Black-Start Capability of DFIG Wind Turbines
Through a Grid-Forming Control Based on the Rotor Flux Orientation

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ABSTRACT The increasing penetration of renewable energies in the power system is demanding new services from wind farms. In particular, system operators are concerned about system restoration after a black-out and new grid codes are under consideration that demand the participation of wind farms in the restoration process. Black start requires the wind farms to be capable of controlling voltage and frequency in an isolated grid. This paper proposes the use of a novel grid forming control for doubly fed induction generators (DFIG) for restoring the system after a black-out. The proposed grid forming control uses the rotor flux orientation principle, that allows to generate an internal electromotive force for controlling in this way the terminal voltage and frequency. Then, it is demonstrated that the rotor flux magnitude and frequency can be controlled by means of the rotor voltage applied the rotor side converter of the DFIG. The paper also proposes a wind turbine control system for balancing the power demanded by the load at the wind turbine mechanical system. Black start capability of the proposed control system has been validated through a comprehensive simulation. The simulated system consists of a wind farm with two DFIG-based wind turbines connected in parallel to a point of common coupling that supplies an induction motor through a feeder. Also, the synchronization of the isolated system to a main grid has been simulated, demonstrating the ability of the proposed control system for successfully completing the restoration process.

INDEX TERMS Grid-forming power converter, wind energy, doubly fed induction generator, frequency response.

NOMENCLATURE

ABBREVIATIONS

BESS battery energy storage system.
BSU black start unit.
DFIG doubly fed induction generator.
FFR fast frequency response.
GFM grid-forming.
GSC grid-side converter.
HVDC high voltage direct current.
LVRT low-voltage ride through.
MPPT maximum power point tracking.
PCC point of common coupling.
PI proportional-integral controller.
PLL phase locked loop.

SYMBOLS

λ, β tip speed ratio, pitch angle.
δ load angle.
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\( \omega \) stator frequency.
\( \omega_r \) electrical rotational speed of the rotor.
\( \sigma \) leakage factor.
\( \theta \) synchronizing angle.
\( \theta_r, \theta_{slip}, \theta_{PLL} \) rotor, slip and PLL angle.
\( e_s \) internal electromotive force.
\( J, D, R \) inertia, damping and droop constants.
\( K_s \) synchronization constant.
\( k_v \) voltage controller droop constant.
\( L_s, L_r \) total stator and rotor inductances.
\( L_m \) magnetizing inductance.
\( P, Q \) active and reactive power.
\( \rho \) pole pairs.
\( R_s, R_r \) stator and rotor resistances.
\( s \) slip.
\( T_s, T_r \) stator and rotor time constants.
\( T_w, T_v \) frequency and voltage secondary control integrator time constants.
\( v, \lambda, i \) voltage, flux and current.
\( v_w \) wind velocity.

**SUBSCRIPTS**

\( \alpha, \beta \) real and imaginary components in a stationary reference frame.
\( a, b, c \) instantaneous phase magnitudes.
\( d, q \) direct and quadrature components.
\( s, r \) stator and rotor.

## I. INTRODUCTION

Large scale integration of renewable generation in power systems has been taking place over the last few years. In 2019, the share of renewables in new generation capacity reached 70% [1]. Consequently, conventional synchronous generators, such as thermal units, are being displaced by converter-based renewable generation, therefore reducing not only system inertia, but frequency and voltage regulation capability as well. This transformation has a significant impact on the power system, which is being operated closer to its technical limits at the cost of an increased blackout risk. Our societies are increasingly dependent on electricity, and therefore the huge social and economic costs associated to a wide-scale blackout require that the power system be restored as soon as possible.

In order to accommodate as much of the available renewable energy as possible, conventional generation units are frequently off-line, and therefore the number of generators that are ready to participate in power restoration after a blackout at a given time may be limited. Cold-starting and bringing these units online may greatly extend power outage duration. Recent wind power generation technologies, due to their increased flexibility and controllability, can contribute to the early stages of power restoration, in addition to conventional generators, such as hydro and gas units [2]. There are two main options for network restoration after a blackout. The first one is a top-down process where the high-voltage grid is energized from the surrounding networks that were not affected by the blackout. After that, it is relatively simple to restore the sub-transmission network to supply critical loads and the auxiliary systems of other generators, which can in turn contribute to the restoration process. The second option is a bottom-up approach in which several independent islands are energized by black- start units (BSUs) to feed critical loads. Later, these islands are synchronized and progressively reconnected to restore the original power system [3]. This approach, while more complex, is mandatory when the neighboring power grids are not available during a severe and wide-spread blackout. Renewable systems can contribute to a bottom-up restoration by operating as grid-forming generators, keeping voltage and frequency stable, and feeding local loads in an electric island. However, this is only possible if the available primary energy source exceeds the load demand. Therefore, to overcome this limitation, battery energy storage systems (BESS) are expected to provide additional back-up power for renewable generation during the restoration process [4].

Over last years, grid codes have become increasingly stringent, and recently the European network of transmission system operators for electricity (ENTSO-E) grid code included islanding operation and black-start requirements [5]. Also, some TSOs, like the British and Belgian, are studying to require black-start capability to wind farms [6]. Following this trend, wind turbines have been progressively implementing grid-supporting features, such as fast frequency response (FFR), low-voltage ride through (LVRT), as well as more advanced services, currently under heavy development, such as inertia emulation, power oscillation damping, and fast reactive power response [7]. Recently, Scottish Power has successfully implemented black-start capabilities in the Dersalloch wind power plant (69 MW), in South Ayrshire (Scotland) [8]. This is only possible if the wind turbines are controlled in grid-forming mode (GFM), operating as a voltage source by emulating a virtual synchronous machine (VSM) [6], [9]. The integration of renewable sources in the distribution grid using GFM converters has been extensively studied for microgrids [10], [11].

