Disturbance attenuation control for LVRT capability enhancement of doubly fed wind generators

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Funding Information
This work was supported by National Natural Science Foundation of China (U1766215, 51707147) and Science and technology project of State Grid Corporation of China (Control Strategy Optimization Technology for Large-Scale Photovoltaic Power Generation on the sending-end and receiving-end of DC power system). The authors are with State Key Laboratory of Electrical Insulation and Power Equipment, and school of Electrical Engineering, Xi’an Jiaotong University, Xi’an 710049, Shaanxi Province, China.

Abstract
Low voltage ride through (LVRT) requires wind generation systems (WGS) to maintain continuous operation and provide reactive power support under grid voltage dips. This paper proposes a novel disturbance attenuation control (DAC) approach based on state-dependent Riccati equation (SDRE) technique to enhance the LVRT capability of doubly fed induction generator-based (DFIG-based) WGS. The DAC problems are formulated with the control objectives for rotor side converter and grid side converter, and the weighting matrices are designed with fully studied principles to balance the control effect and cost. The SDRE technique is adopted to solve the DAC problems, and an alternative feasible state dependent coefficient construction algorithm is applied to improve computational efficiency. An active Crowbar circuit with overcurrent limiting mechanism is applied to ensure the rotor current and DC link voltage within the secure zone. Comparisons with conventional PI controller, exact linearization controller and coordinated control strategy are performed, the results demonstrate the proposed DAC approach has a better transient performance and enhances the LVRT capability of DFIG-based WGS.

1 INTRODUCTION

Under the global crisis of fossil energy shortage and environmental pollution, the development of renewable energy has attracted extensive attention. Among various types of wind generation systems (WGS), doubly-fed induction generator (DFIG)-based WGS have been widely adopted in onshore wind farms due to the advantages of smaller size, lower cost [1, 2], and flexibility in control [3].

Due to the direct connection between stator windings and the power grid, DFIG-based WGS is susceptible to grid disturbances especially under grid voltage dips. Most countries have issued certain grid codes that require WGS to maintain continuous connection and provide dynamic reactive power support during grid voltage dips [1], which is stated as low voltage ride-through (LVRT) capability. With large-scale integration of wind farms, DFIG-based WGS without LVRT strategy may lose connection with power grid during severe voltage dips, which even effects the stability of the whole power system. Therefore, it’s necessary to improve the LVRT capability for WGS under the case of grid faulty events.

The rotor overcurrent and DC link overvoltage are two main factors limiting the integration of large-scale wind farms. In literatures, extensive research works have been carried out to enhance the LVRT capability of DFIG-based WGS. Crowbar protection circuits [4, 5] are usually installed at rotor side to deal with rotor overcurrent during grid faults. However, once the crowbar protection circuit is activated, DFIG-based WGS will operated in induction motor mode and absorb reactive power from the power grid, which leads to further deterioration of
the grid voltage. In [6], Series dynamic resistances (SDR) circuit is connected in series with rotor windings to limit the rotor overcurrent directly. In [7–9], the DC Chopper consisting of a braking resistor connected in parallel with the DC link capacitor is applied to limit the DC link overvoltage. However, these methods cannot provide sufficient reactive power support during grid faults. A transient reconfiguration method for power converters with an energy storage device is proposed to improve the reactive power support capability of DFIG in [10]. In addition, dynamic reactive power compensators, such as static synchronous compensators (STATCOM) and static Var compensators (SVC), have also been applied to provide dynamic reactive power support [11, 12]. However, the implementation of hardware devices will incur high extra costs.

Among various LVRT schemes of DFIG-based WGSs, the most economical and effective way is to make full use of DFIG’s own control capability through properly designed converter control strategies. Several modified control approaches based on conventional PI controllers have been applied to DFIG-based WGSs, such as particle swarm optimization (PSO) based control scheme [13], improved demagnetization control [14], and flux linkage tracking control [15], etc. However, the dynamics of DFIG exhibits nonlinear characteristics, and the control performance of linearized controllers cannot be guaranteed under large disturbances. Differential geometry theory is adopted in [16], and a decentralized nonlinear control strategy for DFIG-based wind turbine is proposed. However, exact linearization requires certain assumptions, and the control law is complicated for practical applications. In [17], a discrete-time neural sliding mode indirect power control (N-SMIPC) is proposed to enhance the DFIG’s LVRT capability. However, this control method cannot provide sufficient reactive power support during grid faults. Input-to-State stability (ISS) theory [18], which is widely adopted in the control of nonlinear systems with uncertainties, has been applied to develop a nonlinear feedback control law for the rotor side converter (RSC) of doubly fed wind generators [19]. However, ISS-based controller can only guarantee inverse optimality, and further optimization on ISS control parameters is yet to be investigated for a better control performance.

