval $[-1,1]$ (normalization stage). In fact, the attention is focused on the tuning of the output scaling factor (called $K_{\Delta u}$) because it has a dominant impact on the total performance of the fuzzy controller [23].

Numerous papers have discussed the derivation of the best fuzzy rules used for control applications such as the studies of MacVicar and Boverie. Eventually, there is a quasi consensus about a systematic approach based on the typical time response of the error in closed-loop control of the second-order system as shown in Fig. 7, for a step control action, the time response of the error may have an oscillatory form with a damped exponential component. Since it includes multiple overshoots that leading the rule base to represent more generalized cases [24].

The error and its change ($e$ and $\Delta e$) axis are divided into three fuzzy membership functions (MFs) as negative ($N$), zero ($Z$), and positive ($P$) as shown in Fig. 7. In order to imitate the reasoning of a human operator, it is necessary to observe the behaviors of the error and its change in different operating regions (or quadrants), as shown in Figs. 7 and 8. The sign of $\Delta u$ in each quadrant is listed in Table 1, which can be summarized as follows:

**IF** $e$ is zero **THEN** $\Delta u$ takes the sign of $\Delta e$. **ELSE** $\Delta u$ takes the sign of $e$.  

![Fig. 5. The proposed pitch control scheme for different operating changes of WTS.](image)

![Fig. 6. The structure of the employed FLC used to accelerate the WT associated with its triggering mechanism.](image)
Referring to Fig. 7, a plot of $e$ versus $\Delta e$ in space phase can be used to determine the regions for fuzzy dividing as shown in Fig. 8. As can be seen, there are four quadrants according to the sign of the error and its change; however, there are nine ($3 \times 3$) rules that can be formed according to the number of the used MFs as presented in Table 2.

A closer look at Fig. 8 and Table 2 shows that there are many transitions of the controller output ($\Delta u$) between positive and negative MFs happen without using zero MF. These transitions are always happening in the quadrants $Q_1$ and $Q_3$, these two quadrants called the “convergence quadrants” where the error response is going towards the zero, the fuzzy controller uses active control actions ($P$ or $N$) for braking around the equilibrium point ($e=0$ and $\Delta e=0$) and this fact destabilize the response, the solution is to adjust the rule table.

In this paper, a bigger rule table is used with seven MFs for each input or output signal, also forty-nine rules are presented in Table 3 [23]. This rule table contains zero MFs in every square of the anti-diagonal line which is equivalent to the qualitative natural convergence line (as the dead point in the gearbox of cars). Also, the three conditions of qualification (consistent, continuous and complete) are achieved in this rule table [24].

Fig. 9 shows the fuzzy MFs employed in the FLC. The choice of shape, number, and range of the MFs and scaling factors are just a matter of experience. The acronyms $NB$, $NM$ and $NS$ mean: Negative Big, Negative Medium, Negative Small, also $PB$, $PM$, $PS$ mean: Positive Big, Positive Medium and Positive Small.

**Table 1**
The signs of basic control actions.

<table>
<thead>
<tr>
<th>Operation regions</th>
<th>$R_1$</th>
<th>$a_2$</th>
<th>$R_2$</th>
<th>$a_3$</th>
<th>$R_3$</th>
<th>$a_4$</th>
<th>$R_4$</th>
<th>$a_5$</th>
<th>$\ldots$</th>
<th>$E_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e$</td>
<td>+</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>$\ldots$</td>
<td>$0$</td>
</tr>
<tr>
<td>$\Delta e$</td>
<td>-</td>
<td>-</td>
<td>0</td>
<td>$+$</td>
<td>$+$</td>
<td>$+$</td>
<td>$0$</td>
<td>$\ldots$</td>
<td>$0$</td>
<td></td>
</tr>
<tr>
<td>$\Delta u$</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>$+$</td>
<td>$+$</td>
<td>$+$</td>
<td>$\ldots$</td>
<td>$0$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The Mamdani-type inference method collaborating with the center-of-area defuzzification method is used to generate the fuzzy controller output. The proposed PI-like FLC is capable of controlling different types of systems with different orders [24]. This generalized FLC requires only small adjustments in input and output gains to be adapted for different systems.