Several GFM control strategies have been recently proposed in the literature for full-converter Type-IV wind turbines [12]–[16]. For doubly fed induction generator (DFIG) turbines, some control schemes have also been developed. In [17], a control named virtual synchronous control (VSynC) is presented for DFIG Type-III wind turbines, which includes active power control, voltage and reactive power control, an additional power oscillation damping control, and current limitation during voltage dips using a virtual resistor. The active power synchronization loop emulates the synchronous generator (SG) characteristic swing equation. The same technique is used in [18] to implement black-start capabilities. A similar control scheme is presented in [19] where the electromagnetic equations of a SG are implemented in a dq reference frame, including the emulation of a governor and an exciter to provide active power-frequency (P/f) and
voltage regulation, respectively. In [20] a DFIG vector control is presented that allows black-start operation with a BESS connected to the DC bus. Using synchrophasors during the power restoration process in a system that includes DFIG wind power plants and voltage source converter (VSC) HVDC links is considered in [21]. GFM operation during black-start in offshore wind power plants is presented in [22]. In [23] a novel control of a DFIG for stand-alone applications is proposed. Likewise, [24] proposes the control of a full-converter wind turbine for stand-alone application.

In conclusion, nowadays wind farms do not participate in the system restoration after a black-out, because they do not have the grid-forming capability required for energizing the system and feeding islanded loads. So, currently, conventional restoration is based on thermal and hydraulic power plants. However, as wind power is displacing those units, they will have to provide such service as well. On the other hand, it is widely assumed that grid-forming control is the mean for wind farms contributing to the system restoration. At this respect, National Grid ESO successfully tested the capabilities of a small scale VSM converter [25]. Also, Scottish Power Renewables in collaboration with Siemens Gamesa applied a grid forming control to the Dersalloch Wind Farm in Scotland [26], demonstrating the black start capability as well in [27].

It has been therefore shown that DFIG turbines are capable of black-start operation by implementing a GFM control. However, these publications do not propose any contribution on how to achieve the black-start process involving several parallel-connected wind turbines within a wind farm. Such a control scheme should first allow synchronizing the wind turbines to restore voltage and frequency at the point of common coupling (PCC) of the wind farm. It should later be able to feed a local load, and finally synchronizing and reconnecting to the neighboring grid. Moreover, when feeding the islanded loads, the wind turbine power must be equal to the power demanded by the loads. Therefore, the control system must be able to achieve a proportional sharing of the load power between the wind turbines and also to balance the power demand at the wind turbine mechanical system.

Consequently, the main contributions of this paper are:

- It proposes a novel grid forming control for doubly fed induction generators (DFIG) for restoring the system after a black-out.
- The generated voltage and frequency are controlled through the rotor flux magnitude and angle by means of the rotor voltage applied by the rotor side converter of the DFIG through a technique named rotor flux orientation.
- The proposed grid forming control allows also for the synchronous operation of a plurality of wind turbines, achieving also sharing the demanded power between them.
- A wind turbine control system is also proposed for balancing the power demanded by the load at the wind turbine mechanical system, so the wind turbine supplies the power demanded by the electrical load.

The GFM control strategy for the DFIG turbines shown in this paper is based on a dq rotary reference frame whose rotational speed is determined by an implementation of the SG swing equation. The machine rotor flux vector is then aligned toward that frame by directly acting on the rotor voltages. Controlling the rotor flux orientation allows controlling the DFIG torque, while controlling the rotor flux magnitude allows regulating the machine reactive power and the stator voltages.

This paper is organized as follows: in Section II the DFIG wind turbine is described, including its control system. In Section III the DFIG dynamic equations in a dq rotary reference frame are presented, as well as the expressions of the electromagnetic torque and the reactive power as a function of the generator load angle. In Section IV the torque synchronization loop and the DFIG rotor flux orientation principles are presented. In Section V the wind turbine control for black-start is presented. Section VI introduces the configuration of the power system where the black-start process takes place. The system includes two DFIG wind turbines connected to the PCC. From the PCC, the wind farm is connected to the main grid through a main switch, while a local dynamic load is connected through a feeder. Also, in this section a secondary control scheme is presented for controlling frequency and voltage at the PCC, by acting on the DFIG wind turbines setpoints. Section VII shows simulation results for the wind farm black-start process and synchronization to the main grid. Finally, in Section VIII the final conclusions of this work are discussed.

![FIGURE 1. Grid-forming DFIG control scheme.](image-url)
connected to the other low voltage winding through a back-to-back converter consisting of a grid-side converter (GSC) and rotor-side converter (RSC). An auxiliary battery is connected to the DC bus of the back-to-back converters to energize the DC bus just during wind turbine start-up [18].

The DFIG control operates as follows. The torque synchronization loop (TSL) determines the control angle \( \theta \), which is the angular position of the d-axis of a synchronous dq rotating frame. The rotor flux will be oriented along that d-axis, as it will be shown later. The input of the TSL is the difference between the reference torque \( T^*_e \) and the estimated electromagnetic torque \( T_e \). In grid-tied operation, the reference torque \( T^*_e \) is determined by following the maximum power point, that depends on the wind turbine rotational speed \( \omega_r \). In isolated operation, the torque is determined by the load that is being supplied by the generator, as it will be shown later.

The torque \( T_e \) is estimated from the measured stator currents and voltages, \( i_{s,abc} \) and \( v_{s,abc} \). The rotor flux dq components \( \lambda_{dr} \) and \( \lambda_{qr} \) are obtained using the control angle \( \theta \) and the measured stator and rotor currents \( i_{s,abc} \). The RSC control obtains the rotor voltages to regulate the rotor flux.

The q component of the flux reference \( \lambda_{qr} \) is zero so that the rotor flux is oriented along d-axis of the rotating dq reference frame, and the d component \( \lambda_{dr} \) is given by a voltage regulator. From the errors between those references and the estimated components \( \lambda_{dr} \) and \( \lambda_{qr} \), the components of the desired rotor voltage \( v_{dr} \) and \( v_{qr} \) are obtained. From there, the instantaneous rotor voltages \( v_{r,abc} \) that will be modulated by the RSC are found using the control angle \( \theta \) and the rotor position \( \theta_r \) that is measured by the DFIG shaft encoder.

The GSC control employs the conventional voltage-oriented control to maintain a constant DC bus voltage \( V_{dc} \) and unity power factor at the converter output, based on the grid voltage angle \( \theta_{PLL} \) obtained through a PLL [28].

Finally, Table 1 provides an overview of the different controllers and how they are related based on their input and output signals, and also where their detailed control schemes can be found through the paper.