The above studies are carried out from the perspective of RSC control, while less attention is paid to the control of grid side converter (GSC) for better stabilizing DC link voltage. Without properly designed GSC controllers, severe voltage dips may lead to an overvoltage at DC link. Excessive voltage will break through the insulation layer, thereby breaking the power electronic devices or even damaging the DFIG [9]. In [20], a current control scheme consisting of a PI controller and a resonant (R) compensator is proposed. In [21], a PI-DFR controller is adopted with robustness of parameters fully discussed through theoretical analysis. However, these linear control schemes cannot fully capture the nonlinear characteristics of GSC model. To avoid solving the Hamilton-Jacobi–Bellman equation, a neural discrete-time inverse optimal controller is proposed in [22], while the desired control performance may not be guaranteed. In [23], a nonlinear control scheme of GSC is proposed to stabilize the internal dynamics and reduce the overvoltage of DC link under grid faults. However, this control scheme mainly focuses on stabilizing the DC link voltage, while good dynamic performance during the transient period may not be guaranteed.

The results of the aforementioned researches indicate that to enhance the LVRT capability of DFIG-based WGS, the following issues need to be addressed in the controller design: (1) Control strategies for both RSC and GSC should be designed considering the intrinsic nonlinearities of DFIG-based WGS; (2) disturbance attenuation capability should be fully considered in the design of LVRT strategies to withstand grid disturbances. The disturbance attenuation control (DAC) law can be obtained by solving Hamilton-Jacobi–Issacs (HJI) partial differential inequality, where developing an analytical solution is complicated for general nonlinear systems. The state-dependent Riccati equation (SDRE) technique [24] provides an alternative way to efficiently design the feedback control laws for nonlinear systems. By converting the nonlinear system into a linear-like structure via extended linearization, the relevant results of linear control schemes can be applied to approximately solve the DAC problems [25, 26].

To make full use of converters’ own control capability, this paper proposes an SDRE-based disturbance attenuation control design approach for GSC and RSC to enhance the LVRT capability of DFIG-based WGS. The main contributions of this paper are: First, control problem construction: the DAC problems for both RSC and GSC are formulated with the objective of providing reactive power support and maintaining the DC link voltage, respectively. The weighing matrices are designed with certain principles to meet LVRT requirements and improve the control effect; Second, feasible solution algorithm: the proposed DAC problems are solved through SDRE technique. Repetitive verification of the controllability and detectability is avoided by applying an alternative state-dependent coefficients (SDC) construction algorithm. Third, Auxiliary protection mechanism: rotor overcurrent limiting mechanism is proposed to fully utilize the converters’ capability of providing reactive power support for the power grid without exceeding the rotor current limit. The main advantages of the proposed DAC approach are its simplicity and flexibility in dealing with nonlinearities. By performing the extended linearization, the dynamic models of both the RSC and GSC can be formulated in linear-like structures with SDC matrices, thus providing a possibility for solving the DAC problems.

This paper is organized as follows: the DAC problems are formulated in section 2. Section 3 proposes the solution method of the proposed DAC problems. Section 4 presents the detailed description of the proposed comprehensive LVRT strategy. Time-domain simulations are performed in section 5 as a verification. Section 6 concludes the paper and highlights future research directions.

2 | PROBLEM FORMULATION

The structure diagram of a grid connected DFIG-based WGS is depicted in Figure 1. The stator windings of DFIG are directly
connected to the power grid, and the rotor windings are connected to the power grid through two back-to-back converters. To enhance the LVRT capability of DFIG-based WGS, the control strategies of both RSC and GSC should be properly designed, and corresponding DAC problems are formulated in this section.

## 2.1 DAC problems for RSC

A 5th order model of DFIG-based WGS [27] is adopted to study the transient control strategy of RSC as shown in Equation (1).

\[
\begin{align*}
\frac{d\tilde{\omega}}{dt} &= -\frac{1}{T_\xi}\tilde{\omega} + \frac{L_m}{T_m} \tilde{\omega} - \tilde{\omega} + \frac{L_m}{T_m} \frac{L_{rr}}{L_{ss}} \Delta \tilde{\theta}_{ab} + \omega \tilde{\theta}_{ab} - \omega \tilde{\theta}_{ab} \frac{1-\eta}{X_1} \\
\frac{d\tilde{\theta}_{ab}}{dt} &= \left( \frac{R_\omega}{X_1} + \frac{L_m}{T_m} \frac{L_{rr}}{L_{ss}} \frac{1-\eta}{X_1} \right) \tilde{\theta}_{ab} + \omega \tilde{\theta}_{ab} - \omega \tilde{\theta}_{ab} \frac{1-\eta}{X_1} \\
\frac{d\tilde{\theta}_{ab}}{dt} &= \left( \frac{R_\omega}{X_1} + \frac{L_m}{T_m} \frac{L_{rr}}{L_{ss}} \frac{1-\eta}{X_1} \right) \tilde{\theta}_{ab} + \omega \tilde{\theta}_{ab} - \omega \tilde{\theta}_{ab} \frac{1-\eta}{X_1} \\
P_d &= \tilde{\omega} \tilde{\theta}_{ab} + \tilde{\theta}_{ab} \tilde{\theta}_{ab} \\
\end{align*}
\]

where

\[
\begin{align*}
\tilde{X}_1 &= I_{1,x} - \frac{L_{1,x}}{T_{1,x}} \tilde{\omega}, \tilde{\omega} = (I_{1,x} / I_{1,y}) \times \tilde{X}_y, \tilde{\omega} = (I_{1,x} / I_{1,y}) \\
\times \tilde{X}_y, \tilde{\omega}_y = I_{1,y} \times \tilde{X}_y + I_{1,x} \times \tilde{\omega} \\
\tilde{X}_a &= I_{1,x} \times \tilde{\theta}_{ab} + I_{1,y} \times \tilde{\theta}_{ab} \\
\end{align*}
\]

and the detailed implication of variables is shown in Table 1.

