Improved Control Strategy for Low Voltage Ride Through Capability of DFIG with Grid Code Requirements

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Abstract

This paper deals with a protection and control strategy to enhance the low voltage ride through capability of a wind turbine driven doubly fed induction generator (DFIG). As the wind power penetration continues to increase, wind turbines are required to provide Low Voltage Ride-Through (LVRT) capability. Crowbars are commonly used to protect the power converters during voltage dips and their main drawback is that the DFIG absorbs reactive power from the grid during grid faults. According to emergency grid code requirements, wind farms should have the ability to stay connected and continue generation under external voltage failure conditions, that is, wind turbines have to keep in connection with grid and own continue reactive power supply. This paper proposes a hysteresis current control strategy for the crowbar protection and a reactive power control to satisfy the grid code requirements. Consequently, the dynamic model of double fed wind turbines is established to study the transient behavior of DFIG. Simulation results are presented to show the effectiveness of the proposed control scheme.

Keywords

Crowbar, Doubly fed induction generator, Hysteresis control, Low voltage ride through.

Nomenclature

- \( f \) Grid frequency (Hz)
- \( n_s \) Synchronous speed (rpm)
- \( \rho \) Air density (around 1.23 kg/m\(^3\) at sea level)
- \( V \) Wind velocity (m/s)
- \( A \) Swept area (m\(^2\))
- \( n_g \) Generator speed (rpm)
- \( Z_p \) Number of pole pairs
- \( V_{ds}, V_{qs} \) Stator voltage in the dq frame (V)
- \( i_{ds}, i_{qs} \) Stator current in the dq frame (A)
- \( i_{dr}, i_{qr} \) Rotor current in the dq frame (A)
- \( \phi_{ds}, \phi_{qs} \) Stator flux in the dq frame (Vs)
- \( L_s \) Stator inductance (H)
- \( L_m \) Magnetising inductance (H)
- \( R_s \) Stator resistance (\( \Omega \))
- \( R_r \) Rotor resistance (\( \Omega \))
- \( J \) Inertia of the rotor and turbine (kg.m\(^2\))
- \( F \) Coefficient of friction
- \( m_i \) Modulation index of each converter phase
- \( \lambda \) Tip speed ratio
- \( R \) Radius of the blade (m)
1. Introduction

Due to the economical and environmental benefits, Wind Energy Conversion Systems (WECS) have received tremendous growth in the past decade. The increased interest in wind energy has made it necessary to model and experimentally evaluate entire WECS, so as to attain a better understanding and to assess the performance of various systems. Wind energy has been noted as the fastest growing renewable power generation technology in the world, with an annual growth rate in excess of 30% and a foreseeable penetration of 12% of global electricity demand by 2020 [1]. Due to their advantageous characteristics, most of the grid-connected wind turbines operate at a variable speed. Nowadays, the wind market is dominated by doubly fed induction generators (DFIG) with a multiple-stage gearbox, since they are able to generate controllable high power thanks to reduced rated power converters in comparison with other wind generator technologies for the same power. The steady-state performance of DFIG wind turbines under normal grid condition is now well understood [2-3]. However, as the wind power penetration continues to increase, recent grid codes require wind turbines to remain connected during grid disturbances to ride-through the grid faults. Moreover, this Low Voltage Ride-Through (LVRT) capability also requires wind turbines to supply reactive power, which helps the recovery of the grid voltage. Because of the relative small rating of the power converters, wind turbines based on the DFIG are very sensitive to grid disturbances, especially to voltage dips during grid faults.

Faults in the power system, even far away from the location of the turbine, can cause a voltage dip at the connection point of the wind turbine. A voltage dip is a sudden reduction (between 10% and 90%) of the voltage at a point in the power system, which lasts for half cycle to 1 minute. The dip in the grid voltage will result in an increase of the current in the stator windings of the DFIG. Because of the magnetic coupling between stator and rotor, this current will also flow in the rotor circuit and the power converters. So that it will cause over current in the rotor windings and over voltage in the dc bus of the power converters. When the situation after the fault is not serious enough, improved vector control strategy can provide adequate control of the DFIG during voltage dips with much smaller rotor currents and DC bus voltage. However, its capability is limited by the relatively small rating of the power converters compared to the DFIG.