5. Proposed control system of the Rotor Side Converter

If the grid voltages are within the normal conditions, the stator can be synchronized using only the rotor currents. Otherwise, an additional stator voltage control loop must be added to achieve better synchronization and zero-power exchange at the moment of grid connection [10]. For this reason, we decided to design a direct control scheme for the stator voltages. In this paper a standard hysteresis controller is used to control the rotor current in each phase (inner control loop), a sine wave generation block is used to generate the reference rotor currents. Magnitude and angle of the reference rotor currents are the outputs of the outer control loops as shown in Fig. 10. In the grid synchronization phase or standalone mode, a sensorless DVC with two standard PI controllers is employed. The first one is used to control the magnitude of stator voltages
and deliver the reference magnitude of rotor currents, the second controller is used to control the angle of stator voltage vector and deliver the reference slip frequency [13,14].

In grid-connected mode, a modified sensorless DPC scheme with two standard PI controllers is used. The first PI controller is used for the reactive power control which delivers the $d$-component of the rotor currents, the second one is used for the speed control which delivers the $q$-component of the rotor currents. Then, the magnitude and angle of the rotor currents are calculated using a Cartesian to Polar transformation; the advantages of this control system are many:

- Despite its variable switching frequency, the hysteresis controller is a very practical solution in power electronics and electrical drives, because it is simple, robust and ensures the highest dynamic response.
- Rotor speed and rotor position angle which are usually got from the incremental encoder are unnecessary in the proposed control scheme (only measured stator voltages, stator, and rotor currents are required).
- Encoder zero position correction problem during synchronization was overtaken in the grid synchronization stage.
- In the case of a grid fault, a temporary standalone operating mode can be obtained by the proposed DVC, using the rated stator voltage magnitude and frequency as references [13,14].
- No control loops for active power or electromagnetic torque are needed in the grid-connected control system.

PI controllers are sufficient in the normal operating conditions; however, they are poor in some uncertain conditions of the controlled system. In this paper, an intelligent FLC has been proposed to replace the PI controllers in Fig. 10, which is known by its ability to control nonlinear and uncertain systems. Moreover, a cascaded fuzzy and hysteresis controller form a robust control system with no need for any prior knowledge of the controlled system, the structure of the employed FLC is similar to the FLC already presented in Fig. 6.

Additionally, the supervision mechanism of the different mechanical switches in Fig. 1 is presented in Fig. 11; also the switching between the different operating stages of the WTS is decided through this mechanism.

5.1. Stator voltage control

According to [25], fixed output voltage and frequency are required during the grid synchronization stage (with no load) or standalone operation mode of the WTS. Using filtering capacitor on the stator side eliminates the switching harmonics produced by the power converter, and compensates a portion of the reactive power required for magnetization. The standard model of the DFIG in a synchronously rotating reference frame is expressed by -(Eqs. (7)-(10)) using the space vector notation. The model includes Eq. (11) of the stator circuit consisting of a filtering capacitor and local load.

$$\dot{V} = \frac{V}{s} = R_s i + \frac{d\Phi_s}{dt} + j\omega_s \Phi$$  \hspace{1cm} (7)

$$\dot{V} = \frac{V}{r} = R_r i + \frac{d\Phi_r}{dt} + j(\omega_s - p\omega_m) \Phi$$  \hspace{1cm} (8)

$$\Phi = L_s i + L_m \frac{i}{s}$$  \hspace{1cm} (9)

$$\dot{\Phi} = L_r \frac{i}{r} + L_m \frac{i}{r}$$  \hspace{1cm} (10)

$$\frac{i}{s} = -C_f \frac{dV}{dt} + \frac{i}{r} - j\omega_s C_f V$$  \hspace{1cm} (11)
where $V_s, V_r$ are stator and rotor voltage; $\Phi_s, \Phi_r$ are the stator and rotor flux; $i_s, i_r$ and $i_l$ are stator, rotor and load currents; $R_l, R_r$ are stator and rotor resistances, $L_s, L_r, L_m$ are stator, rotor and magnetizing inductance; $p$ is number of poles pairs; $\omega_s, \omega_m$ are synchronous and mechanical speed, $C_f$ is filtering capacitance. Based on Eqs. (7), (9) and (11) for a filtering capacitance equal to zero ($C_f=0$) and a resistive load, the model of the DFIG in standalone mode can be derived:

$$
\vec{V}_s = \frac{R_l L_m}{Z_s} \frac{d \vec{i}_r}{dt} + j \omega_r R_l L_m \vec{V}_s - \frac{L_s}{Z_s} \frac{d \vec{V}_s}{dt}
$$

(12)

Stator resistance can be neglected in high power machines, $R_l$ is the load resistance, and $Z_s$ is the stator side impedance: $Z_s = R_l + j \omega_L L_s$. The presence of rotor current derivative term in Eq. (12) shows that the stator voltage is perturbed by rotor current ripples caused by the converters. The negative sign of the stator voltage derivative contributes to the damping of the stator voltage ripples. The transfer function between stator voltage and rotor current as:

$$
H_{VS} = \frac{\vec{V}_s(s)}{\vec{i}_r(s)} = \frac{R_l L_m s + j \omega_r R_l L_m}{L_s s + Z_s} = \frac{j \omega_r R_l L_m}{Z_s} \left( \text{in...steady...state} \right)
$$

(13)

Where $s$ here is the Laplace operator. In the worst-case which is the no-load operation (synchronization stage), $R_l$ and $Z_s$ are infinite, so Eq. (12) becomes:

$$
\vec{V}_s = L_m \frac{d \vec{i}_r}{dt} + j \omega_s L_m \vec{i}_r
$$

(14)

This means that the transfer function for the stator voltage control loop is given as:

$$
H_{VS} = \frac{\vec{V}_s(s)}{\vec{i}_r(s)} = L_m s + j \omega_s L_m (= j \omega_s L_m \text{in...steady...state}).
$$

(15)

To obtain high quality generated voltage in the synchronization stage, only filtering capacitors are needed on the stator side, and the stator voltage can be described by:

$$
\vec{V}_s = \frac{1}{1 - \omega_s^2 L_m C_f} \left( L_m \frac{d \vec{i}_r}{dt} + j \omega_s L_m \vec{i}_r - j 2 \omega_s L_m C_f \frac{d \vec{V}_s}{dt} - L_c \frac{d^2 \vec{V}_s}{dt^2} \right)
$$

(16)

The negative sign of the second derivative of the stator voltage in Eq. (16) is the element responsible for maximum damping of the voltage perturbations caused by rotor current ripples. Also, the filtering capacitor must be equal to:

$$
C_f = \frac{1}{4 \pi^2 f_r^2 \sigma L_m}
$$
where
\[ \sigma = 1 - L_m^2 / L_sL_r, \]
and \( f_r \) is the resonant frequency of the \( \sigma L_mC_f \) filter.

Using Eq. (16), the open-loop transfer function between stator voltage and rotor current can be written as:
\[
H_{Vs} = \frac{V_s(s)}{i_r(s)} = \frac{L_m s + j \omega_s L_m}{-(L_sC_f)s^2 - (j2\omega_sL_sC_f)s + (1 - \omega_s^2 L_sC_f)} = \frac{j\omega_s L_m}{1 - \omega_s^2 L_sC_f} \text{ (in...steady...state)}.
\] (17)

Based on the transformations of components from Cartesian to polar coordinates which is illustrated in [1,13,14,26], the stator voltages are first transferred from \( abc \) stator coordinates to \( d-q \) synchronous coordinates, and eventually from \( d-q \) into polar coordinates, and gives the stator voltage vector became related to the \( d \)-axis. Measured amplitude and angle of the stator voltage space vector are easy to be calculated using:
\[
V_s = |V_s| = \sqrt{V_{sd}^2 + V_{sq}^2} \quad \text{and} \quad \theta_s = \arg(V_s) = \tan^{-1} \left( \frac{V_{sq}}{V_{sd}} \right).
\] (18)

Based on Eq. (13), (15) and (17), for certain speed (speed and load), the amplitude of induced stator voltage during grid synchronization (standalone mode) of the DFIG is proportional to the amplitude of the rotor current. Control of the voltage amplitude is easy to implement using a PI controller [13,14,25]. Frequency control during standalone mode consists of the synchronization between the measured stator voltage and a specific reference vector. The stator voltage frequency is also proportional to the slip frequency and a PI controller is capable to guarantee this relationship.