The active and reactive power output of DFIG-based WGS is controlled by RSC through rotor voltage. To design the LVRT strategy of RSC, Equation (1) can be reformulated as Equation (2) with the equilibrium point shifting to the origin.

\[
\begin{align*}
\begin{cases}
\dot{x} &= f(x) + g_1(x) d + g_2(x) u \\
\xi &= h(x) + k(x) u 
\end{cases}
\end{align*}
\]

where

\[
x = [\Delta \tilde{\theta}_{ab} \Delta \tilde{\omega} \Delta \tilde{\omega} \Delta \tilde{\theta}_{ab} \Delta \tilde{\theta}_{ab}]^T, \quad d = [\Delta \tilde{\theta}_{ab} \Delta \tilde{\omega} \Delta \tilde{\omega}]^T, \\
u = [\Delta \tilde{\theta}_{ab} \Delta \tilde{\omega}]^T, \quad f(x), g_1(x)
\]

and \( g_2(x) \) are shown at the bottom of next page. \( \zeta \) represents the regulation output, which can be selected through matrices \( h \) and \( k \) according to the control objectives.

DAC problem denotes that a stable closed-loop system can reduce the adverse effect of disturbance on the output to a small enough extent with a state feedback control law. The general form of DAC problem can be presented through the following max-min differential game problem in Equation (3).

\[
\begin{align*}
\max \min_d \int_0^\infty \left( \| \zeta(x, u) \| ^2 dt - \gamma^2 \int_0^\infty \| d(t) \| ^2 dt \right) dt \\
s.t. \dot{x} = f(x) + g_1(x) d + g_2(x) u \\
\end{align*}
\]

where \( \| \zeta(x, u) \| ^2 = \zeta^T(x, u) \zeta(x, u), \| d(t) \| ^2 = d^T(t) d(t) \gamma \) is a constant representing the disturbance attenuation capability. The constraints are the system dynamic model as in Equation (2).

The LVRT process of DFIG-based WGS can be divided into two stages: (1) At the initial stage of grid voltage dips, due to the large induced transient electromotive force, the rotor windings are prone to generate a large current. In this paper, the initial stage is considered as two system cycles. During this period, the main control objective is to reduce the rotor current as much as possible. The rotor current of DFIG can be represented as follows.

\[
\begin{align*}
\begin{cases}
\tilde{\omega}_{ab} &= \left( \tilde{\omega}_{ab} - \frac{L_{1,x}}{I_{1,y}} \tilde{\theta}_{ab} \right) 1 - \frac{L_{1,x}}{I_{1,y}} \tilde{\omega}_{ab} \\
\tilde{\omega}_{ab} &= \left( \tilde{\omega}_{ab} - \frac{L_{1,x}}{I_{1,y}} \tilde{\theta}_{ab} \right) 1 - \frac{L_{1,x}}{I_{1,y}} \tilde{\omega}_{ab} \\
\end{cases}
\end{align*}
\]

### Table 1: Implication of variables

| Variable | Implication |
|----------|-------------|
| \( \tilde{\omega} \) | rotor circuit time constant |
| \( I_{1,x}, I_{1,y}, I_{1,x} \) | stator, rotor and mutual inductance |
| \( \tilde{\omega}_{ab}, \tilde{\omega}_{ab} \) | \( d/q \) axis stator currents |
| \( s \) | rotor slip |
| \( \omega_x, \omega_y, \omega_z \) | synchronous angle speed, |
| \( v_{dr}, v_{ds}, v_{qs}, v_{qs} \) | rotor voltage and stator voltage |
| \( H \) | inertia constant of DFIG |
| \( P_l, P_m \) | generated and mechanical power of WGS |
| \( R_s \) | stator and rotor resistance |
| \( X_1 \) | transient circuit reactance |
| \( \tilde{L}_{ed}, \tilde{L}_{eq} \) | the rotor circuit reactance |
Thus, the regulation output $\zeta$ is selected as follows.

$$\zeta_1 = h_1(x) + k_1(x)u = \begin{bmatrix} C_1 x \\ D_1(x)u \end{bmatrix}$$

(5)

where $h_1(x)$ and $k_1(x)$ are denoted by $[C_1, 0]^T$ and $[0, D_1(x)]^T$, respectively. $C_1$ is selected to satisfy $i_r = C_1 x$ which can be derived from Equation (4) as follows.