When the grid fault is serious enough, the rotor current becomes too large and cannot be controlled by the power converters. Without any protection, this large current will damage the power converters. For protecting the converter, a common used solution is to connect the rotor circuit with a crowbar, which limits the high current in the rotor windings and provides a safe path for the high magnitude transient current [4-5]. This paper proposes an improved control strategy for the crowbar protection. The crowbar is activated as soon as the rotor current exceeds a threshold value and it is disconnected when the rotor currents are reduced to a secure value. So that the controllability of the DFIG will only be lost for a short time and the DFIG can resume normal operation quickly after the clearance of the grid faults. Simulation results show the effectiveness of the improved crowbar protection scheme against voltage dips.

2. Requirements and Strategies

Wind turbine capacity scale increases and when large scale wind turbine generators break from power grid, they would lost the support of voltage, lead to serious effect and cause serious impact on the stable operation of power grids. In response, many foreign power grid operators proposed a mandatory requirement LVRT. The general rules for connecting to the transmission system in Italy are given in [6], [7] and [8]. The voltage profile for the fault ride-through capability of the wind turbines is given in Fig. 1.
3. Modeling of the Wind Turbine System

Fig. 2. shows the overall schematic for DFIG based wind generation system. The system employs a back to back converter with reduced power rating.

This bidirectional power converter consists of two conventional pulse width modulated (PWM) inverters and is nowadays one of the most widely used converter topology in wind energy conversion systems. The rotor side inverter is controlled so as to extract the maximum power from the wind turbine and to regulate the reactive power transferred to the utility grid. The main objective of the grid side inverter is the control of DC link voltage regardless of the wind speed.

The DFIG is based on a wound rotor type induction machine. The torque-speed profile of a typical induction machine with a short circuited rotor is shown in Fig. 3. Thanks to the presence of a back-to-back converter that allows a bidirectional power flow between the rotor and the grid, the induction machine has two operating regions, i.e. sub synchronous and super synchronous, that correspond to rotational speed below or above the synchronous speed.

The synchronous speed of the generator in rpm is defined by

\[ n_s = \frac{f}{z_p} \times 60 \]
4. WECS- Modeling

The simulation model takes into account the dynamics of the wind turbine, the mechanical and electrical dynamics of the induction machine, and the electrical dynamics of the grid and rotor side inverters and dc bus. Owing to the slower dynamics of blade pitch control, it is assumed that the blade pitch angle remains constant and the wind speed never exceeds the rated value of 12 m/s.

4.1 Wind Turbine Model

The wind turbine is modeled by converting the aerodynamic power created by the wind into a mechanical torque that drives the induction machine [9]. The aerodynamic power, \( P_w \), is calculated using Eq. (1).

\[
P_w = 0.5 \rho \, C_p(\lambda, \beta) \, V^3 \, A
\]  

(1)

The mechanical torque is calculated with

\[
T_m = \frac{P_w}{\omega_g} = 0.5 \rho A \, C_p \, V^3 \, \frac{30}{\pi n_g}
\]

(2)

The performance characteristic, \( C_p \), is approximated with the following equation:

\[
C_p = 0.224 \left( \frac{130}{\lambda} \cdot 6.56 \right) e^{\frac{13.3}{\lambda}}
\]

(3)

4.2 DFIG Model

For a DFIG associated with a back-to-back converter on the rotor side and with the stator directly connected to the grid, an SFOC (stator flux oriented control) system is used in order to control separately the active and reactive power on the stator side. In the dq reference frame rotating synchronously with the stator flux, the stator voltages and fluxes can be written as follows [10]-[11]:

\[
V_{ds} = R_s i_{ds} + \frac{d\varphi_{ds}}{dt} - \omega \varphi_{qs}
\]

