An Integrated Reactive Power Control Strategy for Improving Low Voltage Ride-through Capability

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Abstract: Among all renewable energies, wind power is rapidly growing, where it has the most participation to supply power. Doubly fed induction generator (DFIG) is the most popular wind turbine, as it can play a very significant role to enhance low voltage ride through (LVRT) capability. Ancillary services such as voltage control and reactive power capability are the main topics in wind power control systems that should be handled profoundly and carefully. The lack of reactive power during fault period can result in instability in generators and/or disconnection of the wind turbine from the power system. The main aims of this study are to illustrate the most effective approaches subject to improve the efficiency, stability, and reliability of wind power plant associated with LVRT capability enhancement. This effectiveness and efficiency are demonstrated by, firstly, comparison between all types of wind turbines, focusing on the ancillary services, after the existing advanced control strategies. According to the literature, there is a consensus that modifying converter-based control topology is the most effective approach to enhance LVRT capability in DFIG-based wind turbine (WT). Therefore, an advanced integrated control strategy is designed by considering the effect of the rotor side converter (RSC) and the grid side converter (GSC). A model of the wind power plant is presented based on the control objectives. MATLAB/Simulink is also used to illustrate the effectiveness of the designed algorithm.

Keywords: Doubly fed induction generator, low voltage ride-through, series dynamic braking resistor, reactive power

1 Introduction

Wind energy is rapidly growing over the past decades due to numerous competencies offered by modern wind generators such as low cost, easy construction, and the cleanliness in which it can save 10 billion tons of CO$_2$ produced in different processes per year. However, setting the climate change program has to take place as a business and economic opportunity which be a driving factor to protect our environment. The total installed capacity is planned to reach 800 GW by 2020, and subsequently 2 000 GW by 2030, according to the Global Wind Energy Council (GWEC) outlook 2016. Fig. 1 depicts the regional breakdown directing 2020 and 2030 [1]. This figure clearly illustrates why wind power generation is regarded as one of the most fast-growing renewable sources.

The quality of the delivered power is entitled as one of the main attractive characteristics of wind generation to guarantee the stability and reliability of the power plant [2].

There are four main types of generator systems using in wind farms. Type A is a fixed-speed generator, where synchronous squirrel cage induction generator (SCIG) is connected to the grid through capacitor bank and soft starter. The capacitor bank is employed to compensate for the reactive power required by SCIG. The configuration of this type of generator is straightforward, and no converter is needed. However, not supporting speed control and demand of a stiff grid can be listed as the main drawbacks of type A. Meanwhile, the mechanical construction of SCIG must handle high mechanical stresses which caused by wind gusts [3-4].

Type B is also known as a limited variable speed generator. A wound rotor induction generator (WRIG) is used to connect the transformer through a series of capacitor banks to compensate the reactive power. Also, a converter is employed to control a rotor resistance, which is installed on the rotor shaft. This type can eliminate the requirement of expensive slip rings, in which the output power and the slip can be controlled with this control system [3-4]. The main drawback of type B can set the stage as its low efficiency comes from loses in connected resistors in the rotor circuit.

Type C is a variable speed-partially scale frequency converter. This type is also known as a doubly fed induction generator (DFIG). Type C can be
installed on variable speed wind turbines with WRIG. The frequency converter is also located on the rotor side of the circuit. The stator is directly connected to the grid side. The concept of this type of generator is designed to compensate for the reactive power and to have a smoother grid connection. This generator has a speed range of up to 30%-40% of synchronous ones [3].

Type D is a variable speed-full scale frequency converter. This is known as the permanent magnet synchronous generator (PMSG). It is a variable speed generator connected to the grid with a full-scale frequency converter. The main characteristic of this converter is its ability to compensate the reactive power. Direct driven multiple generators with a large diameter are installed instead of the gearbox. This concept can be added to its high efficiency as the main advantages of type D [4].

1.1 Ancillary services comparison between four types of generators

Voltage control and reactive power capability play a very significant role to have smooth output power and reliable system also. Here, there is a brief comparison between four types of generators, considering the concept of primary ancillary services, voltage and reactive power capabilities.

1.1.1 Voltage control

A wind turbine can start absorbing reactive power during a fault, which leads to voltage instability and consequently, power system unreliability. The necessity of studying voltage stability is now a foregone conclusion, where the voltage stability problem leads to catastrophic effects on safety and low efficiency of power plant [5]. Clearly, each type of wind turbine treats differently during grid faults and disturbances.

The voltage control of type A and B are limited to power factor correction. The underlying philosophy of voltage control in type C is established based on controlling the $d$-axis current of RSC. In other words, DFIG can directly take part in voltage regulation because of its flexible reactive power control capability. Meanwhile, type D employs the GSC to control the voltage by supplying the reactive power.

1.1.2 Reactive power control

Another critical parameter which has a significant impact on wind power operation is the power factor at point of common coupling (PCC). An actual limit is designed for each type of wind turbine. The reason for this limit basically goes back to the capability of a wind power plant to produce reactive power, which is the main extra cost in comparison to the conventional ones.

The capabilities of type A and B may be set to keep a fixed power factor, while the typical range for type C and D is 0.9 to 0.95 [6]. It is worth to mention that only types C and D can support reactive power even if active power is not producing. That is to say, DFIGs and PMSGs contribute to the circumstance under which they provide stability and security of grid-connected large-scale wind power by adjusting the reactive power.

1.2 Significance of DFIG in LVRT capability enhancement

Low-voltage-ride-through (LVRT) is another main issue that should be considered for the wind power plant operation. Notably, the wind system needs to stay connected to the grid during faults and even short-term after fault [7]. This specification, according to the grid code requirements (GCRs), is termed as
LVRT. In the other world, LVRT is the ability of recovery of the wind power plant from different fault scenarios \[8\]. As stated in Ref. \[9\], a real example of stability problem occurred in Western Europe in November 2006, while disconnection from the grid led to losing a considerable amount of 4 892 MW of wind farm.