### III. DFIG MODEL

The electrical equations of an induction machine in a reference frame rotating at the speed of \( \omega \) are

\[
\begin{align*}
\dd{\bar{v}_s} &= -R_s \bar{v}_s + \frac{d\lambda_s}{dt} + j\omega \lambda_s \\
\dd{\bar{v}_r} &= R_r \bar{i}_r + \frac{d\lambda_r}{dt} + j(\omega - \omega_r) \lambda_r
\end{align*}
\]

(1)

where \( \bar{v}_s, \bar{\lambda}_s, \) and \( \bar{i}_s \) are the space vectors of the stator voltage, flux and current, respectively, and \( R_s \) is the stator winding resistance per phase. While \( \bar{v}_r, \bar{\lambda}_r, \) and \( \bar{i}_r \) are the space vectors of the rotor voltage, flux and current, respectively, and \( R_r \) is the rotor resistance and \( \omega_r \) is the electrical rotational speed of the rotor. Note that in Fig. 1 the reference for the current \( \bar{i}_s \) is outgoing from the stator terminals and the reference for the current \( \bar{i}_r \) is incoming to the rotor terminals.

### A. TORQUE AND REACTIVE POWER

The electromagnetic torque of the DFIG is proportional to the product of the magnitude of the flux vectors \( \lambda_s \) and \( \lambda_r \) and the sine of the angle \( \delta \) between both vectors [28]

\[
T_e = \frac{3}{2} p \left( \frac{L_m}{\sigma L_s L_r} \right) \lambda_s \lambda_r \sin \delta
\]

(5)

where \( p \) is the number of pole pairs.
On the other hand, the reactive power can be expressed, according to [28], as
\[
Q_s = \frac{3}{2} \left( \frac{\omega}{\sigma L_s} \right) \lambda_s \left( L_m \lambda_r \cos \delta - \lambda_s \right)
\] (6)
where \( \omega \) is the stator angular frequency. Namely, the reactive power is proportional to the product of the stator flux and the difference between the projection of the rotor flux over the stator flux.

**B. INTERNAL EFM AND VECTOR DIAGRAM**

Developing the last term of the stator equation in (1), by using the first equation of (2) and the second of (3)
\[
\vec{v}_s = -R_s \vec{i}_s + \frac{d\vec{\lambda}_s}{dt} - j\omega \sigma L_s \vec{i}_s + j\omega L_m \vec{\lambda}_r
\] (7)

Then, defining the generator internal electromotive force (emf) as
\[
\vec{e}_s = j\omega L_m \vec{\lambda}_r
\] (8)

The equation (7) can be written as
\[
\vec{v}_s = -R_s \vec{i}_s + \frac{d\vec{\lambda}_s}{dt} - j\omega \sigma L_s \vec{i}_s + \vec{e}_s
\] (9)

In steady state \( d\vec{\lambda}_s/dt = 0 \) and the former equation stands as
\[
\vec{v}_s = -R_s \vec{i}_s - j\omega \sigma L_s \vec{i}_s + \vec{e}_s
\] (10)

Or, in a different way
\[
\vec{e}_s = (R_s + j\sigma X_s) \vec{i}_s + \vec{v}_s
\] (11)

here \( X_s = \omega L_s \) is the stator reactance.

**FIGURE 2. DFIG vector diagram.**

Fig. 2 shows the DFIG vector diagram, neglecting the stator resistance. Note that the stator resistance is usually smaller than 0.01 p.u. The stator voltage vector \( \vec{v}_s \) is taken as the phase reference and the stator current lags an angle of \( \varphi \), indicating that the machine works as a generator delivering active and reactive power to the grid. Neglecting the stator resistance, the stator flux vector \( \vec{\lambda}_s \) lags the stator voltage by an angle of 90° and the rotor flux vector \( \vec{\lambda}_r \) is obtained from the first equation of (3) as
\[
\vec{\lambda}_r = \frac{L_r}{L_m} (\vec{\lambda}_s + \sigma L_r \vec{i}_s)
\] (12)
leading the stator flux by an angle of \( \delta \), which is the torque angle, and the modulus of its projection over \( \vec{\lambda}_r \) is a magnitude higher than \( \lambda_s \), \( \left( \frac{L_r}{L_m} \lambda_r \cos \delta > \lambda_s \right) \), indicating that the reactive power is positive, according to (6). Both conditions determine that the DFIG behaves as a generator injecting active and reactive power to the grid. According to (8) the emf \( \vec{e}_s \) leads 90° to \( \vec{\lambda}_r \), and therefore the angle between the emf and the stator voltage is equal to the torque angle \( \delta \).

Defining a \( d \) axis aligned along \( \vec{\lambda}_r \) and \( q \) axis along \( \vec{e}_s \), the analogy of the DFIG with the SG is clearly stated, where the excitation current produces the rotor flux in the direct axis, which induces an emf in the quadrature axis (see Fig. 2).

To continue with the analogy, the expressions for the active and reactive power generated at the stator of the DFIG in steady state will be obtained as follows.

Multiplying (5) by \( \omega/p \) yields
\[
P_e = \frac{3}{2} \left( \frac{1}{\sigma L_s} \right) \lambda_s e_s \sin \delta
\] (13)
where \( P_e \) is the DFIG airgap power.

In steady state, neglecting the voltage drop in \( R_s \), \( \lambda_s = v_s/\omega \), and the airgap power is equal to the stator power
\[
P_s = \frac{3}{2} \left( \frac{1}{\sigma X_s} \right) v_s e_s \sin \delta
\] (14)

In the same way, in steady state (\( \lambda_s = v_s/\omega \)), neglecting \( R_s \), expression (6) can be written as
\[
Q_s = \frac{3}{2} \left( \frac{v_s}{\sigma X_s} \right) (e_s \cos \delta - v_s)
\] (15)

In (14), the stator active power is positive if the emf vector leads the voltage vector. To increase the stator power, the speed reference \( \omega \) has to increase beyond the grid angular speed \( \omega_s \), producing an increment of the torque angle \( \delta \). On the other hand, in (15), the reactive power can be controlled by modifying the emf magnitude, \( e_s \). If the projection of the emf vector onto \( \vec{v}_s \) is higher than the magnitude \( v_s \), the reactive power is positive, and this can be incremented by increasing the emf magnitude.