$$C_1 = \begin{bmatrix} 0 & 1 & -I_{mu} & 0 \\ -1 & 0 & 0 & -I_{mu} \end{bmatrix}$$

(2) After the initial stage, the main control objective is to meet the LVRT requirement of providing as much reactive power as possible during the transient period. The reactive power of DFIG-based WSG can be denoted by Equation (6).

$$Q_s = \tilde{e}_r i_d - \tilde{e}_q i_q$$

(6)

Thus, the regulation output $\zeta$ is selected as Equation (7) to track the desired reactive power support.

$$\zeta_2 = h_2(x) + k_2(x)u = \begin{bmatrix} C_2(x) - Q_{desire} \\ D_2(x)u \end{bmatrix}$$

(7)

where $h_2(x)$ and $k_2(x)$ are denoted by $[0, D_2(x)]^T$ and $[C_2(x) - Q_{desire}, 0]^T$, respectively. $C_2(x)$ denotes the reactive power output of DFIG, which is selected as $C_2(x) = Q_s$, $Q_{desire}$ denotes the desired reactive power.

Combining the regulation outputs of the two stages given in Equations (5) and (7), two DAC problems for the RSC controller design can be obtained.

### 2.2 | DAC Problem for GSC

According to [23], a third-order dynamic model in Equation (8) is adopted for transient analysis of GSC.

$$\begin{cases}
\dot{i}_d = \frac{1}{L} v_d - \frac{R}{L} i_d + \omega L i_q \\
\dot{i}_q = \frac{1}{L} v_q - \frac{R}{L} i_q - \omega L i_d \\
\frac{1}{2} \frac{dV_{dc}^2}{dt} = P_g - P_{s} - \frac{V_{dc}^2}{R_{loss}} \\
P_g = v_d i_d + v_q i_q
\end{cases}$$

(8)

where $V_{dc}$ represents the DC link voltage, $R$ and $L$ are the filter resistance and inductance, respectively. $i_d, i_q$ are $d, q$-axis components of output current, $v_d, v_q$ are $d, q$-axis components of output voltage, $v_d, v_q$ are the $d, q$-axis components of grid voltage, $C$ is the DC link capacitor, $P_s$ represents active power output of GSC, $P_{s}$ represents the output active power of RSC, and $R_{loss}$ is the equivalent resistance of GSC.

Similar to RSC, the third-order model shown in Equation (8) can be reformulated as a general form, and the DAC problem for GSC is presented as follows.

$$\begin{align*}
\max_{\delta} & \min_{u} \left( \int_{0}^{T} \left\| (\tilde{x}(\tilde{\delta}, \tilde{x}) - \tilde{u}) \right\|^2 dt - \gamma^2 \int_{0}^{T} \left\| \tilde{d}(\tilde{\delta}) \right\|^2 dt \right) \\
\text{s.t.} & \quad \tilde{\dot{x}}(\tilde{\delta}) = \tilde{f}(\tilde{x}) + \tilde{g}_1(\tilde{x})\tilde{d} + \tilde{g}_2(\tilde{x})\tilde{u}
\end{align*}$$

(9)

where

$$\tilde{x} = [\Delta i_d \Delta i_q \Delta V_{dc}]^T, \tilde{u} = [\Delta V_{dc}]^T,$$

$$\left\| \tilde{d}(\tilde{\delta}) \right\|^2 = \tilde{d}^T(\tilde{\delta})\tilde{d}(\tilde{\delta}), \left\| (\tilde{x} - \tilde{\delta}) \right\|^2 = \tilde{x}^T\tilde{x},$$

$$\tilde{g}_1(\tilde{x}) = \tilde{g}_1 = \text{diag}(-1/L, -1/L, -2/C),$$

$$\tilde{d} = [\Delta V_{dc} \Delta i_d P_{s}]^T, \tilde{g}_2(\tilde{x})$$

and $\tilde{f}(\tilde{x})$ can be represented as follows.

$$\tilde{g}_2(\tilde{x}) = \begin{bmatrix} \frac{1}{T} & 0 \\
0 & \frac{1}{T} \\
-2 \frac{i_d + \Delta i_d}{C} & -2 \frac{i_q + \Delta i_q}{C} \end{bmatrix}$$

$$\tilde{f}(\tilde{x}) = \begin{bmatrix}
R \Delta i_d + w \Delta i_q \\
-\frac{w}{L} \Delta i_d - \frac{R}{L} \Delta i_q \\
-2 \frac{v_{dc}}{C} \Delta i_d - \frac{2v_{dc}}{C} \Delta i_q - \frac{2}{C R_{loss}} \Delta V_{dc}^2
\end{bmatrix}$$

For the GSC, the main control objective is to keep the DC link voltage stable. Since $\Delta V_{dc}^2$ is one of the state variables, the regulation output $\tilde{x}$ should be selected as the combination of state variables $\tilde{x}$ and control variables $u$ as follows.

$$\tilde{x} = h(\tilde{x}) + k(\tilde{x})u = \begin{bmatrix} \tilde{C}(\tilde{x})\tilde{x} \\ \tilde{D}(\tilde{x})u \end{bmatrix}$$

(10)

where $h(\tilde{x})$ and $k(\tilde{x})$ can be denoted by $[\tilde{C}(\tilde{x}), 0]^T$ and $[0, \tilde{D}(\tilde{x})]^T$, respectively. $\tilde{C}(\tilde{x})$ is a state-dependent weighing matrix, and the weight of $\Delta V_{dc}^2$ should be properly selected.