After considering the impacts of the voltage-time profile, and grid fault on active and reactive power, these two parameters should remain delivered even during fault period \[1\]. Consequently, recalling what mentioned earlier, types C and D can set the main stage to LVRT capability enhancement. Apart from advantages of PMSG such as no additional power supply, high efficiency, and premiere reliability because of the absence of mechanical components \[10\], PMSG has main drawbacks such as high cost of permanent magnetic, difficulties in handling in maintenance, and demagnetization of permanent magnetic at high temperature. As a result, it seems that DFIG has a very significant contribution to enhancing LVRT capabilities compared to other types of generator. DFIG directly connected to the grid in which it can decouple real and reactive power. This characteristic gives DFIG the ability to control the flow of real and reactive power between the rotor and the grid. Also, only electrical power injected by the rotor needs to be handled in DFIG. In terms of cost, DFIG can improve system yield at a lower cost compared to PMSG. The DFIG-based wind turbine is highly reactive to voltage dips and grid disturbances, and this is mainly because of its configuration (see Fig. 2). This fact illustrates why most researchers have focused on DFIG behavior to have better LVRT capability \[11-20\].

\[2\]  DFIG behavior in different modes

The two fundamental issues that must be adequately addressed in LVRT capability enhancement are over-current in rotor and stator and over-voltage in DC-Link. In fact, there is not a very clear reason for the main leading of generating over-current so that some of the viewpoints are even contradictory. For instance, Thiringer in Ref. \[21\] proves that the rotor over-current is mainly because of the increase of stator current result from voltage dips, while Ref. \[22\] supposes that this over-current is due to instantaneous change stator flux. This paper studies the DFIG behavior in different modes to show the effectiveness of stator flux in LVRT capability enhancement.

2.1 DFIG behaviour during normal operation

According to Ref. \[23\], the transient of DC-link voltage, electrical torque, and rotor current have been influenced by the flux, which is usually damped very slowly. The authors in Ref. \[4\] have pointed out that the oscillation of electrical torque and rotor current can be limited by increasing the stator flux damping. Meanwhile, it can reduce the instantaneous fluctuation of DC-link voltage and rotor power, which in turn contributes to the increase of time of operation and reliability.

As Ref. \[4\] has stated, the component of voltage and rotor current in \(d\)-axis play the leading role to control the terminal voltage, and reactive power flowed between the generator and the grid. However, the rotor voltage can be expressed as follows

\[ V_r = (R_s + p\sigma L_s)i_r + e_r \]  

(1)

Where \(R_s + p\sigma L_s\) is the voltage drop which is the
function of rotor resistance \( R \) and transient inductance \( \sigma L \), \( (\sigma \) is leakage coefficient). The rotor error (rotor oscillation) can be given by

\[
e_\tau = \frac{L_m}{L_s} p \lambda_{sr}
\]  

(2)

2.2 DFIG behaviour under voltage dips

Commonly, the fault that occurs at DFIG terminals is known as a bolted three-phase fault. In this case, \( v_s \) is assumed to be zero for \( t>0 \). By neglecting the term \( R \left( L_n / L_s \right) i \), the stator dynamic can be given by

\[
\left( \frac{R}{L_s} + p \right) \lambda_{sl} = v_s = 0 \Rightarrow \begin{cases} \frac{R}{L_s} \lambda_{s0} + p \lambda_{s0} = 0 \\ \frac{R}{L_s} \lambda_{sr} + p \lambda_{sr} = 0 \end{cases}
\]  

(3)

Where \( v, i, R, L, p \) and \( \lambda \) represent voltage, current, resistance, pole pairs, and flux linkage, respectively. Subscript 's' and 'r' denote stator and rotor quantities. To solve formula (3), the initial condition in \( d-q \) direction is introduced as

\[
\lambda_{s0}(0) = \lambda_{s0}(0) + j \lambda_{sr}(0)
\]  

(4)

It is approved in practice that natural stator flux component is a fixed vector during full voltage dip where the amplitude goes to zero, exponentially by considering the stator time constant \( \tau_s \). Moreover, in this case, the rotor speed can be defined as

\[
w_r = (1-s) w_e
\]  

(5)

Hence, after full voltage dips, the internal rotor error can be given by

\[
e_\tau = -\frac{L_m}{L_s} \sqrt{3} v_s \left( \frac{1}{\tau_s} + jw_r \right) \exp \left( -\frac{t}{\tau_s} \right) \exp(-jw_r t), t \geq 0
\]  

(6)

Naturally, \( 1/\tau_s \) is smaller than the rotor speed. So, it can be assumed that the maximum magnitude of internal rotor error can be approximated as

\[
|e_\tau(t=0)| \approx (1-s) \sqrt{3} v_s
\]  

(7)

Clearly, the internal rotor error is proportional to \((1-s)\), whereas \(-0.3<s<0.2\), and \( s \) is the slip of DFIG.

From the above analysis, it can be summarized that it is necessary to protect converter components, such as DC-link, and rotor side converter. This is because of overvoltage and overcurrent problems, which may lead to exceeding the maximum voltage, resulting in instability due to absorbing or generating non-required reactive power.