5.2. Grid synchronization stage control

Before generating any power, the DFIG has to be synchronized and softly connected to the grid [10], the detailed start-up process proposed in this paper is described by the flowchart presented in Fig. 12. Normally, when the rotor speed exceeds a certain edge, it is assumed that the wind is strong enough to produce electric power beneficially, so the control system gives an order to initiate the grid synchronization process.
The measured grid voltage vector is taken as a reference of stator voltage; a fixed frequency can be obtained by a fixed angle $\theta_s$ between the d-axis and the measured stator voltage vector. The d-q coordinates rotate at the synchronous speed $\omega_s$ in a positive way, thus, the reference stator voltage angle $\theta_{s,\text{ref}}$ is chosen to be zero as illustrated in Fig. 13e, which means that the d-axis overlaps the reference stator voltage vector. Calculation of angle between a grid and stator voltage vectors ($\theta_{\text{err}}$) allows synchronizing of these two voltages. The error angle $\theta_{\text{err}}$ is calculated using the d and q components of the grid voltage vector $[13,14,25]$: $\theta_{\text{err}} = \arctan (V_{gq}/V_{gd})$

Then, this angle is minimized by iterative rotating of the d-q reference frame in the direction of the grid voltage vector. The rotation angle of the d-q reference frame during the synchronization process is given by: $\theta_{dq} = \int \omega_s \, dt - k \theta_{\text{err}}$

The $k$ factor is used to decide the synchronization speed and it is in the range between 0.01 and 0.001. After the synchronization is achieved, the switch SW3 is closed, and the generator became connected to the grid. The pitch angle controller sets the blade pitch at the optimum point if the blades are at another point (generally equal to zero).

5.3. Control of the stator reactive power and rotational speed

After the grid connection, output power maximization became the main purpose of the control system; however the reactive power reference is set according to the grid requirements. Independent control of output active and reactive power is the only way to achieve these goals, hence, stator flux oriented control (VC) is employed where the d-axis oriented along with the stator-flux vector position. After some simplifications and substitutions $[10]$, the stator reactive power and the
Electromagnetic torque can be manipulated through rotor currents which are found to be:

\[ Q_s = \frac{V_s^2}{\omega_s L_s} - \frac{L_m V_s}{L_s} i_d \]  \hspace{1cm} (19)

\[ T_{em} = -p \frac{L_m}{L_s} \frac{V_s}{\omega_s} i_q \]  \hspace{1cm} (20)

Note that the reactive power has a term that does not depend on rotor current. It is left to the controller to deal with this term as a disturbance, and no feed-forward structure will be used to cancel it out. Additionally, the rotor speed dynamics of the DFIG is given as:

\[ 2H_m \frac{d\omega_m}{dt} + D_m \omega_m = T_{em} - T_m \]  \hspace{1cm} (21)

Where \( T_m \) is the mechanical torque on the shaft originating from the WT, \( H_m \) is the inertia constant of the lumped-mass system (turbine + generator) [s], \( D_m \) represents the damping factor of the lumped-mass system [pu].

Fig. 13. Continued
The rotational speed equation has a term that does not depend on the electromagnetic torque. Also it is left to the controller to deal with this term as a disturbance. Using the last three relations, two transfer functions are derived where the reactive power and the rotational speed are manipulated through rotor current components $i_{rd}$ and $i_{rq}$ respectively.

$$H_{qs/i_{rd}} = \frac{Q_{s}(s)}{i_{rd}(s)} = -\frac{L_{m}V_{s}}{L_{s}}$$

$$H_{\omega_{m}/i_{rq}} = H_{\omega_{m}/m_{s}, H_{\omega_{m}/i_{rq}}} = \frac{\omega_{m}(s)}{i_{rq}(s)} = \frac{1}{2H_{m}^{s} + D_{m}.p.\frac{L_{m}}{L_{s}}.\frac{V_{s}}{\omega_{s}}}$$

(22)

(23)

When the rotor current is under control, the speed can be dealt with separately in an outer loop with another controller, where the dynamics of the inner loop is ignored safely because they are happening so fast in comparison with rotational speed dynamic. However, the inner loop is approximated with a first-order system in the reactive power closed loop control.