**IV. DFIG GRID-FORMING CONTROL**

Next, the proposed DFIG GFM control based on the rotor flux orientation is presented. This section is divided in two subsections: a) torque synchronizing loop and b) rotor side converter control.
A. TORQUE SYNCHRONIZATION LOOP

As it is shown in Fig. 1, the synchronizing loop allows to obtain the control angle \( \theta \), which determines the position of the rotating axis dq over a stationary reference frame, from the difference between the reference torque \( T_e^* \) and the actual torque \( T_e \). The dq axis rotational speed is equal to \( \omega \) (see Fig. 2) and it is obtained as the sum of the reference speed \( \omega_0 \) (which is the grid nominal frequency) and \( \Delta \omega \). The frequency increment is obtained from the swing equation, using a parameter \( J \), which represents the inertia constant of the VSM in seconds and a parameter \( D \), which represents the damping constant in p.u., which represents the rate of change of the frequency increment over nominal \( \Delta f / f_n \) and the power increment over nominal \( \Delta P / P_n \). The control angle \( \theta \) is obtained through the integration of \( \omega \), which in turn is obtained as the sum of \( \Delta \omega \) and the nominal frequency \( \omega_0 \).

\[
\frac{1}{\omega_0} \frac{d \Delta \delta}{dt} = (\Delta \omega - \Delta \omega_s)
\]

where \( \Delta \omega \) and \( \Delta \omega_s \) are the increments of the dq axis angular frequency and the stator frequency respectively, in p.u. As shown in Fig. 4, the torque increment \( \Delta T_e \) depends on \( \Delta \delta \) by the function \( T_e(\delta) \).

where \( K_s \) is the synchronizing torque, which is obtained by calculating in (5) the partial derivative of \( T_e \) with respect to \( \delta \) in the equilibrium point as follows

\[
K_s = \left( \frac{\partial T_e}{\partial \delta} \right)_0 = \left( \frac{L_m}{\sigma L_s L_r} \right) \lambda_s \lambda_t \cos \delta_0
\]

This equation does not include the factor \( (3/2)p \) because the torque \( T_e \) is expressed in p.u.

Taking the DFIG parameter values of Appendix and assuming that at the equilibrium point the stator and rotor fluxes are close to one, \( \lambda_s = \lambda_r = 1 \) p.u., the synchronizing constant is equal to \( K_s = 4.2 \) p.u. This value is much higher than that of a SG, which is close to one [29]. This means that in a DFIG, power is transmitted with a smaller torque angle.

Considering the block diagram of Fig. 4 and using the synchronizing torque \( K_s \), the transfer function between the angle \( \Delta \delta \) and the reference torque \( \Delta T_e^* \) is equal to

\[
\frac{\Delta \delta}{\Delta T_e^*} = \frac{\omega_0}{Js^2 + Ds + K_s \omega_0}
\]

which is analogous to the oscillation equation of a SG.

The choice of the parameters \( D \) and \( J \) is not free. The damping constant \( D \) affects the torque increment produced by a frequency increment. Being the inverse of the droop constant \( D = 1/R \), for a typical value of \( R = 0.05 \) p.u., the damping constant is \( D = 20 \) p.u., which indicates that under a stator frequency increment of 0.05 p.u. (2.5 Hz in a 50Hz grid), the DFIG must increase the torque by 1 p.u. Appendix gives the values of \( D \) and \( J \) chosen for obtaining a damping factor equal to \( \xi = 0.707 \).

B. ROTOR SIDE CONVERTER CONTROL

The objective of the conventional control of the RSC is to regulate the DFIG torque and stator reactive power through the control of the rotor current. The control scheme proposed here also regulates the DFIG torque and stator reactive power, but through the control of the angle and magnitude of the rotor flux. In this way, the DFIG behaves as a voltage source unlike with the conventional control. Also, another important advantage is that during isolated operation for black-start, the torque developed by the DFIG is determined by the supplied load, and therefore the torque developed by the DFIG will not be equal to the reference torque. In the proposed control, this error is adjusted through the torque-frequency droop relationship of the synchronizing loop. The same happens with the reactive power. The reactive power supplied by the DFIG must be equal to the reactive power demanded by the load. For this purpose, a reactive-voltage droop control will set the reactive power reference to obtain the reactive power demanded by the load.

Expression (5) shows a nonlinear relationship between the torque \( T_e \) and the angle \( \delta \). By linearizing this equation, the following linear relationship between torque and angle is obtained

\[
\Delta T_e = K_s \Delta \delta
\]
To avoid the offset due to unknown initial condition in the integration, the integral is approximated by a first order filter with a cutoff frequency close to 1 Hz [30], [31]. This produces an error at low frequency, but the error is very small for the estimation of the stator flux at the grid frequency (50 Hz). Torque estimation $T_e$ is calculated as the cross product of the components of the stator flux vector and the stator current [28] as

$$T_e = \frac{3}{2} p (\lambda_{as} i_{bs} - \lambda_{bs} i_{as})$$

(21)

The components of the rotor flux in a stationary reference frame are calculated according to (12) as

$$\lambda_{ar} = \frac{L_r}{L_m} (\lambda_{as} + \sigma L_s i_{as})$$

$$\lambda_{br} = \frac{L_r}{L_m} (\lambda_{bs} + \sigma L_s i_{bs})$$

(22)

Rotor flux vector, $\lambda_{dr} + j\lambda_{qr}$, in a rotating reference frame is then calculated by applying the operator $e^{-j\theta}$ to the vector $\lambda_{ar} + j\lambda_{br}$ obtaining the following expression

$$\lambda_{dr} = +\lambda_{ar}\cos\theta + \lambda_{br}\sin\theta$$

$$\lambda_{qr} = -\lambda_{ar}\sin\theta + \lambda_{br}\cos\theta$$

(23)

where $\theta$ is the reference axis angle.

Once the components of the rotor flux in dq axis have been estimated, the control takes place to maintain the rotor flux vector oriented along the d axis of the rotating reference frame. Fig. 5 shows the angular position of the stator and rotor fluxes, the dq reference frame, rotating at an angular speed of $\omega$, and the torque angle $\delta$ and control angle $\theta$.

When the rotor flux space vector $\lambda_r$ is aligned along the d axis, the DFIG is operating in synchronism. To reach the alignment, it is required to control $\lambda_r$ through the rotor voltage $v_r$.

The dynamic equation of $\lambda_r$ presented in (1) can be written as

$$\frac{d\lambda_r}{dt} = v_r - R_r i_r - j\omega L_m i_r$$

(24)

Separating the real and imaginary parts of this equation, it is obtained that the direct component of the rotor flux can be controlled through the direct component of the rotor voltage, and the quadrature component of the rotor flux through the quadrature component of the rotor voltage.