3 Technical grid code requirements for wind farms

As mentioned above, different countries have defined different grid code requirements. The main objective behind these definitions is minimizing the adverse effects of large-scale wind power plants, besides maximizing the reliability of the power systems. The grid code observed is usually collected by transmission system operation (TSO) of countries or regions. Consequently, TSO is the result of the incorporation of long-time system operation at a significant wind penetration level \(^1\). However, grid code requirements are regarded as one of the major drivers to develop WT technology, as several publications have pointed it out \(^6, 24-28\). The main things that should be considered in grid code requirements are; frequency control, fault ride through, active power regulation, expanded frequency and voltage variation limits \(^1\). Time of recovery and having smooth reconnection mood are other key objectives of this topic.

Wind turbine power plants must have this ability to work with the required voltage variation to feed conventional power system with the same voltage. To do so, different countries have introduced different LVRT requirements for WT grid codes. Based on Fig. 3a the terminal voltage must be in areas A and B to keep WT connected to the grid where the dynamic reactive power should be supported, and when the terminal voltage drops to area C, isolation wind turbine from the grid is allowed. Fig. 3b plots the required reactive current, according to Danish grid codes, to support transient voltage stability \(^13\). In the case of voltage drop by more than 10\%, the reactive current output should follow the path, shown in Fig. 3b \(^29\).

The new grid code requirements can also be discussed subject to reactive power support. Some countries have targeted, exclusively, reaching specific amounts of the reactive current so that they can perform smoothly during and after a fault. For instance, Spain is required to provide additional reactive current amounting to at least 2\% of the nominal value. The
UK is about to offer maximum reactive current during a fault. The goal for Germany is to retain the voltage at PCC in area A or B, recalling what is shown in Fig. 3. Meanwhile, this requirement for Australia is to provide 4% of the reactive current component support for every 1% reduction in PCC. Tab. 1 summarizes the power factor, range of required reactive power and Q range for different countries, and how reactive power has influenced grid code requirements.

**Tab. 1 Grid code requirements of selected countries**

| Country     | Considered point | Q range/p.u. | Power factor |
|-------------|------------------|--------------|--------------|
| Australia   | Connection point | 0.395        | 0.90~0.95    |
| Canada      | HV side of transformer | −0.33~0.33 | 0.95~0.95    |
| Denmark     | Power plant operation point | −0.33~0.33 | 0.95~0.95    |
| Germany     | Connection point | —            | 0.95~0.95    |
| Ireland     | Connection point | −0.33~0.33   | 0.95~0.95    |
| Spain       | —                | −0.3~0.3     | —            |
| UK          | Grid entry point | —            | 0.95~0.95    |

After studying the significance of reactive power in a large-scale wind power system, the discussion, now, focuses on the effectiveness of reactive power in the improvement of low voltage ride-through capability, particularly for wind turbines equipped with DFIGs. The next section discusses and looks at all the existing LVRT enhancement methods to shape the framework of this paper in a step-by-step way.

**4 LVRT capability enhancement methods**

Generally, there are two basic methods to enhance LVRT capability in DFIG-based WT: methods based on external devices, and methods based on control improvement.

The previous example can be listed as crowbar protection, FACTS devices, and energy battery storage systems, and the latter are pitch angle control and modifying AC-DC-AC converter. The advantages and disadvantages of all these methods are already discussed in Ref. [30]. Among all mentioned methods, modifying back-to-back converter has gained the most popularity in the field of wind power control system. The main reason for this popularity is that other mentioned methods require additional equipment such as STATCOM, DC-chopper, SVR etc., which increase the cost of the system. Consequently, the section below is focused on and reviewed the major literature that has been done in this area.

Considering the solutions as mentioned above, offering external devices-based methods, improving the converter-based controller is another solution for having better LVRT capability for WTs equipped by DFIGs. The inherent nonlinear behavior of the power system makes LVRT improvement more complicated, as stated by Ref. [31]. Another critical challenge to this topic is the time, regarding how long a fault lasts and the time following the clearance of such a fault. In the latter scenario, a post-fault condition, all the parts of the system is not functioning well. Nonetheless, the conventional linear methods cannot perform ideally under severe voltage dips due to the limited range of the linear controller. This section summarizes the existing typical solutions for LVRT improvement based on converter controller techniques. The method presented in Ref. [32] is a globally stabilizing technique. All the state-feedback information required complying with this approach and this is practically impossible. Most importantly, the system cannot cope with severe faults, resulting in the system’s robustness cannot be guaranteed [31].

The control of active and reactive power is proposed in Ref. [32], in which DFIG contributes to the improvement of grid stability. This method is applicable if the nonlinearities of DFIG consider to...
design active and reactive power control. Another existed method is demagnetization. The main objective of this approach is to decrease the rotor current during the fault period. The induced electromagnetic can be eliminated in this method by controlling the RSC output \[32\]. This method cannot be easily implemented in industrial contexts due to the converter capacity limits.

The reactive power generated by DC-link is a driving factor for having better LVRT capability, where it can balance the exchanged reactive power between the DFIG and the grid. On the other hand, it is challenging to keep the DC-link voltage constant during a fault due to strong nonlinear behavior of DC-link. Consequently, it is proposed to limit the DC-link voltage as an alternative solution to improve LVRT capability. The linear control methods cannot address this requirement adequately, especially under severe voltage dips. Hence, the feedback linearization was introduced by Ref. [13] to overcome this shortage whereby a vast region of state space will be selected and linearized to guarantee the system's robustness.

Rahimi et al. [33] proved that the stator dynamic has a significant effect on dynamic DFIG behavior under substantial voltage dips. This is true because the stator is directly connected to the grid and any fault in the grid, regardless of how far that is, can be transferred to the stator. This issue has been addressed by increasing the closed-loop rotor current and restricting rotor current transience, which results in tracking error. However, the converter overloading is still a big issue when using this method. On this topic, Ref. [33] proposed a control strategy based on passive and active LVRT compensator. The passive method employs crowbar protection, and the active method realizes rotor voltage control. The former is based on external devices (the disadvantages of which have been already described). The latter solution is acceptable if the dynamic of reactive power is also considered.