6. Simulation results

To evaluate the performances of the proposed control strategy, the model of the DFIG-based WTS was simulated under Matlab/SimPowerSystems environment, the simulation is performed in the per unit (pu) system where the system rating and the simulation parameters are cited in Tables A.1 and A.2. Two tests were considered for the simulation.

6.1. First test: normal operating condition of the DFIG without local load (start-up and shutdown of WTS)

The first simulation test had been proposed to illustrate the grid synchronization and connection of the DFIG, also the tracking accuracy and the dynamic response of rotor speed, active and reactive power under the normal conditions. The wind speed profile has been chosen in order to make the WTS passes twice (wind up/wind down) over all the operating stages of the operating stages presented in Fig. 3. Sufficient time is given to reach the steady-state in each operation mode (i.e. constant wind speed & constant rotor speed & constant output power).

A good initialization of the simulation model is essential because oscillations at the start of simulation test can lead to numerical instabilities, then, due to the large inertia of the WT; it has to wait a long time before reaching the steady-state. Therefore, the initial steady-state point is taken as: $(V_{sd}=3 m/s, \omega_{m}=0.3pu, \beta_{0}=20deg, i_{sd}=i_{rd}=0pu)$. The simulation results are presented in Fig. 13.

Before $t=8.75$ s, the WTS was almost in stop (initial condition: $\omega_{m}=0.5pu$); this means that the kinetic energy of the wind is insufficient to produce electrical energy with acceptable efficiency. In this case, the pitch system is used to aerodynamically slow down the WT, so there are no currents in stator and rotor circuits as illustrated at Fig. 13f. At the $t=8.75$ s, the wind speed exceeds the cut-in threshold (6 m/s), so, the start-up procedure is activated starting with the DC-link capacitor charging using the grid side converter as presented in Fig. 13b. Hence, the pitch angle is maintained at the lowest point in order to increase the aerodynamic torque of the WT and accelerate the generator as illustrated in Fig. 13c and d. The mechanical torque rises as presented in Fig. 13g, at the same time the generator torque remains zero because the RSC control is not activated yet. Due to the inertia of the heavy weight WT, this step takes the longest time.

At $t=12.8$ s, the rotational speed reaches 70% of the synchronous speed as shown in Fig. 13d, thus, the third step of the start-up procedure is activated, which is the induction of stator voltage using the RSC as presented in Fig. 13e. Simultaneously, the fourth step is activated by minimizing the phase error between stator and grid voltages until it becomes zero as presented in the zoom inside the Fig. 13e. This phase takes about 50ms to satisfy the synchronization conditions.

At $t=12.85$ s, the stator voltage coincides with the grid voltage in amplitude, frequency and phase, so all the synchronization conditions have been achieved according to Fig. 12. This is the most critical phase of the whole process, because if the stator switch is closed with an unequal stator and grid voltages, heavy transient stator and rotor currents would occur, which means unsuccessful synchronization process. However, no heavy impact on the generator currents has been observed in the test at $t=12.85$ s which proves the success of the grid connection process.

After $t=12.85$ s, the RSC control scheme has been switched from the grid synchronization into the power generation mode, now the MPPT system is then responsible for output power maximization by controlling the electromagnetic torque of the generator as shown in Fig. 13g, in order to reach the maximum efficiency (Fig. 13i) and the optimum TSR (Fig. 13j). In steady-state, the generator torque and the mechanical torque of the WT are equal and the output reactive power is controlled to remain zero as shown in Fig. 13h. Stator voltage and the currents in stator and rotor circuits are illustrated in Fig. 13f. A phase shift of 180deg between the stator current and voltage has been detected, which means that the DFIG is supplying the grid with power with unity power factor. The two grid synchronization instants are zoomed and illustrated in Fig. 13f. The pitch control system is deactivated in this operating mode in order to receive the highest aerodynamic energy from the wind as shown in Fig. 13c.