### 3 | SOLUTION METHOD FOR DAC PROBLEMS

In section 2, DAC problems for both RSC and GSC have been formulated with different control objectives in Equations (3) and (9). Theoretically, closed form expression of the feedback control law can be obtained by searching $V^*_x$ to
the HJI inequality [28]. However, it is difficult to obtain the analytical solution of HJI inequality directly, especially for nonlinear systems. In order to design the controllers of GSC and RSC, an approximate solution of \( u^* \) via the SDRE technique is presented.

4 BRIEF INTRODUCTION OF SDRE TECHNIQUE

By performing extended linearization, the SDRE technique transforms an affine nonlinear system into a linear-like structure with state-dependent coefficient (SDC) matrices. Taking system (2) as an example, it can be reformulated as follows.

\[
f(x) = A(x)x, \quad h(x) = C(x)x, \quad k(x) = D(x)
\]

where \( A(x), C(x) \) can be regarded as constant matrices with respect to the current states at each sampling instant. Then, the feedback control law can be obtained through the solution of state-dependent Riccati inequality below:

\[
A(x)^T \dot{P} + \dot{P}A(x) + P(y^{-2}g_2(x)g_2^T(x)) \dot{P} - \dot{P}(g_2(x)g_2^T(x)) \dot{P} + C(x)^T h(x)C(x) < 0
\]

4.1 SDC parameterization

Under the assumptions of \( f, h \in \Omega^1 \) \( f(0) = 0, h(0) = 0 \), the SDC parameterization \( A(x) \) and \( C(x) \) always exist by mathematical factorization [29, 30]. For an nth-order system with multiple variables, there are infinite selection of SDC matrices. Different SDC parameterizations result in different dynamic performance, which provides an additional freedom for the design of SDRE controller. It can be seen from Equation (2), the nonlinear terms appear as the product of two multiple variables, there are infinite selection of SDC matrices. Under the assumptions of \( f, h \in \Omega^1 \) \( f(0) = 0, h(0) = 0 \), the SDC parameterization \( A(x) \) and \( C(x) \) always exist by mathematical factorization [29, 30]. For an nth-order system with multiple variables, there are infinite selection of SDC matrices. Different SDC parameterizations result in different dynamic performance, which provides an additional freedom for the design of SDRE controller. It can be seen from Equation (2), the nonlinear terms appear as the product of two multiple variables, there are infinite selection of SDC matrices.

4.2 SDRE-based DAC solution for RSC

Through extended linearization, the nonlinear model of RSC in Equation (2) can be reformulated as

\[
\dot{x} = A(x)x + B_1(x)d + B_2(x)u
\]

\[
C_i(x) = \begin{bmatrix} -\gamma_{qi} + (1 - \alpha_1)\Delta \gamma_{qi} \\ \gamma_{d1} + (1 - \alpha_0)\Delta \gamma_{d1} \\ -\gamma_{di} \end{bmatrix}
\]

where \( B_1(x) = g_1(x), B_2(x) = g_2(x), A(x, x), C_i(x) \) are corresponding SDC matrices, \( y \) denotes a constant satisfying \( y_1 = 0, y_2 = \gamma_{desire}, A(x, x) \) is shown at the bottom of the next page. \( C_i(x) = C_1, C_2(x, x) \) can be represented as follows:

\[
C_2(x, x) = \begin{bmatrix} -\gamma_{qi} + (1 - \alpha_1)\Delta \gamma_{qi} \\ \gamma_{d1} + (1 - \alpha_0)\Delta \gamma_{d1} \\ -\gamma_{di} \end{bmatrix}
\]

At the initial stage of grid voltage dips, the main objective is to reduce the rotor current. According to the design principles of linear output regulator [34] and SDRE technique, the feedback control law can be obtained as follows:

\[
u_1 = -r_1^{-1}B_2(x)^T \dot{P}x
\]

where \( \dot{P} \) denotes the solution of Equation (12), \( r_1 = k_1^T k_1 \) is a positive definite symmetric matrix.

After the initial stage, the DAC problem is formulated with the regulation output \( z_2 \), and the RSC controller is designed to make the WGS generate reactive power to track \( \gamma_{desire} \) during the transient period. According to the relevant results of linear tracking control [34, 35] and SDRE technique, the feedback control law can be obtained in the form of Equation (15), and the influence of desired output is represented by an extra term \( r_2^{-1}B_2(x)^T \dot{g} \) on the right hand side of Equation (15).

\[
u_2 = -r_2^{-1}B_2(x)^T \dot{P}x + r_2^{-1}B_2(x)^T \dot{g}
\]

where \( \dot{g} \) denotes the solution of the differential equation

\[
\dot{g} = [\dot{P}B_2(x)r_2^{-1}B_2(x)^T - A(x, x)\dot{P} - C_2(x, x)^T \gamma_{desire}]
\]

\( r_2 = k_2^T k_2 \) is a positive definite symmetric matrix.