All the above-discussed methods have simply carried out single fault ride-through (FRT) requirements separately, while one inclusive control strategy can benefit LVRT capability, maintainability, and operability. The authors in Ref. [34] proposed a unified control algorithm that fulfills the need of LVRT improvement for WTs equipped by DFIGs. Two steps have been designed for accompanying this control strategy. The first step is based on series dynamic resistor (SDR) to reduce peak rotor fault current, which results in limiting DC-link voltage fluctuation in the following step. This is done to reduce the power fed to the DC-link. Although this control mechanism has successfully improved LVRT capability, chattering is still a problem which needs more attention. An LVRT scheme is proposed in Ref. [35] for PMSG using interval type-2 fuzzy logic. In this algorithm, the excess power is stored to keep the DC-link voltage constant. The injection of maximum reactive power has not yet been guaranteed, especially during a very weak grid connection. Artificial bus method is applied in Ref. [36] to improve LVRT by injecting maximum nominal power during the grid fault. The minimum change in control strategy is needed there, which is the main advantage of the proposed algorithm, but not interfering with the influence of interconnection leads to increase the conservativeness of the strategy. A coordinated control strategy is proposed in Ref. [37] for DC-link voltage and crowbar for LVRT improvement. In this method, energy storage system (ESS) is employed to control the DC-link voltage. In the meantime, GSC is engaged to control the reactive power subject to addressing FRT requirements. The RSC completely blocked while generator consumes the reactive power. This can result in dwindling of the grid voltage [38].

From the system stability perspective, an advanced control approach and a predictive control method are presented in Refs. [39-40]. Another critical issue to this topic is the transmission line’s capability. This is important due to the need to adjust the flow rate of power in large-scale plants. According to Ref. [41], this generates a smooth voltage profile and voltage stability. The inherent nonlinearities of wind power systems can be more difficult if other research perceives how each system is interconnected, where yet not many studies have paid attention to this critical issue (for example see the following Refs. [31-33, 39-40, 42-43]).

Apart from control strategies, discussed above, Sliding mode control (SMC) and Model predictive control (MPC) are the main two types of controllers
which are employed as supervisory control, top level of control philosophy, scheme in this topic. Sliding mode control can achieve a successful compromise between torque oscillation and conversion efficiency\cite{44} higher order sliding mode control is employed by Ref. [45] to enhance FRT capability in WTs equipped with DFIG. The robustness of the system is guaranteed in this topology for grid faults, but no solution is suggested to control the output power according to reactive power. Authors in Ref. [46], artificial neural network (ANN) is engaged with SMC to extract maximum power from wind used for power regulation. In this approach, RSC regulation is directly affected by blade angle control, while generator dynamic, including stator dynamic, is not considered. In other words, this system cannot deal with severe voltage dips.

It is worth pointing out that MPC has been investigated for its role in power and renewable energy control systems design \cite{47-49}. The ability to manage constraints and short time needed for reconfiguration are the main two advantages of MPC. To this topic, RSC \cite{50} can be protected by MPC, considering the incorporation between rotor current and voltage constraints. Also, the prediction model keeps the MPC input updated at each sampling time, in which bringing unhealthy voltage as close to its desired value\cite{51}. This characteristic is also useful in case of using SDR, as the dynamics of the controlled system changing if SDR switch is activated or deactivated. In Ref. [52], an idea of using a fuel cell system by SDBR is proposed to improve FRT capability. In this algorithm, the fuel cell output voltage is converted into an AC voltage and SDBR is located between the transformer and the inverter to minimize the effect of fault happened at interface device. This algorithm has successfully improved the LVRT capability, but the system robustness cannot be guaranteed during transient disturbances. Also, there is no possibility to manage the injected reactive power optimally.

Employing MPC brings many advantages to the class of decentralized control such as size reduction and addressing optimization problem, which makes it tractable \cite{53-54}. For instance, Ref. [53] proved that different level of information can be achieved based on the linear control system and among the distributed controllers. Consequently, this approach can evaluate the strategy where the robustness and stability of the power systems are a significant concern.

Most importantly, considering the interaction between subsystems helps improving the system’s efficiency, and, therefore, system capability. This illustrates that the plant-wise controller needs to be system-wide decentralized to improve system robustness, and this concern needs further investigation. Finally, when DMPC takes place, it makes it possible to design multiple local controllers that stabilize the whole system. Therefore, it can address state constraints and enable the plant to be adequately controlled compared to other conventional techniques \cite{55}.

Tab. 2 summarizes and compares the benefits and drawbacks of fault ride-through (FRT) categories according to protection circuits, reactive power injecting-device, and modifying back-to-back converter for DFIG-based WTs.

| Classes                          | Benefits                                      | Drawbacks                                      |
|---------------------------------|-----------------------------------------------|-----------------------------------------------|
| Protection circuits Refs. [15, 19, 46, 47, 49, 53] | Useful under symmetrical and asymmetrical grid faults | Reduce reliability                           |
|                                 | Easy to implement                             | Add extra hardware                            |
|                                 | Reduce rotor over-current                     | Increase complexity and system cost           |
|                                 | Reduce DC-link voltage oscillations           |                                               |
| Reactive power compensation     | Reduce rotor overvoltage and overcurrent      | Increase system cost and system complexity    |
| Refs. [31, 54, 55]             | Easy to control frequency and voltage         |                                               |
| Modifying back to back converter control Refs. [7, 33, 52, 56] | Effectively improve system reliability        | Difficult to design                           |
|                                 | No extra cost needed                          |                                               |
|                                 | Reduce rotor overcurrent                      |                                               |
|                                 | Reduce torque oscillation                      |                                               |
|                                 | Control DC-link overvoltage                   |                                               |

Fig. 4 illustrates the development of FRT technology for DFIG-based WTs from the early 2000s to the present day whereby it proves that introducing a control strategy is a new, but high efficiency, method.
to address FRT requirements.