Voltage drop in $R_r$ can be neglected, because this resistance is usually smaller than 0.01 p.u. Also, in (24) there are cross components of the rotor flux, that depend on the slip, affecting the rotor flux dynamics. But these cross components can be easily compensated through the corresponding feedforward signals.

![Stator and Rotor Flux Vector Diagram and dq Axis](image)

![Rotor Flux Control](image)

The rotor flux control scheme is given in Fig. 6. In the q axis, the commanded signal $\lambda_{qr}^*$ allows for the alignment of $\lambda_r$ along the d axis. The error in $\lambda_{qr}$ is then corrected by a PI controller that obtains the corresponding rotor voltage component $v_{qr}$. The direct rotor voltage component is obtained in the same way to maintain the reference direct rotor flux $\lambda_{dr}^*$ (equal to the magnitude of the rotor flux vector $\lambda_r^*$ when the vector is aligned) by comparing it to the feedback signal $\lambda_{dr}$. The outputs of both PI controllers are the dq components of the rotor voltage space vector $\lambda_r$.

Applying the inverse Park transformation to these components, using the slip angle ($\theta_{slip} = \theta - \theta_r$), rotor voltage phase components $v_{ar}$, $v_{br}$, and $v_{cr}$ are obtained, and using pulse width modulation (PWM) the IGBTs trigger signals are finally obtained. As stated before, the slip angle is obtained as the difference between the control angle $\theta$ obtained in the synchronization loop, and the rotor angle $\theta_r$ measured by an encoder coupled to the DFIG shaft.

The reference rotor flux magnitude $\lambda_r^*$ is set to reach the required DFIG magnetization. In grid-connected systems,
when \( \lambda_r \) increases, the stator reactive power \( Q_s \) injected to grid also increases. In an isolated system, the DFIG must maintain the voltage, and therefore the rotor flux magnitude reference is obtained by a voltage controller. Fig. 7 shows the voltage control scheme. A droop control is used to obtain an equitable reactive power sharing between the wind turbines in a wind farm. Consequently, a certain voltage error is obtained, depending on the value of the droop constant \( k_v \). Being \( V_r \) the voltage at the common bus (PCC), the voltage error obtained in each wind turbine is the same, which thus will produce the same rotor flux increment, that according to (15) will produce the same reactive power injection by each wind turbine. \( \lambda_{r,0} \) is a feed-forward signal whose value in p.u. corresponds to the rotor flux required to obtain the nominal stator voltage at no-load. Also, as it will be shown later, this feed-forward signal can be used to compensate the voltage error at the PCC.

V. WIND TURBINE CONTROL

The objective of variable speed wind turbine control [30] is the maximum power point tracking (MPPT), by changing the wind turbine rotational speed \( \omega_r \) according to the incoming wind velocity. Fig. 8 shows the wind turbine power \( P_m \), in p.u., as a function of the rotational speed \( \omega_r \), in p.u., for different wind velocities, in m/s, for a pitch angle of \( \beta = 0^\circ \). This relationship has been obtained for a wind turbine model with the characteristic function \( C_p(\lambda, \beta) \) given in Appendix.

Fig. 8 also shows the loci of maximum power points for the different wind velocities. This MPPT curve allows to obtain the torque of maximum power \( T^*_e \), from the rotational speed \( \omega_r \), up to the maximum rotational speed \( \omega_{r,max} \), which has been fixed at 1.3 p.u., being 1 p.u. the synchronous speed. Namely, the slip at that speed is \( s = -0.3 \). It can also be observed that the speed variation is symmetrical respect to synchronous speed, being the minimum rotational speed equal to 0.7 p.u. \( (s = +0.3) \).

In a grid connected system, the control strategy consists in tracking the maximum power point, as indicated in Fig. 9, until the maximum rotational speed is reached. Then, when the wind turbine nominal power is reached, if wind velocity increases the pitch control acts increasing the pitch angle \( \beta \) to reduce the wind turbine torque to control the rotational speed, limiting in this way the wind turbine rotational speed and power. The pitch control scheme is given in Fig. 28 of Appendix.

In an isolated system, the generator power must be equal to the power demanded by the load and the wind turbine must supply the load power to the generator. To obtain such power balance, the wind turbine control is now based on the wind turbine speed regulation.

The generator supplies the power demanded by the load and opposes a braking torque to the wind turbine. The wind turbine speed regulation allows to obtain the wind turbine torque that balances the generator braking torque and in this way the wind turbine supplies the power demanded by the load to the generator. The wind turbine speed regulation scheme to perform such adjustment is represented in Fig. 9.

In the regulation scheme of Fig. 9, a maximum rotational speed is set as reference. The mechanical torque \( T_m \) developed by the wind turbine depends on wind velocity \( v_w \), rotational speed \( \omega_r \), and pitch angle \( \beta \). As stated before, the generator torque \( T_e \) depends on the load power. The difference between both torques produces the rotor acceleration, that also depends on the inertia constant \( J = 2H \), which is the sum of the inertia constant of the wind turbine and the generator (see Appendix). The speed controller will set the pitch angle required for the wind turbine torque to equal the generator torque, maintaining constant rotational speed. For wind velocities under nominal, the maximum power that the wind turbine can supply is given by the MPPT characteristic of Fig. 9, that now represents the stability limit of wind turbine – generator group. Namely, if the power demanded by the load is higher than the maximum power for the current wind velocity, the pitch angle will reach its optimal position (close to zero). From there it will not be possible to extract more power from the current incoming
wind. Therefore, being the generator torque higher than the wind turbine torque, the wind turbine will decelerate until stopping. Obviously, the generator can supply a given load only if the wind velocity is high enough to obtain such power.

In the TSL scheme of Fig. 4, a torque command equal to 0.5 p.u. is established. If the generator torque, produced by the power demanded the load, is equal to 0.5 p.u., $\Delta \omega = 0$, and the DFIG will generate the nominal frequency $\omega = \omega_0$. If the load power increases, the DFIG torque will also increase and there will be a torque error that will produce a frequency drop. The DFIG will supply the power demanded by the load at a frequency given by the droop characteristic torque-frequency according to the droop constant $R = 1/D$.