(4)
where $\omega$ is the stator flux speed. In steady state conditions, by neglecting the stator phase resistance and by introducing the magnetizing current $i_{dms} = \phi_d/L_m$, the stator voltage and current components become

$$V_{ds} \equiv 0$$

(8)

$$V_{qs} \equiv V_s \equiv \omega \varphi_{ds}$$

(9)

$$i_{ds} = \frac{L_m}{L_s} (i_{dms} - i_{dr})$$

(10)

$$i_{qs} = -\frac{L_m}{L_s} i_{qr}$$

(11)

The active and reactive powers are as follows

$$P_s = 1.5 (V_{ds} i_{ds} + V_{qs} i_{qs})$$

(12)

$$Q_s = 1.5 (V_{qs} i_{ds} - V_{ds} i_{qs})$$

(13)

By introducing (8)–(11) in (12) and (13), it is possible to rewrite the active and reactive power as function of stator voltage and rotor current components, leading to

$$P_s \equiv -1.5 \ V_s \ L_m \ i_{qr}$$

(14)

$$Q_s \equiv 1.5 \ V_s \ L_m \ \left( \frac{V_s}{2\pi f L_m} \cdot i_{ds} \right)$$

(15)

By using (14) and (15) and assuming constant stator voltage magnitude $V_s$ and frequency $f$, it is possible to consider the stator active power proportional to the q-axis rotor current component $i_{qr}$ and the stator reactive power related to the d-axis rotor current component.

On the basis of the assumptions made, electromagnetic torque of DFIG is given by

$$T_e = 1.5 \ z_p \ \varphi_{ds} \ i_{qs}$$

(16)

The mechanical dynamics of the rotor are represented by using
\[ \frac{d\omega_g}{dt} = \frac{1}{J}(T_e - F_\omega - T_m) \quad (17) \]

where \( T_m \) is the external torque input from the wind turbine.

### 4.3 Power Converters Model

Two different converter models could be used in the simulation study; a switched 3 phase PWM converter model shown in Fig. 4 and an averaged PWM converter model shown in Fig. 5. The switched model is used to simulate the fast electrical dynamics of the system and the averaged model idealizes the switching action, making it suitable for longer simulations in which the slower mechanical and wind speed dynamics are studied. With the averaged PWM converter model, the assumption is that the PWM is ideally imposed.

The ac-side voltages are therefore modelled as controlled voltage sources whose magnitude is calculated using

\[ V_i = 0.5 m_i V_{dc} \quad (18) \]

where \( m_i \) is the modulation index of each converter phase. The dc-side current is then calculated from the measured ac currents as follows

\[ I_{dc} = 0.5 (m_a i_a + m_b i_b + m_c i_c). \quad (19) \]
4.4 Modeling of Crowbar Circuit

The active crowbar is composed of three-phase diode bridge in series with a bypass resistor and an IGBT power switch. A switching function $s$ is defined for the power switch, which takes the values 1 when the switch is closed and 0 for its open state. The operation of the crowbar protection can be expressed as:

\[ \text{Activated, } s = 1 \]
\[ \text{Deactivated, } s = 0 \]

Then the crowbar protection component can be modeled by a simple equation as:

\[ V_{\text{crow}} = S_c R_{\text{crow}} I_{\text{crow}} \quad (20) \]

The behavior of such system during grid faults is greatly affected by the resistor value of crowbar. It has been shown by simulation in [12] that a small crowbar resistance leads to higher electrical torque, over currents and low rotor voltages, by contraries, high values for the crowbar resistor will result in a lower electrical torque and rotor currents but also higher rotor voltages. Therefore, the crowbar resistors should be sufficiently low to avoid large voltages on the converter terminals. On the other hand, they should be high enough to limit the rotor current. In our study, this resistance value is chosen to be equal to $30 R_r$.

5. Control for Low Voltage Ride Through

The LVRT control block diagram of the DFIG system presented in the paper is shown in Fig. 6. The rotor supply circuit comprises a grid side inverter and rotor side inverter that is linked through a dc bus. The dc bus capacitor decouples the two inverters, allowing them to be independently controlled.