Hence, Section 5 introduces a control strategy by the integration of protection circuits, SDBR, into the back-to-back converter control so that the required reactive power can be adjusted during a fault period.

5 Problem formulation

In this paper, a model of a large-scale wind farm is given in the form of discrete time, as follows

\[ x(k + 1) = Ax(k) + Bu(k) + B_d d(k) \]

\[ y(k) = C_y x(k) \] (8)

After linearization, formula (8) can be represented in the form of the state-space model

\[ \dot{x} = Ax + Bu + B_d d \]

\[ y = C_y x \] (9)

where the system matrix \( A \) is

\[
A = \begin{bmatrix}
\frac{\sigma s L_s}{\sigma s L_s} & \frac{\alpha_2 + \frac{\alpha_1^2}{\sigma s L_s}}{\sigma s L_s} & \frac{\alpha_1 + \frac{\alpha_2^2}{\sigma s L_s}}{\sigma s L_s} & \frac{\alpha_1 + \frac{\alpha_2^2}{\sigma s L_s}}{\sigma s L_s} \\
\frac{\alpha_1 + \frac{\alpha_2^2}{\sigma s L_s}}{\sigma s L_s} & \frac{\sigma s L_s}{\sigma s L_s} & \frac{\alpha_1 + \frac{\alpha_2^2}{\sigma s L_s}}{\sigma s L_s} & \frac{\alpha_1 + \frac{\alpha_2^2}{\sigma s L_s}}{\sigma s L_s} \\
\frac{\alpha_1 + \frac{\alpha_2^2}{\sigma s L_s}}{\sigma s L_s} & \frac{\alpha_1 + \frac{\alpha_2^2}{\sigma s L_s}}{\sigma s L_s} & \frac{\alpha_1 + \frac{\alpha_2^2}{\sigma s L_s}}{\sigma s L_s} & \frac{\sigma s L_s}{\sigma s L_s} \\
\frac{\alpha_1 + \frac{\alpha_2^2}{\sigma s L_s}}{\sigma s L_s} & \frac{\alpha_1 + \frac{\alpha_2^2}{\sigma s L_s}}{\sigma s L_s} & \frac{\alpha_1 + \frac{\alpha_2^2}{\sigma s L_s}}{\sigma s L_s} & \frac{\sigma s L_s}{\sigma s L_s}
\end{bmatrix}
\]

\[ B_d = \begin{bmatrix}
0 & 0 & \frac{1}{\sigma L_s} & 0 \\
0 & 1 & \frac{1}{\sigma L_s} & \frac{1}{\sigma L_s} \\
0 & 0 & -\frac{1}{\sigma L_s} & \frac{1}{\sigma L_s}
\end{bmatrix} \]

\[ C_y = \begin{bmatrix}
0_{2 	imes 2} & I_2
\end{bmatrix} \] (11)

The states of the system are \( x = [i_{d_r} \ i_{d_q} \ i_{q_r} \ i_{q_q}]^T \in \mathbb{R}^4 \), the rotor voltage is presented as control input \( u = [v_{d_r} \ v_{d_q}]^T \in \mathbb{R}^2 \). As the DFIG stator is very sensitive to the fault, so this term is considered as the measurable disturbance, where \( d = [v_{d_s} \ v_{q_s}]^T \in \mathbb{R}^2 \).

Note that the introduced parameter, \( u_{\text{SDBR}} \), can be zero or 1 if the switch is OFF or ON.

5.1 Optimization

In this section, the abrupt changes are targeted for addressing the optimization problem. Model predictive control (MPC) is a powerful tool that can manipulate and handle a wide range of constraints. Therefore, the rotor current and voltage are also taken into account to, first, minimize the need of complex computational methods, second, to keep the constraints within the safe limits, and third, to optimize the required reactive power during the fault, which in turn results in LVRT capability enhancement. To address the above-mentioned objectives, the quadratically constrained quadratic program (QCQP) is called

\[
\min_{j=0, \ldots, N_p - 1} \sum_{j=1}^{j=N_p} \| e_j(k+j) \|_2^2 + \rho \| \Delta u(k+j) \|_2^2
\]

\[ + \sum_{j=0}^{j-N_p-1} \| \Delta u(k+j) \|_2^2 + \rho \varepsilon^2 \] (12)

with the following constraints

\[ \| e_j(k+j) \|_2^2 \leq V_{r, \text{max}}^2, j = 0, 1, \ldots, N_p - 1 \]

\[ \| e_j(k+j) \|_2^2 \leq I_{r, \text{max}}^2 + \varepsilon, j = 1, 2, \ldots, N_p \] for \( \varepsilon > 0 \) (13)

In this case, the control input and the output are norm bound, which mathematically limited by maximum rotor voltage and current, respectively. \( N_p \) and \( N_c \) are the prediction horizon and control horizon. The error \( e_j \) is introduced as the difference between the rotor reference values \( [i_{d_r} \ i_{d_q}] \), given by the PI controller, and the output. So, these values feed the MPC to comply with the optimization objectives. The
internal input-output loop block diagram is shown in Fig. 5.