In a wind farm, the TSL also allows for maintaining the synchronism between the DFIGs, while at the same time the droop characteristic allows for the load sharing between the generators of the wind farm. Generally, the generators will reach the synchronism at a frequency different from nominal $\omega_0$, except when the torque produced by the load is exactly equal to the reference torque. In steady state, $\Delta \omega$ must be the same for all the generators, so given the same droop constant $R$, all the generators supply the same power.

If nominal frequency was required independently of the load, a secondary frequency regulation can be employed based on an integral control action that modifies the reference frequency $\omega_0$ so that for the frequency increment $\Delta \omega$ obtained in the droop characteristic, the output frequency is nominal. This regulation scheme will be presented in the next section.

VI. WIND FARM DESCRIPTION AND CONTROL

This section introduces the electrical scheme of the wind farm and the proposed secondary control system for the regulation of the voltage and frequency at the PCC, during the black-start process with the wind farm supplying a dynamic load.

A. WIND FARM DESCRIPTION

Fig. 10 shows the electrical scheme of a wind farm made of two DFIG wind turbines, like the one shown in Fig. 1, connected in parallel to the PCC, through three windings step-up transformers $T_1$ and $T_2$ (20kV/0.69kV/0.4kV).

The proposed GFM control is applied to the DFIGs. In the PCC there is a switch $SW_1$, for the connection to the main grid, after checking for the synchronism conditions are met. Namely, that voltages at both sides of the switch should have the same amplitude, frequency, and phase angle. During back-start, switch $SW_1$ is open and both wind turbines maintain constant voltage and frequency at the PCC, feeding the dynamic load (an induction motor) through an electrical line, represented by its $\pi$ model, and a step-down transformer $T_3$ (20kV/0.69kV). At the motor terminals, there is a switch $SW_2$, that allows to analyze the black-start process in two situations.

First, when the switch is closed while building the voltage and second, when the switch is initially open and once the voltage is built the switch is closed. In the last case, the wind farm must withstand the direct starting of the induction motor.

B. VOLTAGE AND FREQUENCY CONTROL AT THE PCC

During the black-start process the wind farm is not connected to the main grid. Therefore, the voltage and frequency control at the PCC must be done by the wind turbines without the support of any other auxiliary generation source.

In islanding operation, the wind turbines are synchronized between them through the TSL and they operate at a frequency that, in general, will not be the nominal frequency, as it was explained in the previous section. Also, the droop voltage control of Fig. 7 allows an equitable sharing of the reactive power demanded by the load between the generators, but at the cost of maintaining a voltage error at the PCC. Although this control mode is admissible during the system restoring after a black-out, a secondary regulation scheme for frequency and voltage is presented hereafter to achieve the operation at nominal frequency and voltage at the PCC.

As it is shown in Fig. 11, secondary regulation is done through measuring the voltage $V_{pcc}$ and frequency $\omega_{pcc}$ at the PCC by means of a phase locked loop (PLL). The voltage is built gradually by ramping the reference $V^*_{pcc}$ to avoid the inrush current of the transformers. The voltage secondary regulation uses an integral controller with a time constant $T_i$ that produces a signal $\lambda_{r0}$ that it is sent to the DFIGs voltage controllers. According to (8), the DFIG internal emf is proportional to the $\lambda_{r0}$. In this way, the voltage secondary regulation will modify the DFIGs internal emf until the voltage error at the PCC is zero $V^*_{pcc} = V_{pcc}$. However, due to the voltage drop in the step-up transformers, at the wind turbines terminals there is still a voltage error, allowing the reactive power sharing between them.

Fig. 12 shows the relationship between rotor flux reference $\lambda_r^*$ and voltage error $\Delta V_s$, according to the following
expression, as given also in Fig. 7

$$\lambda^*_r = \lambda_{r0} - k_r \Delta V_s$$  \hspace{1cm} (25)

where $\Delta V_s = V_s - V^*_s$.

Fig. 12 shows the droop characteristic. Flux reference is obtained as a function of the voltage deviation. Then, as the reactive power is a function of the rotor flux $\rho_D$ (6), the same reactive power is obtained in each wind turbine under the same voltage deviation. Under secondary control, $\lambda_{r0}$ is modified affecting the voltage deviation at the wind turbines until the nominal voltage is obtained at the PCC.

Secondary frequency control at the PCC is done in a similar way. The difference between frequency reference $\omega^*_{pcc}$ and measured frequency $\omega_{pcc}$ is processed in an integral controller with a time constant $T_w$, producing a frequency signal $\omega_0$ that is sent to each wind turbine controller. An increment of $\omega_0$ means an increment of the frequency generated by each DFIG for any given load. In this way, frequency error due to load variations is compensated and the secondary frequency control then guarantees that $\omega^*_{pcc} = \omega_{pcc}$.

\[ \omega = \omega_0 - \frac{\Delta T_e}{D} \]  \hspace{1cm} (26)

where $\Delta T_e = T_e - T^*_e$.

Without secondary frequency regulation, frequency is a function of torque deviation $\Delta T_e$ with respect to reference $T^*_e$ for a given droop constant $R = 1/D$ and reference frequency $\omega_0$. Fig. 13 also shows that by modifying reference frequency, for a given torque deviation, generated frequency can be nominal.

Also, Fig. 13 shows that it is possible to increase the load in one turbine by reducing that turbine droop constant. In the example of the figure, the wind turbine with a smaller droop constant, in blue, will assume a higher load, as frequency must be the same in both wind turbines.

VII. SIMULATION RESULTS

The assessment of the black start capability of the proposed VSM-based control of the DFIG has been done through simulation. A comprehensive model of the DFIG, the proposed control system and a simulation benchmark has been employed in the simulation for demonstrating such capability. Fig. 10 denotes the scheme of the simulated system, already described above. The main parameters of the simulated system are given in the Appendix.

Simulation results presented below include the energization of the system while starting an induction motor and start-up of the motor after the system voltage has been built. Simulation results validate the proposed DFIG rotor flux orientation-based control system for system restoring after a black-out. These simulations have been performed using PSIM software.

A. MOTOR START-UP DURING SYSTEM ENERGIZATION

The first test consists of starting a dynamic load (an induction motor) during the system energization. In the general scheme of Fig. 10, SW2 is closed, while SW1 is open. Moreover, in order to prevent the inrush current from the transformers and the induction motor, the system energization is done by
applying the voltage gradually, i.e., the voltage generated by the DFIGs is ramped-up and built in 3 seconds. Wind turbines are operating at a wind velocity over nominal.