![Fig.6: Control block diagram of DFIG.](https://ssrn.com/abstract=3425824)
5.1 Grid Side Converter Control

The task of the grid side inverter is to regulate the voltage of the dc bus, \( V_{dc} \). To achieve this, a voltage can be controlled by the d-axis component of the line current that affects the real power exported to or imported from the grid. The grid side converter can also be used for system power factor control by adding a reactive power loop to control the q-axis current.

5.2 Rotor Side Converter Control

The purpose of the rotor inverter is to control the generator speed to achieve maximum power from the wind over a range of wind velocities. The rotor side inverter control scheme is based on a multitiered structure that comprises a speed, power and current control loop. It should be noted that omission of the power control loop is possible by implementing decoupled current control \[14\]. The reference speed for the outer speed control loop is set by rated speed of the machine that is 2000 rpm. Speed control is implemented by controlling the active power reference to the power control loop.

In the power control loop, the reactive power reference is set to zero because it is assumed that the grid side converter will supply the needed reactive power to the system. The current controller tracks the power reference by controlling the rotor currents. Current control is performed in a \( dq \) reference frame that is rotating with the stator flux.

5.3 Reactive Power Control under Grid Voltage Dips

During a symmetrical grid fault, there will be high oscillations of the stator and rotor currents due to the dc component of the stator flux. \[16\] the authors suggest to control the rotor current in order to compensate for this dc component of the stator flux. Normally, a very large rotor current is needed to counter this flux. But due to the limited capacity of the power converter, its capability is greatly restricted.

When the stator flux vector is oriented along the d-axis of the synchronously rotating frame, it can then be expressed as:

\[
\varphi_{ds} = \frac{L_s}{R_s} V_{ds} + L_m i_{dr}
\]  

Therefore, the stator flux is reduced as a consequence of the grid voltage dip. Moreover, if the d-axis component of the rotor current \( i_{dr} \) is reduced, the stator flux can be further limited and then the oscillations of the currents will be attenuated. A simple demagnetization method can be obtained by setting the reference of \( i_{dr} \) to zero as soon as a voltage dip is detected. It is clear that for implementing this strategy, the DFIG should be kept under full control during the grid fault, and should not be disconnected as in standard control schemes.

5.4 Hysteresis Control of the Crowbar

Generally the crowbar is triggered in case of over voltage on the DC bus or over current in rotor windings. When the crowbar is triggered, in standard control schemes the rotor side converter is disconnected from rotor at the same time. As a result, the controllability of the DFIG is lost during the voltage dip, which is the main drawback of the crowbar protection. Moreover, the DFIG then behaves as a classical squirrel cage induction generator with an increased rotor resistance until the crowbar is cut off and the rotor side converter resumes normal operation \[15\].

Electronic copy available at: https://ssrn.com/abstract=3425824
In this situation, the DFIG absorbs reactive power from the grid for magnetization, which will even deteriorate the stability of the weak grid.

In order to reduce the operation time of the crowbar, an improved hysteresis control strategy is adopted, as it is shown in Fig. 7. The maximum absolute value of rotor current $|i_r|_{\text{max}}$ is compared with a threshold value $i_{\text{th}}$ and a safety value $i_{\text{sa}}$. If $|i_r|_{\text{max}}$ is greater than $i_{\text{th}}$, the crowbar is activated for protecting the power converters. When $|i_r|_{\text{max}}$ decreases to be less than $i_{\text{sa}}$, the crowbar will be cut off. During the grid fault the power converters remain connected in order to continuously control the reactive power. In this way the DFIG is able to supply reactive power to the grid, as required by recent grid codes, to help the grid voltage recovery.

![Fig.7: Hysteresis control of the crowbar.](image)

6. Simulation Results and Analysis

The parameters of the turbine and induction machine are given in Table 1. The parameters have been adapted from a GE (General Electric) 1.5MW turbine [13]. In order to examine the effects of the proposed control strategies, such as reactive power control and crowbar hysteresis control, against three phase voltage dips, simulations for a practical 1.5MW DFIG wind turbine have been carried out using PLECS and Matlab Simulink™.