![Internal Input-Output Loop Block Diagram](image)

Fig. 5 Input-output internal loop block diagram

The weighting matrices, $Q_i$ and $R_i$, presented in formula (12) are defined as

$$
Q_i = \begin{bmatrix} q_i^1 & 0 \\ 0 & q_i^2 \end{bmatrix}, \quad R_i = \begin{bmatrix} r_i^1 & 0 \\ 0 & r_i^2 \end{bmatrix} 
$$

(14)

Note that $\|q\|_M$ assigned based on norm definition as follows

$$
\|q\|_M^2 = q^T M q, \quad \|q\|_M^2 = q^T M q
$$

(15)

To implement MPC, the approximated QCQP is used, and multi-parametric toolbox (MPT) is employed for the explicit MPC calculation, as presented in Ref. [57].

5.2 Task description and controller performance evaluation

The DFIG stator is connected to the grid directly. In the meantime, DFIG is fed from both sides of the converter, so any fault happens in the grid can result in severe effects on a system’s performance. A series dynamic braking resistor (SDBR) is located on the rotor side converter (RSC) to protect it from inrush current. After the fault has been completely cleared, the decision-maker part of algorithm activates the switching function, and the MPC computes the prediction model at each sampling time. Also, the rotor current reaches its maximum, and the safe limit is remarked.

5.3 Results and simulations

The MPC takes the main part of the control strategy to protect RSC from inrush current, and also to comply with the optimization objectives. Figs. 6-19 show the system responses to the designed advanced control strategy. Technically, the fault is given at DFIG terminal, at $t=100$ ms, to analyze the system performance. Then, the results are compared if the system cannot exert some level of control. Obviously, the integrated converter-based control algorithm could successfully reject the disturbance in a short period of time. Fig. 6 shows the active power output and Fig. 8 shows the generator torque response, emphasizing that the oscillation is reduced effectively. Figs. 7-9 prove the necessity of MPC when the torque and active power unable to restore the original system, in the post-fault period, without the controller taking any part of that.

![Active power output with MPC](image)

Fig. 6 Real power output with MPC, $P_s$, single line fault to the ground given at $t=100$ ms

![Active power output without MPC](image)

Fig. 7 Real power output without MPC, $P_s$, single line fault to the ground given at $t=100$ ms

![Generator torque with MPC](image)

Fig. 8 Generator torque with MPC, $T_q$, unable to restore the original system after fault appeared at $t=100$ ms
As stated earlier, the direct connection between the DFIG stator and the grid has made the stator very sensitive to the fault. Therefore, the stator DFIG reactive power takes a critical part for gaining better performance during a fault condition. Fig. 10 shows the output of DFIG stator reactive power, demonstrating the successfulness of the proposed algorithm to deal with a critical fault, happened at \( t = 100 \) ms. This result leads to less fluctuation along with keeping the stator reactive power within acceptable limits. This achieved by; employing MPC to increase the rotor currents and keeping the DC-link voltage within the limits allowed of the RSC, as shown in Figs. 12-14.

From Fig. 14, the fluctuation range of capacitor voltage is limited to 1.5 p.u. These results are also compared in the absence of MPC. As can be seen, the system is unable to retain the stator reactive power, Fig. 11, rotor current, Fig. 13, and DC-link voltage, Fig. 15, within safe limits during the fault period.

The output of the rotor voltage by employing MPC is also shown in Fig. 16, and this proves that the MPC could successfully keep the rotor voltage within the safe limits. Fig. 17 shows a very fluctuating response during the fault period in the absence of
MPC. The designed controller is also applied for line current $I_{abc}$. The result, Fig. 19, emphasizes the effectiveness of MPC by keeping the line current within the predicted range, while the line current cannot be kept within the safe limit if MPC cut off, as shown in Fig. 19.

Moreover, the proposed algorithm could behave smoothly to control the line current after a large disturbance (in Fig. 18) suddenly happened at line.

The simulation parameters for the DFIG and wind turbine are given in Tab. 3 and Tab. 4, respectively.

**Tab. 3 DFIG parameters**

| Parameter | Value |
|-----------|-------|
| Nominal power $P$/W | $3.6 \times 10^6$ |
| Voltage (line-line) $V_{n(rms)}$/V | $4.6 \times 10^3$ |
| Frequency $f_n$/Hz | 60 |
| Stator resistance $R_s$/p.u. | 0.019 65 |
| Stator inductance $L_s$/p.u. | 0.013 97 |
| Rotor resistance $R_r$/p.u. | 0.019 09 |
| Rotor inductance $L_r$/p.u. | 0.039 7 |
| Mutual inductance $L_m$/p.u. | 1.354 |
| Inertia constant $H(s)$ | 0.095 26 |
| Friction factor $F$/p.u. | 0.054 79 |
| Pole pairs/p.u. | 2 |
| Initial conditions | [0.3, 0, 0, 0, 0, 0, 0, 0] |

**Tab. 4 Turbine parameters**

| Parameter | Value |
|-----------|-------|
| Power $P$/MW | 1.5 |
| Power coefficient | 0.9 |
| Wind speed/(m/s) | 2.5 |
| Pitch angle/(°) | 8 |
6 Conclusions

In this paper, the configurations of four types of generators have been studied. The influence of ancillary services, voltage, and reactive power control, on LVRT capability, is also discussed. All existing methods have been presented in this study in which prove that modifying converter-based controller is the most effective and affordable strategy among all current methods to improve the system’s performance during the fault. An integrated advanced control strategy is designed in this paper, which could successfully address the LVRT requirements along with the enhanced reactive power support. This improvement achieved by considering the effects of RSC, GSC, and incorporation of RSC currents and voltages. In this method, RSC is well protected against inrush currents by applying MPC to RSC, results in keeping the capacitor voltage fluctuation within the safe limits and restoring the system to the original one after fault clearance.