At $t=27$ s, the wind speed reaches the rated value as can be seen in the Fig. 13a, hence the rotational speed and the output power have reached their rated values as shown in Fig. 13d and h respectively. Now the pitch angle system is reactivated in order to limit the speed and the power at their rated values. Hence, the efficiency coefficient decreases
until it reaches the zero at $V_{\text{ref}}=28 \text{ m/s}$. At $t=37.66 \text{ s}$, the wind speed exceeds the cut-out value, the pitch angle control system is switched from the power limitation mode into the braking mode in order to protect the WT from the overloading as presented in Fig. 5. So, the output power become zero and the rotational speed become below the relaxation speed ($<0.5 \text{ pu}$). A 50deg pitch angle can keep the rotational speed below the relaxation speed; however, if the wind speed exceeded the 40 m/s the applied pitch angle will become 90deg which leads to the total stopping of the WTS.

Between $t=0 \text{ s}$ and 47.33 s, we have marked one round from and into the relaxation condition under decreasing wind speed. then, after the $t=47.33 \text{ s}$, the wind speed has decreased under the cut-out speed, so the WT was accelerated again by the pitch system, so all the operating stages of Fig 3 have been repeated under increasing wind speed. So we can observe a similarity between all the recorded data before and after the instant $t=42.25 \text{ s}$ of the test.

Table 4 gives a short comparison study between the proposed grid synchronisation method and three other different methods from literature, it can be seen that the proposed method has lower complexity in implementation and faster dynamic response.

6.2. Second test: faulty operating condition of the DFIG supplying a local load (Autonomous mode of WTS)

At $t=22 \text{ s}$ of the previous test, another wind speed profile is introduced as presented in Fig. 14b, the transition from grid-connection mode into the standalone mode of the DFIG has been tested because of temporary failure of the grid (for five seconds) as presented in Fig. 14a. Only a local load is supplied by the WTS, the consumed power by the local load changes from $(P_1=1 \text{ MW}+Q_1=0)$ into $(P_1=2 \text{ MW}+ Q_1=1 \text{ MVAR})$ between the moments $t=23 \text{ s}$ and $t=25 \text{ s}$, and also between $t=33 \text{ s}$ and $t=35 \text{ s}$. The simulation results are presented in Fig. 15. In this test, the robustness of the proposed FLC is compared to that of PI controller in case of machine parameters variation fault, the variations of machine parameters are taken for the whole simulation time as: $R_r=1.5 \times R_r$, $L_t=0.5 \times L_t$, $H_m=1.5 \times H_m$ and $D_m=1.5 \times D_m$.

In grid-connected mode, stator side voltage and grid side voltage are the same, unlike the case during the standalone mode as presented in Fig. 15a. The FLC maintains the stability of the faulty system in both grid-connected and standalone operating modes, as well as under variable local load. Minimum disturbance has maintained in the currents of stator and rotor terminals and the rotational speed as illustrated in Fig. 15a, e and b respectively. The grid reactive power is maintained constantly zero, so the stator reactive power can be positive or negative depending on the local load variation as shown in Fig. 15d. The total active power of the generator is divided between the filter, local load and the grid as illustrated in Fig. 15c, however during the standalone mode it is consumed only by the local load and the filter.

By applying the FLC in the DVC strategy, a slight disturbance is appeared in the stator voltages as illustrated in Fig. 15a for $31 \text{ s}<t<36 \text{ s}$. Besides, the total harmonic distortion (THD) of the stator voltage is almost four times smaller compared to the case with PI control, this causes the THD of the stator currents to lessen by almost six times as presented in Fig. 15f. In case of PI control, a degraded performance has been achieved in grid-connected and standalone operating modes, huge disturbance was appeared in rotor speed, stator and rotor currents, then active and reactive output powers, and eventually, the system has lost completely its stability at $t=36 \text{ s}$ because of the unstable performance of the rotor speed control.