Case 1

The system performance of the DFIG is shown in Fig. 8. In this case, no protection circuit is used during a voltage dip of 60% for 500 ms (Fig. 9a). Once the fault occurs at $t=3.2$ s, the rotor current increases reaching and the peak values of about four times the rated current, and also the DC bus voltage shows a large increase in voltage (Figs. 9b-9c). These severe operating conditions are not acceptable for the power converters. As a first step for reducing the initial peak of the rotor current the effects of crowbar activation is analyzed in case 2.

![Simulation results and analysis](image)
Case 2

When the fault occurs at $t=3.2s$, the crowbar is activated and reference values of $i_{dr}$ and $i_{qr}$ are set to zero. After a short transient, the rotor current decreases to zero for the whole period of fault, as represented in Fig. 9a. This way it is possible to reduce the rotor current peak, but the DC bus voltage shows the same oscillation as in case 1 (Fig. 9b), and a certain amount of reactive power is absorbed from the grid which deteriorates the stability of the grid (Fig. 9c).
Thus, a new control strategy which can overcome all the disadvantages in case 1 and 2 and meet the grid code requirements is presented and discussed in case 3.

**Case 3**

Fig. 10 shows the simulated results of the LVRT operation of the DFIG with the proposed protection strategy. A grid voltage dip of 60% which has duration of 500 ms is considered as in cases 1 and 2.
Fig. 10: Case 3 - Crowbar and reactive power control of WECS (a) Stator current, (b) rotor voltage, (c) rotor current, (d) DC bus voltage, (e) generator speed, (f) reactive power, (g) active power, (h) electric torque, (i) crowbar signal.

|                |               |               |
|----------------|---------------|---------------|
| Rated Power    | 1.5 MW        |               |
| Rated Voltage  | 575 Vrms      | Pole pairs    |
| Stator resistance | 1.4 mΩ      | Lm            |
| Rotor resistance | 0.99 mΩ     | Lr            |
| Bus capacitance | 38 mF        | Ls            |
| Turbine radius  | 35 m          | Inertia       |
|                |               | 50 kg.m²      |

Table 1: WECS Parameters

As soon as the voltage at the wind turbine terminal drops at 3.2s, thanks to the crowbar protection, the rotor current decreases to the secure region rapidly (Fig. 10c). From Fig. 10i, it is clear that crowbar only works for a few milliseconds, which means the DFIG is controllable for most of the time during the voltage dip.

Immediately after the fault grid detection, the q-axis rotor current reference is set to zero, and the d-axis rotor current is set to a suitable reference value corresponding to a reactive power of 0.5 MVAR injected into the grid. From the Fig.10, we can see that after a short transient the active power is zero (Fig. 10g), and the reactive power (Fig. 10f) equals the reference value. The reference value of the reactive power should be chosen according to the converter size. As a result, in most time of the voltage dip, the DFIG can supply reactive power to the weak grid, which will increase the grid voltage and help the grid recovery.

The DC bus voltage shows lower oscillations with respect cases 1 and 2, as presented in Fig. 10d. The generator speed is given in Fig. 10 e, showing a small increase as a consequence of the electromagnetic torque behavior (Fig. 10h). The transient behavior of the stator currents and rotor voltages is characterized by acceptable values and is illustrated in Figs. 10a and 10b, respectively.

It can be noted that about 0.2 s after the grid voltage recover, the active power and reactive power resume the reference values as before the fault occurrence. Moreover, with the help of the reactive power, the crowbar does not need to be activated after the clearance of the fault, which means that the rotor side converter can control the DFIG to resume normal operation in less time.

7. Conclusion

This paper has been focused on the control strategy of a DFIG wind turbine system equipped with an active crowbar against severe grid faults. In order to reduce the activated time of the crowbar as much as possible, an improved hysteresis control strategy has been proposed. Moreover, the reactive power control has been adopted to decrease the oscillations of the transient current both during the voltage dip and after the clearance of the fault. With the help of the proposed control strategy, the DFIG can be controllable for most of the time during voltage dip. As the crowbar is not required to provide a bypass for the potential high rotor current, the wind turbine can resume normal operation in a few hundred milliseconds after the fault is cleared. Simulation results have
shown that an enhanced low voltage ride through capability of the generator can be achieved with the proposed technique.

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