References

[1] Global Wind Energy Council. Global wind statistics 2012[EB/OL]. 2013-02-11. www.gwec.net.
[2] M Tsili, S Papathanassiou. A review of grid code technical requirements for wind farms. IET Renewable Power Generation, 2009, 3(3): 308-332.
[3] A D Hansen, F Lov, F Blaabjerg, et al. Review of contemporary wind turbine concepts and their market penetration. Wind Engineering, 2004, 28(3): 247-263.
[4] T Ackermann. Wind power in power system. New York: John Wiley& Sons, 2005.
[5] J G Slootweg, H Polinder, W L Kling. Representing wind turbine electrical generating systems in fundamental frequency simulations. IEEE Transactions on Energy Conversion, 2003, 18(4): 516-524.
[6] Y Chi, Y Liu, W Wang, et al. Voltage stability analysis of wind farm integration into transmission network. In International Conference on Power System Technology, 2006: 22-26.
[7] J Liang, W Qiao, R G Harley. Feed-forward transient current control for LVRT enhancement of DFIG WT. IEEE Transactions on Energy Conversion, 2010, 25(3): 836-843.
[8] L Xu. Coordinated control of DFIGs rotor and grid side converters during network unbalance. IEEE Transactions on Power Electronics, 2008, 23(3): 1041-1049.
[9] O G Bellmunt, A J Ferre, A Sumper, et al. Ride through control of DFIG under unbalanced voltage sags. IEEE Transactions on Energy Conversion, 2008, 23(4): 1036-1046.
[10] P J Maria, M F P Garcia, A Tobias, et al. Wind turbines reliability analysis. Renewable and Sustainable Energy Reviews, 2013(23): 463-472.
[11] L Yang, Z Xu, J Ostergaard, et al. Advanced control strategy of DFIG WT for power system fault ride through. IEEE Transactions on Power System, 2012, 27(2): 713-722.
[12] M Mohseni, S Islam, M A S Masoum. Fault ride through capability enhancement of doubly fed induction wind generators. IET Renewable Power Generation, 2011, 5(5): 368-376.
[13] D Xie, Z Xu, L Yang, et al. A comprehensive LVRT control strategy for DFIG wind turbines with enhanced reactive power support. IEEE Transactions on power System, 2013, 28(3): 3302-3310.
[14] J Yao, H Li, Z Chen. An improved control strategy of limiting the DC-Link voltage fluctuation for a DFIG. IEEE Transactions on Power Systems, 2008, 23(3): 1205-1213.
[15] S Hu, X Lin, Y Kang, et al. An improved LVRT control strategy of DFIG during grid faults. IEEE Transactions on Power Electronics, 2011, 26(12): 3653-3665.
[16] L Yu, G Chen, D Cao, et al. LVRT control of DFIG during symmetric voltage sag. Electric Machine and Control, 2010, 14(7): 1-6.
[17] H Kasem, E F El-Saadany, H H El-Tamaly, et al. An improved fault ride through strategy for DFIG based WTs. IET Renewable Power Generation, 2008, 2(4): 201-214.
[18] D Xiang, L Ran, P J Tavner, et al. Control of a DFIG in a wind turbine during grid fault ride through. IEEE Transactions on Energy Conversion, 2006, 21(3): 652-662.
[19] J Lopez, E Gubia, E Olea, et al. Ride through of WTs with DFIG under symmetrical voltage dips. IEEE Transactions on Industrial Electronics, 2009, 56(10): 4246-4254.
[20] S Saman, J Niiranen, A Arkkio. Ride through analysis of DFIG wind power generator under unsymmetrical network disturbance. IEEE Transactions on Power System, 2006, 21(4): 1782-1789.
[21] T Thiringer, A Petersson, T Petru. Grid disturbance response of wind turbines equipped with induction generator and doubly fed induction generator. In Proc. IEEE Power Engineering Society General Meeting, 2003(3): 1542-1547.
[22] J B Ekanayake, L Holdsworth, X G Wu, et al. Dynamic modeling of doubly fed induction generator wind turbines. *IEEE Transactions on Power Electronics*, 2003, 18(2): 803-809.

[23] A Peterson, T Thiringer, L Harnefors, et al. Modelling and experimental variation of grid interaction of a DFIG wind turbine. *IEEE Transactions on Power System*, 2005, 4(20): 878-886.

[24] J B Ekanayake, L Holdsworth, N Jenkins. Comparison of 5th order and 3rd order machine models for doubly fed induction generator wind turbines. *Electric Power Systems Research*, 2003, 67(3): 207-215.

[25] A Molina-Garca, A Honrubia-Escribano, T Garca-Sanchez, et al. Power quality surveys of photovoltaic power plants: Characterisation and analysis of grid code requirements. *IET Renewable Power Generation*, 2015, 9(5): 466-473.

[26] S M Muyeen, R Takahashi, T Murata, et al. A variable speed wind turbine control strategy to meet wind farm grid code requirement. *IEEE Transactions on Power Systems*, 2010, 25(1): 331-340.

[27] I Erlich, U Bachmann. Grid code requirements concerning connection and operation of wind turbines in Germany. *IEEE Power Engineering Society General Meeting*, 2005: 153-157.

[28] M Mohseni, S M Islam. Review of international grid codes for wind power integration: Diversity, technology and a case for global standard. *Renewable and Sustainable Energy Reviews*, 2012, 16(6): 3876-3890.

[29] Australian Energy Market Operator, AEMO. Wind integration: International experience, WP2: Review of grid codes, A. E. M commission, AU, 2011.

[30] H T Mokui, M A S Masoum, M Mohseni. Review on grid codes for wind power integration in comparison with international standards. *Australian Universities Conference*, 2014: 1-6.

[31] W Qiao, R G Harley, G K Venayagamoorthy. Coordinated reactive power control of a large wind farm and a STATCOM using heuristic dynamic programming. *IEEE Transactions on Energy Conversion*, 2009, 24(2): 493-503.