As for the selection of weighing matrices \( D_i (i = 1, 2) \), different principles are applied to different stages:

(1) At the initial stage, the objective is to reduce the rotor current, and \( D_1 \) is selected as an identity matrix.

(2) After the initial stage, the main objective is concentrated on the dynamic performance, the control effect and cost should be balanced. Let \( e_2 \) represent the tracking error between \( Q(x) \) and \( Q_{desire}, D_2 \) is selected as a decreasing function with respect
to \( e_Q \). When \( e_Q \to 0 \), the control cost will decrease quickly:

\[
D_2(e_Q) = \text{diag}\left( 1/\sqrt{m + e_Q^2}, 1/\sqrt{m + e_Q^2} \right)
\]

where \( m \) represents a constant that can be arbitrarily selected based on the consideration of control costs.

### 4.3 SDRE-based DAC solution for GSC

Similar to RSC, the nonlinear model of GSC can also be converted into the formation of Equation (16) as follows.

\[
\dot{x} = \bar{A}(\bar{x}, \bar{x})x + \bar{B}_1d + \bar{B}_2(\bar{x})\bar{u}
\]

where \( \bar{A}(\bar{x}, \bar{x}) = \bar{A}, \bar{B}_1 = \bar{g}_1, \bar{B}_2(\bar{x}) = \bar{g}_2(\bar{x}) \). The regulation output \( \bar{z} \) is selected the same as in Equation (10).

There is a difference in the SDC parameterization process between GSC and RSC. For the dynamic model of GSC, \( \bar{f}(\bar{x}) \) can be naturally written as a product of constant matrix \( \bar{A} \) and state variables \( \bar{x} \). Thus, compared with the design of the RSC control law, it is simpler to perform SDC parameterization during the control design of GSC. The coefficient matrix \( \bar{A} \) can be obtained directly from Equation (8).

The feedback control law of GSC can be obtained as:

\[
\bar{u} = -\bar{r}^{-1}\bar{B}_2(\bar{x})^T\bar{P}\bar{x}
\]

where \( \bar{P} \) is the solution of the following state dependent Riccati inequality, \( \bar{r} = \bar{k}^T\bar{k} \) is a positive definite symmetric matrix.

\[
\bar{A}^T\bar{P} + \bar{P}\bar{A} + \bar{P}(\bar{r}^{-2}\bar{B}_2(\bar{x})\bar{B}_1(\bar{x})^T)\bar{P} - \bar{P}\bar{B}_2(\bar{x})\bar{B}_1(\bar{x})^T\bar{P} + \bar{C}^\Delta(\bar{x})\bar{C}^\Delta(\bar{x}) \leq 0
\]

where \( \bar{C}^\Delta(\bar{x}) \) can be denoted by \( [\bar{C}(\bar{x}) - 0]^T \). It can be seen from Equation (18) that the state-dependent matrices are \( \bar{g}_2(\bar{x}) \) and \( \bar{C}^\Delta(\bar{x}) \). The weighting matrix \( \bar{C}(\bar{x}) \) should be selected according to the following principles: (1) the weight of \( \Delta V_{dc}^2 \) should be larger than other variables. (2) With the state variables approach to the equilibrium point, the weights should decrease. Thus, \( \bar{C}(\bar{x}) \) is selected as:

\[
\bar{C}(\bar{x}) = \text{diag}(n_{11} + |x_1|, n_{12} + |x_2|, n_{13} + |x_3|)
\]

where \( x_1, x_2, x_3 \) represents \( \Delta i_d, \Delta i_q \) and \( \Delta V_{dc}^2 \) respectively, \( n_{11}, n_{12}, n_{13} \) represents constants that can be selected based on the consideration of desired control effect. In this paper, \( n_{13} \) is selected as 1.5, \( n_{11} \) and \( n_{12} \) are selected as 1.

The selection of weighing matrix \( \bar{D}(\bar{x}) \) is similar to \( D_2(e_Q) \) as shown below.

\[
\bar{D}(\bar{x}) = diag(1/\sqrt{m + \bar{x}^T\bar{x}}, 1/\sqrt{m + \bar{x}^T\bar{x}})
\]

where \( m \) represents a constant that can be selected based on the consideration of desired control costs.

### 5 COMPREHENSIVE LVRT STRATEGY OF DFIG-BASED WGS

#### 5.1 Overcurrent limiting mechanism

The grid codes of many countries require that the rotor current of WGS must not exceed the threshold limit during normal operation, otherwise the protection must be activated [1]. To guarantee the rotor current stays within the operational limit, an overcurrent limiting mechanism is proposed in this paper.