Table 4: Comparison between four different grid synchronisation strategies in normal operating conditions:

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Settling time in voltage control</td>
<td>35ms</td>
<td>100ms</td>
<td>62ms</td>
</tr>
<tr>
<td>Complexity</td>
<td>Medium</td>
<td>Medium</td>
<td>high</td>
</tr>
</tbody>
</table>
Table 5 gives a brief comparison study between four different power control methods of the DFIG including the proposed control method. It can be seen that the proposed method has a lower implementation complexity, sufficient harmonic spectrum performance, and slow dynamic response of the reactive power compared to the other methods.

Large scales WTs have a very long inertia constant because of the heavy rotating blades and hub assembly attached to their rotor; so the rotational speed changes very slowly. Thus to see the mechanical response of this system, very long simulation in the order of minutes need to be run, because of that it is difficult to find a similar simulation study with this

Fig. 15. The simulation of temporary standalone operating mode under the machine parameters variations.
conditions, however the rotor speed dynamic response of the proposed method is sufficient compared to the global inertia constant of the employed WTS which is 5.04s as can be seen in Fig. 15b.

7. Conclusion

In this paper, a new control strategy has been developed including start-up procedure, supervision of operating stages, references generation, power maximization and power limitation of wind turbine system equipped with doubly-fed induction generator. Moreover, a new sensorless direct voltage control and direct power control schemes of the rotor side converter using the polar coordinates were designed, to ensure superior performance in autonomous and grid-connected operation modes respectively. Additionally, proportional-integral like fuzzy logic controller has been introduced to improve the system performance and to reinforce the robustness in case of uncertain conditions such as the wind turbulence or variations of the machine parameters. In the case of normal operation, the wind speed profile has been designed carefully in order to pass through all the possible operating stages of the wind turbine system using increased and decreased wind speed. Therefore, a very good dynamic performance was achieved using only conventional proportional-integral and hysteresis controllers with a soft transition between all the operating stages, especially the successful grid connection process.

In order to compare the conventional proportional-integral and fuzzy controllers, a second simulation test has been carried out. This test included a long time failure in grid voltage and the variations in the actual values of the machine parameters which were used for tuning the proportional and integral gains of the controllers. Fuzzy control was used to improve the performance of both control techniques direct voltage control and direct power control. The simulation results have confirmed that the proposed fuzzy logic control approach is effective in improving both system stability and power quality compared to the conventional proportional-integral controller, Hence fuzzy control is proven to be suitable and
reliable in case of controlling uncertain and nonlinear systems. Practical implementation of the proposed approach will be a topic of future work.

Declaration of Competing Interest

None.

Acknowledgments

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Appendix

Tables A1–A3.