[32] Y Guo, D J Hill, Y Wang. Global transient stability and voltage regulation for power systems. *IEEE Transactions on Power Systems*, 2001, 16(4): 678-688.

[33] M Rahimi, M Parniani. Coordinated control approaches for low voltage ride-through enhancement in wind turbines with doubly fed induction generators. *IEEE Transactions on Energy Conversion*, 2010, 25(3): 873-883.

[34] M Rahimi, M Parniani. Efficient control scheme of wind turbines with doubly fed induction generators for low voltage ride-through capability enhancement. *IET Renewable Power Generation*, 2010, 4(3): 242-252.

[35] H M Yassin, H H Hanafy, M H Hallouda. Enhancement low-voltage ride through capability of permanent magnet synchronous generator-based wind turbines using interval type-2 fuzzy control. *IET Renewable Power Generation*, 2016, 10(3): 339-348.

[36] M F M Arani, Y A I Mohamed. Analysis and enhancement of the artificial bus method for successful low-voltage ride-through and resynchronization. *IEEE Transactions on Power Systems*, 2019, 34(3): 1729-1739.

[37] M H Ali, S D Alnajjar. Fault ride through capability enhancement of grid-connected fuel cell system by SDBR. *IEEE Power and Energy Society General Meeting*, 2018: 1-5.

[38] E Gatavi, A Hellany, M Nagrial, et al. Low voltage ride-through enhancement in DFIG-based wind turbine. *IEEE International Power and Energy Conference*, 2016: 1-6.

[39] S Zhang, K J Tseng, S S Choi, et al. Advanced control of series voltage compensation to enhance wind turbine ride-through. *IEEE Transactions on Power Electronics*, 2012, 27(2): 763-772.

[40] G Abad, M N Rodriguez, J Poza. Three-level NPC converter-based predictive direct power control of the doubly fed induction machine at low constant switching frequency. *IEEE Transactions on Industrial Electronics*, 2008, 55(12): 4417-4429.

[41] M J Hossain, H Pota, C Kumble. Decentralized robust static synchronous compensator control for wind farms to augment dynamic transfer capability. *Journal of Renewable and Sustainable Energy*, 2010, 2(2): 1-20.

[42] T H Nguyen, C D Lee. Advanced fault ride-through technique for PMSG wind turbine systems using line-side converter as STATCOM. *IEEE Transactions on Industrial Electronics*, 2013, 60(7): 2842-2850.

[43] A Kanchanakaruthai, V Chankong, K A Loparo. Transient stability and voltage regulation in multi-machine power systems vis-vis STATCOM and battery energy storage. *IEEE Transactions on Power Systems*, 2015, 30(5): 2404-2416.

[44] P E Srensen, A D Hansen, F Lov, et al. Wind farm models and control strategies. Report: Wind Energy Department, Riso National Laboratory Information Service Department, P. O. Box 49 DK-4000, 2005.

[45] J L Rodriguez, J L Armal, J C Burgos. Automatic generation control of a wind farm with variable speed wind turbines. *IEEE Transactions on Energy Conversion,*
2002, 17(2): 279-284.

[46] F Mwasili, J Justo, K S Ro, et al. Improvement of dynamic performance of doubly fed induction generator-based wind turbine power system under an unbalanced grid voltage condition. *IET renewable Power Generation*, 2012, 6(6): 424-434.

[47] J Morren, S W De Haan. Short-circuit current of wind turbines with doubly fed induction generator. *IEEE Transactions on Energy Conversion*, 2007, 22(1): 174-180.

[48] J Lopez, E Gubia, E Olea, et al. Ride-through of wind turbine with doubly fed induction generator under symmetrical voltage dips. *IEEE Transactions on Industrial Electronics*, 2009, 56(10): 4246-4254.

[49] F K Lima, A Luna, P Rodriguez, et al. Rotor voltage dynamics in the doubly fed induction generator during grid faults. *IEEE Transactions on Power Electronics*, 2010, 25(1): 118-130.

[50] J M Maciejowski. Predictive control with constraints. *Prentice Hall Technology and Engineering*, 2012.

[51] G Pannell, D J Atkinson, B Zahawi. Minimum threshold crowbar for a fault ride-through grid code compliant DFIG wind turbine. *IEEE Transactions on Energy Conversion*, 2010, 25(3): 750-759.

[52] S Xiao, G Yang, H Zhou, et al. An LVRT control strategy based on flux linkage tracking for DFIG-based WECS. *IEEE Transactions on Industrial Electronics*, 2013, 60(7): 2820-2832.

[53] O Noureldeen. Behaviour of DFIG wind turbines with crowbar protection under short circuit. *International Journal of Electrical and Computer Sciences*, 2012, 12(3): 32-37.

[54] C Wessels, F Gebhardt, F W Fuchs. Fault ride-through of a DFIG wind turbine using a dynamic voltage restorer during symmetrical and asymmetrical grid faults. *IEEE Transactions on Power Electronics*, 2011, 26(3): 807-815.

[55] A O Ibrahim, T H Nguyen, D C Lee, et al. A fault ride-through technique of DFIG wind turbine systems using dynamic voltage restorers. *IEEE Transactions on Energy Conversion*, 2011, 26(3): 871-882.

[56] E Gatavi, A Hellany, M Nagrial, et al. Advanced reactive power control strategy for better LVRT capability for DFIG-based wind farm. *IEEE International conference on Industrial and Commercial Power Systems Europe*, 2019: 1-6.

[57] M Kvasnica, P Grieder, M Baotic, et al. Multi-parametric toolbox (MPT). Technical Report, http://control.ee.ethz.ch/mpt/, 2006.

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