In [36], transient voltage \( \bar{v} \) and rotor current \( \bar{i} \) satisfy the equation as Equation (19).

\[
\bar{v} = \frac{X_m}{s(X_r + X_m)} \left( \frac{X_m}{X_r + X_m} \bar{r} - R_{se}\bar{i} \right)
\]

Let \( \bar{i}_{\text{limit}} \) denotes the limit of rotor current (to ensure a security margin, \( \bar{i}_{\text{limit}} \) is selected less than the operational limit), \( \bar{i} \approx \bar{i}_{\text{lim}} \). In this paper, the operational limit of rotor current is selected as 2 p.u. according to [37], and \( \bar{i}_{\text{limit}} \) is selected as 1.85 p.u. to ensure a security margin.

---

| \( A(\alpha, x) \) |
|------------------|
| \[ \begin{bmatrix} \omega_i (\bar{r}_{d1} + \alpha \Delta \bar{r}_g) & -\omega_i (\bar{r}_{q1} + (1 - \alpha) \Delta \bar{r}_g) & -\frac{1}{L_0} & 0 & -\frac{1}{L_0} \frac{I^2}{I_{lim}} \\ -\omega_i (\bar{r}_{q1} + \alpha \Delta \bar{r}_g) & \omega_i (\bar{r}_{d1} + (1 - \alpha) \Delta \bar{r}_g) & 0 & -\frac{1}{L_0} \frac{I^2}{I_{lim}} & 0 \\ \Delta P_m & \Delta \bar{r}_g & -\frac{1}{L_0} \frac{I^2}{I_{lim}} & 0 & 0 \\ \omega_i (\bar{r}_{d1} + \alpha \Delta \bar{r}_g) \bar{X}_d & \omega_i (\bar{r}_{q1} + (1 - \alpha) \Delta \bar{r}_g) \bar{X}_d & \omega_i (\bar{r}_{q1} + (1 - \alpha) \Delta \bar{r}_g) \bar{X}_d & -\frac{(R_{se}) \omega_i}{\bar{X}_1} & -\frac{1}{L_0} \frac{I^2}{I_{lim}} \\ \omega_i (\bar{r}_{q1} + \alpha \Delta \bar{r}_g) \bar{X}_d & \omega_i (\bar{r}_{d1} + (1 - \alpha) \Delta \bar{r}_g) \bar{X}_d & \omega_i (\bar{r}_{d1} + (1 - \alpha) \Delta \bar{r}_g) \bar{X}_d & -\frac{(R_{se}) \omega_i}{\bar{X}_1} & \frac{1}{L_0} \frac{I^2}{I_{lim}} \end{bmatrix} \] |
If \( \vec{i}_r \) exceeds the limit, regulating the control output \( \vec{v}_r \) as \( \vec{v}'_r \), the d/q axis of \( \vec{v}'_r \) can be updated as (20).

\[
\begin{align*}
\vec{v}'_{dr} &= \vec{v}_r^* \cos(\varphi) / k + \left( X_r + X_m \right) \times \frac{2}{k} \left( X_r + X_m \right) \times \left( X_r + X_m \right) \times \frac{2}{k} \left( X_r + X_m \right) \times \left( X_r + X_m \right) \times \frac{2}{k} \left( X_r + X_m \right) \times \left( X_r + X_m \right) \times \frac{2}{k} \\
\vec{v}'_{qr} &= -\vec{v}_r^* \sin(\varphi) / k + \left( X_r + X_m \right) \times \frac{2}{k} \left( X_r + X_m \right) \times \left( X_r + X_m \right) \times \frac{2}{k} \left( X_r + X_m \right) \times \left( X_r + X_m \right) \times \frac{2}{k} \left( X_r + X_m \right) \times \left( X_r + X_m \right) \times \frac{2}{k} \left( X_r + X_m \right) \times \left( X_r + X_m \right) \times \frac{2}{k} 
\end{align*}
\]

(20)

where \( \varphi \) is the angle between synthetic vector \( \vec{v}_r \) and \( d \)-axis.

5.2 | Active crowbar protection circuit

Although the weighing matrices have been designed to reduce the initial rotor current, the rotor current may still exceed the operational limit during the initial period of voltage dips. Thus, an active Crowbar circuit [37] is applied as a second insurance to limit the rotor overcurrent at this stage. Different from the traditional Crowbar circuit, the active Crowbar circuit can actively quit when the current is below the limit. If the control system can be restored within two system cycles, the transient power control will contribute to support the grid [37]. Thus, this paper selected 0.02 s (about 1.2 system cycles) as the duration for the protection circuit. By doing this, the proposed RSC control can be restored and the possibility of damages to DFIG-based WGS can be reduced.

5.3 | Comprehensive LVRT strategy

The flowchart of the proposed comprehensive LVRT control scheme is shown in Figure 2. Active Crowbar circuit is applied to reduce the rotor overcurrent and DC link overvoltage at the initial stage, and quits when rotor current goes below the limit. Then, the proposed disturbance attenuation controllers for both RSC and GSC will be activated instead of the original PI controller to achieve reactive power support and better LVRT performance during the transient.