**FIGURE 14. Terminal voltages at each WT and at the PCC.**

Fig. 14 shows the voltage magnitude at each wind turbine and at the PCC. After the voltage is built, a mechanical load is applied to the motor at t=4 s, producing a voltage drop. Fig. 19 shows the motor rotational speed and torque. The motor is started at no-load reaching nearly synchronous speed. At t=4 s, when the mechanical load is applied, the motor slip increases, so rotational speed drops. This figure also shows the accelerating torque and the motor torque after the mechanical load is applied.

**FIGURE 15. Active power generated by wind turbines P1, P2 and active power demanded by the motor.**

On the other hand, Fig. 15 shows the active power delivered by each wind turbine and the active power delivered at the PCC, which is about the sum of the power from each wind turbine. In the simulation, different droop constants have been used in each wind turbine to demonstrate the flexibility of the proposed control system. Accordingly, the active power delivered by each wind turbine is different. Fig. 16 also shows that the power is initially used for accelerating the motor, so once the motor has started-up the power drops to nearly zero. At t=4 s, when the motor is loaded, the power increases again to supply such load.

**FIGURE 16. Reactive power generated by wind turbines Q1, Q2 and reactive power demanded by the motor.**

Fig. 16 shows the reactive power delivered by each wind turbine and the reactive power delivered at the PCC. Here, once the motor has started-up, it demands the no-load reactive power.

At t=4 s, when the motor is loaded, the reactive power increases, as the motor reactive power increases with the slip. Also, as in the torque control loops, different droop constants have been employed for voltage control in each wind turbine to demonstrate the flexibility of the proposed control system. Accordingly, the reactive power delivered by each wind turbine is different.

**FIGURE 17. Frequency at PCC.**

Fig. 17 shows the system frequency as measured at the PCC. Wind turbines start at the reference frequency of 50 Hz, but as soon as they start being loaded, frequency drops, as per the synchronization loop. At t=3 s., when the motor has started-up with no-load, nominal frequency is restored. Then, at t=4 s. frequency drops again when the load is applied.

**FIGURE 18. Wind turbine 1 pitch angle, rotational speed and mechanical and electrical torque.**

Finally, Fig. 18 shows the main variables of one wind turbine. At the top, the pitch angle is regulated to control the wind turbine rotational speed, as per the control scheme of Fig. 9. The torque developed by this wind turbine for the given wind velocity and regulated pitch angle is shown at the figure of the bottom, together with the resulting rotational speed, considering the braking torque exerted by the DFIG, also shown in the figure. These results demonstrate the
mechanical stability of the proposed control scheme for the wind turbine when supplying a varying load.

Following the testing, these figures also show the activation of the voltage and frequency secondary regulation, as given in the control scheme of Fig. 11. Although for the system energization the operation at nominal voltage and frequency is not relevant, these secondary controls have been added to demonstrate such capability. Therefore, at t=5 s, the secondary control is activated taking the PCC voltage and frequency to nominal, as can be observed in Fig. 14 and 17. For this purpose, the secondary frequency control increases the reference frequency so that the resulting frequency for the current wind turbine load is the nominal frequency (see Fig. 17). And on the other hand, the centralized voltage control increases the reference rotor flux so that the resulting voltage at the PCC is the nominal voltage (see Fig. 14). Consequently, small disturbances can be observed in the active and reactive powers and motor speed and torque when the secondary regulation is activated at t=5 s.

Finally, at t=7 s, the islanded system is connected to another energized system by closing SW1 in Fig. 10. To close the switch, the following conditions must be met: same voltage magnitude, frequency and phase angle at both sides of the switch. In practice, there would be a small frequency difference, so one voltage wave is moving in relation to the other and the switch is closed when the phase angle difference is zero. In the simulation this condition is met at t=7 s, and figures show the disturbances produced in the presented variables. Mainly in the PCC frequency, which oscillates until both systems run in synchronism. The frequency disturbance in turn affects the wind turbines active and reactive powers and torque, as it can be observed in Fig. 15, 16 and 17, and also the motor torque (Fig. 19). In any case, simulation results demonstrate the ability of the proposed control system to maintain the synchronism after the switch is closed and the system is no longer isolated.

B. MOTOR DIRECT STARTING

The purpose of this test is to assess the robustness of the proposed control system when the motor is started once the voltage is built at the PCC, so the wind turbines have to withstand the inrush currents of the motor starting. Fig. 20 shows how the voltage is first built in 2 s and then SW2 is closed at t=2.5 s.

First, it has to be pointed out that because the voltage is built at no-load, the wind turbine control can follow the reference voltage ramp precisely, unlike in the previous test. As expected, the switch closing for the direct starting of the motor produces a high disturbance in both the voltage magnitude and frequency, as can be observed in Fig. 20 and Fig. 21.

Fig. 21 shows the frequency at the PCC. As a result of the proposed synchronization loop, frequency changes following the wind turbine torque to maintain both wind turbines in synchronism. This result demonstrates the ability of the proposed control system to maintain the system stability even during such high disturbance.

Fig. 22 shows the motor rotational speed and torque during the direct starting. Note that the motor is first started at no-load and then loaded at t=4 s. The motor torque shows the typical development of a motor starting torque. Synchronous speed is reached at the end of the starting and the slip increases when the motor is loaded. The motor loading causes a second disturbance in the voltage magnitude and frequency, but not as high as during starting.

Fig. 23 and Fig. 24 show the active and reactive powers delivered by each wind turbine and at the PCC.
Figures show that the wind turbines supply the active and reactive powers demanded by the load, following the evolution of the motor starting and loading.

Fig. 25 shows pitch angle, rotational speed and torque and the braking torque of the DFIG in one of the wind turbines. This figure does not differ much from the previous case, although the wind turbine torque is now affected by the motor direct starting, but due to the high inertia of the wind turbine, the wind turbine rotational speed, torque and pitch angle are hardly affected.

Finally, Fig. 26 shows, at the top, the rotor power injected to the grid through the GSC in the second wind turbine during the loading of the motor. In Fig. 26, as the wind turbine is running at super-synchronously with \( s = -0.3 \), rotor power is approximately 23\% of the wind turbine total power, shown in Fig. 23. On the other hand, at the bottom of Fig. 26, the rotor voltage applied by the RSC is shown.