Table A.1
The detailed data of the DFIG based wind farm [22].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of WT units</td>
<td>Pnom</td>
<td>6</td>
</tr>
<tr>
<td>Rated active power for each unit</td>
<td>Sname</td>
<td>1.5 MW</td>
</tr>
<tr>
<td>Rated apparent power for each unit</td>
<td>Sname</td>
<td>1.66 MVA</td>
</tr>
<tr>
<td>Rated frequency</td>
<td>fnom</td>
<td>60 Hz</td>
</tr>
<tr>
<td>Base apparent power for the wind farm</td>
<td>Vbase</td>
<td>575 V</td>
</tr>
<tr>
<td>Base line to line voltage (RMS)</td>
<td>Vbase</td>
<td></td>
</tr>
<tr>
<td>Base current</td>
<td>IBase</td>
<td></td>
</tr>
<tr>
<td>Base impedance</td>
<td>Zbase</td>
<td></td>
</tr>
<tr>
<td>Base generator speed</td>
<td>ωg</td>
<td></td>
</tr>
<tr>
<td>Number of pole pairs</td>
<td>p</td>
<td></td>
</tr>
<tr>
<td>Stator resistance</td>
<td>Rr</td>
<td>0.023 pu</td>
</tr>
<tr>
<td>Rotor resistance</td>
<td>Rr</td>
<td>0.016 pu</td>
</tr>
<tr>
<td>Stator leakage inductance</td>
<td>Ls</td>
<td>0.18 pu</td>
</tr>
<tr>
<td>Rotor leakage inductance</td>
<td>Lr</td>
<td>0.16 pu</td>
</tr>
<tr>
<td>Magnetizing inductance</td>
<td>Lm</td>
<td>2.9 pu</td>
</tr>
<tr>
<td>Rated DC-link voltage</td>
<td>Vdc</td>
<td>1150 V</td>
</tr>
<tr>
<td>DC-link capacitor filter</td>
<td>Cdc</td>
<td>10,000 μF</td>
</tr>
<tr>
<td>AC-side inductive filter of GSC</td>
<td>Rg/g</td>
<td>0.003 / 0.3 μF</td>
</tr>
<tr>
<td>AC-side capacitive filter of GSC</td>
<td>Rg/g</td>
<td>0.53 Ω / 1333 μF</td>
</tr>
<tr>
<td>Stator side capacitor filter</td>
<td>Cst</td>
<td>1000 μF</td>
</tr>
<tr>
<td>Inertia constant of DFIG+WT</td>
<td>Dst</td>
<td>5.04 s</td>
</tr>
<tr>
<td>Dumping coefficient</td>
<td>Dwp</td>
<td>0.01 pu</td>
</tr>
</tbody>
</table>

Table A.2
The detailed data of the WT based wind farm [22].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of WT units</td>
<td>Vw</td>
<td>6</td>
</tr>
<tr>
<td>Rated wind speed</td>
<td>Vw</td>
<td>11 m/s</td>
</tr>
<tr>
<td>Rated rotor speed (pu of base generator speed)</td>
<td>oRm</td>
<td>1.2 pu</td>
</tr>
<tr>
<td>Rated mechanical power for each unit</td>
<td>Prms</td>
<td>1.5 MW</td>
</tr>
<tr>
<td>Total mechanical power for the wind farm</td>
<td></td>
<td>9 MW</td>
</tr>
<tr>
<td>Air density</td>
<td>ρ</td>
<td>1.225 kg/m³</td>
</tr>
<tr>
<td>Rotor diameter</td>
<td>2R</td>
<td>72 m</td>
</tr>
<tr>
<td>Gearbox ratio</td>
<td>Ns</td>
<td>91</td>
</tr>
</tbody>
</table>

References

Table A.3
The detailed data of hysteresis, PI and fuzzy controllers.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hysteresis band of rotor currents</td>
<td>ΔI_r</td>
<td>± 0.01 (pu)</td>
</tr>
<tr>
<td>PI controller of rotor speed</td>
<td>K_p / K_i</td>
<td>100/1000</td>
</tr>
<tr>
<td>PI controller of reactive power</td>
<td>K_p / K_i</td>
<td>15/600</td>
</tr>
<tr>
<td>PI controller of stator voltage magnitude</td>
<td>K_p / K_i</td>
<td>0.2/20</td>
</tr>
<tr>
<td>PI controller of stator voltage angle</td>
<td>K_p / K_i</td>
<td>0.2/1000</td>
</tr>
<tr>
<td>FLC used for WT acceleration</td>
<td>k_d / k_m / k_d_i</td>
<td>3/5000/100</td>
</tr>
<tr>
<td>FLC of rotor speed</td>
<td>k_d / k_m / k_d_i</td>
<td>1/5000/500</td>
</tr>
<tr>
<td>FLC of reactive power</td>
<td>k_d / k_m / k_d_i</td>
<td>1/100/200</td>
</tr>
<tr>
<td>FLC of stator voltage magnitude</td>
<td>k_d / k_m / k_d_i</td>
<td>1/200/10</td>
</tr>
<tr>
<td>FLC of stator voltage angle</td>
<td>k_d / k_m / k_d_i</td>
<td>2/3000/50</td>
</tr>
<tr>
<td>Fixed step size</td>
<td></td>
<td>1e−4</td>
</tr>
</tbody>
</table>


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