VIII. CONCLUSION

This paper has demonstrated the ability of DFIG based wind turbines to contribute to power system restoration after a blackout. Black-start capability demands the application of grid forming control to the DFIG, in order to be able to control voltage and frequency in the islanded system after a blackout. A novel grid forming control for DFIG, based on rotor flux orientation, has been employed.

Rotor flux angle is obtained through the emulation of the synchronous generator swing equation, while rotor flux magnitude is obtained through a voltage controller. Then, rotor flux angle and magnitude can be controlled through the rotor voltage applied by the RSC.

The paper also proposes the wind turbine control scheme for supplying an isolated load, based on the wind turbine speed regulation for balancing the power at wind turbine shaft.

The performance of the proposed control system has been validated through simulation using comprehensive simulation models. The simulation benchmark includes a wind farm made of two wind turbines supplying a dynamic load, an induction motor, through a feeder. Simulation results prove the grid forming capability of the proposed control system. The wind farm is able to build the PCC voltage and supplying the dynamic load maintaining constant voltage and frequency while maintaining both wind turbines in synchronism. Also, the proposed control system allows for the equitable active and reactive power sharing between the wind turbines, based on droop controllers.

A secondary control has also been proposed for the operation at nominal frequency and voltage at the PCC.
Moreover, the system stability has been tested during a strong disturbance, like the direct starting of the induction motor. And, the synchronization to a main grid has also been successfully tested. Results show that once the synchronization conditions are met and the switch is closed, the proposed control system swaps from isolated to grid connected mode automatically, without switching any internal state.

### APPENDIX

#### WIND TURBINE AND DFIG PARAMETERS

**FIGURE 27.** WT power performance coefficient.

**FIGURE 28.** Blade pitch actuator block diagram.

| TABLE 2. DFIG parameters. | PARAMETER | SYMBOL | VALUE | UNITS |
|----------------------------|-----------|--------|-------|-------|
| Rated power                | \( P_w \) | 1500   | kW    |       |
| RSC and GSC power rating   | \( P_r \) | 500    | kW    |       |
| Rated stator voltage       | \( V_s \) | 690    | V     |       |
| Stator frequency           | \( f_s \) | 50     | Hz    |       |
| Poles pair number          | \( p \)  | 2      |       |       |
| Slip range                 | \( s \)  | ±1/3   | p.u.  |       |
| Rotor resistance           | \( R_r \) | 3.46   | mΩ    | (0.0109 p.u.) |
| (referred to stator)       |           |        |       |       |
| Magnetization inductance   | \( L_m \) | 3.33   | mH    | (3.3 p.u.) |
| (3.3 p.u.)                 |           |        |       |       |
| Stator leakage inductance  | \( L_s \) | 0.116  | mH    | (0.115 p.u.) |
| (referred to stator)       |           |        |       |       |
| Rotor leakage inductance   | \( L_{sr} \) | 0.116 | mH    | (0.115 p.u.) |
| (referred to stator)       |           |        |       |       |
| Moment of inertia          | \( J \)  | 650    | kg m² |       |
| Voltage drop constant WT1  | \( K_{s1} \) | 0.20 | p.u.  |       |
| Voltage drop constant WT2  | \( K_{s2} \) | 0.40 | p.u.  |       |
| Power drop constant WT1    | \( 1/D_1 \) | 0.059 | p.u.  |       |
| Power drop constant WT2    | \( 1/D_2 \) | 0.085 | p.u.  |       |

**TABLE 3.** Blade pitch actuator parameters.

| PARAMETER | SYMBOL | VALUE | UNITS |
|-----------|--------|-------|-------|
| Gain      | \( b \) | 2.5   | degree/sec |
| Time constant | \( b_0 \) | 2.5 | sec |
| Minimum pitch angle | \( \beta_{min} \) | 0 | degree |
| Maximum pitch angle | \( \beta_{max} \) | 45 | degree |
| Minimum speed | \( \beta_{min} \) | -10 | degree/sec |
| Maximum speed | \( \beta_{max} \) | +10 | degree/sec |

**TABLE 4.** Induction motor parameters.

| PARAMETER | SYMBOL | VALUE | UNITS |
|-----------|--------|-------|-------|
| Power rating | \( P_m \) | 1.0 | MW |
| Rated voltage | \( V_m \) | 690 | V |
| Stator resistance | \( R_s \) | 19 | mΩ |
| Rotor resistance | \( R_{r} \) | 33.3 | mΩ |
| Magnetization inductance | \( L_m \) | 1.41 | Ω |
| Stator leakage reactance | \( X_{s} \) | 33.3 | mΩ |
| Rotor leakage reactance | \( X_{r} \) | 33.3 | mΩ |
| Inertia constant | \( J \) | 24.32 | kg m² |
| Number of poles | \( 2p \) | 4 | |

**TABLE 5.** Line and transformers parameters.

| PARAMETER | SYMBOL | VALUE | UNITS |
|-----------|--------|-------|-------|
| T1: Power rating | \( S_1 \) | 2 | MVA |
| T1: Rated line-line voltage primary | \( V_{1N} \) | 20 | kV |
| T1: Rated line-line voltage secondary | \( V_{2N} \) | 0.69 | kV |
| T1: Short-circuit ratio | \( Z_{SC} \) | 10 | % |
| T1: X/R ratio | \( X/R \) | 15 | p.u. |
| T1: Frequency | \( f \) | 50 | Hz |
| T3: Power rating | \( S_3 \) | 2.5 | MVA |
| T3: Rated line-line voltage primary | \( V_{1N} \) | 20 | kV |
| T3: Rated line-line voltage secondary | \( V_{2N} \) | 0.69 | kV |
| T3: Short-circuit ratio | \( Z_{SC} \) | 8 | % |
| T3: X/R ratio | \( X/R \) | 15 | p.u. |
| T3: Frequency | \( f \) | 50 | Hz |
| LINE: Inductance | \( X_l \) | 0.462 | Ω/km |
| LINE: Resistance | \( R_l \) | 0.329 | Ω/km |
| LINE: Susceptance | \( B_l \) | 71.314 | μS/km |

Transformers T1 and T2 have the same values:
The line has a length of 10 km

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