6 | CASE STUDY

In this section, tests on a single machine infinite bus (SMIB) system and a microgrid are performed to verify the effectiveness of the proposed comprehensive LVRT strategy. The parameters of DFIG-based WGS can be obtained from the detailed model in MATLAB/Simulink R2018b. The desired reactive power should be selected considering the wind farm’s reactive power output capacity limit [37]. In this paper, \( Q_{desired} \) is selected as 5 and 8 Mvar in SMIB system and microgrid system, respectively.

The structure of SMIB system is depicted in Figure 3, including a DFIG-based WGS, a 30 km transmission line, and two transformers. The rated active power of wind farm is 9 MW (six 1.5 MW DFIG-based WGS). The wind speed can be regarded as a constant during the transient period, which is selected as 15 m/s in the simulation.

In Figure 3, a three-phase to ground fault with grounding resistance 1 \( \Omega \) occurs near the 25 kV 1 bus at 3 s, and the fault is cleared at 3.1 s. During the fault period, the DFIG-based WGS adopts four control strategies for comparison: conventional PI controller, exact linearization based nonlinear controller [16], coordinated control strategy [24], and the proposed method. To avoid the influence of protection circuit on the control effect, all control strategies adopt the same active Crowbar protection circuits, and the simulation results are depicted in Figures 4–9.

It can be seen from Figure 7 that the terminal voltage of the wind farm suddenly drops to around 0.3 p.u. with conventional PI controller when the fault occurs. Since the stator flux cannot be mutated, a huge induced current is generated at rotor windings, which is shown in Figure 6. At the same time, the peak value of rotor current has exceeded 2.0 p.u., thus active
crow-bar circuit is activated. As shown in Figure 4, the DFIG-based WGS with the proposed LVRT strategy can quickly track the expected reactive power and provide enough reactive power support during the fault period. With the proposed LVRT strategy, the terminal voltage rises rapidly from 0.3 to 0.68 p.u. as shown in Figure 7, while the voltages with PI, Exact linearization, and Coordinated controllers maintain at about 0.32, 0.6 and 0.29 p.u., respectively. In Figure 9 the DC link voltage with proposed LVRT strategy is smoothly maintained near the rated value, while the DC link voltages with other control strategies have larger fluctuations, higher peaks, and lower troughs. Based on the results in Figure 5, larger active power output can be obtained with the proposed LVRT strategy, which results in less rotor speed oscillations as shown in Figure 8. In addition, with the proposed overcurrent limiting mechanism, the rotor current can be maintained at the setting value 1.85 p.u. to make full use of the control capability of converters as shown in Figure 6.

To further verify the control performance of the proposed LVRT strategy, an islanded microgrid system consisting of a wind farm, a PV power station, an energy storage system, six constant impedance loads, two induction motors, and three general generation systems is constructed as shown in Figure 10. A three-phase to ground fault occurs between bus 2 and bus 6 at 2 s, and the fault is cleared at 2.1 s. The grounding resistance is selected as 0.5 Ω. Three control strategies are adopted for comparison: conventional PI controller, Exact linearization based nonlinear controller, and the proposed LVRT strategy. The simulation results are depicted in Figures 11–13.

It can be seen from Figures 11 and 12 that WGS with the proposed LVRT strategy can provide more reactive power to support the entire microgrid system during the fault period. Compared with conventional PI controller and Exact linearization based nonlinear controller, WGS with the proposed LVRT strategy significantly improves the grid voltage dynamics. Compared with other control strategies, the DC link voltage with the
proposed LVRT strategy returns to the equilibrium point more smoothly with lower peaks and fewer fluctuations as shown in Figure 13.

To further verify the proposed LVRT strategy against parameter uncertainties, simulation tests with the parameter perturbations ranged by 5% and 10% are shown in Figures 14 and 15 (The parameters involved are inductance, reactance, and DC capacity). It can be seen from the simulation results, the DFIG-WGS with proposed LVRT strategy can maintain stability and has good transient performance even under parameter uncertainties.

7 | CONCLUSION AND FUTURE WORK

This paper proposes a comprehensive control scheme for DFIG-based WGS to enhance the LVRT capability under the impact of severe grid disturbances. Two main factors that directly limit LVRT capability are rotor overcurrent and DC link overvoltage. To address the above key issues, the DAC problems for both RSC and GSC are formulated with the objective of providing reactive power support and stabilizing the DC link voltage, respectively. The tracking regulator is designed for RSC to track the expected reactive power, which can support the grid voltage during the transient period. The SDRE technique is adopted to obtain the approximate solutions for the proposed DAC problems. An alternative SDC construction algorithm is adopted to generate appropriate SDC matrices in advance, and thus avoid huge computational burden in SDC parameterization process. To further reduce the rotor overcurrent at the initial stage of grid voltage dips, an overcurrent limiting mechanism and active Crowbar circuit are proposed. Simulations on an SMIB system and a microgrid have been performed to verify the control performance of the proposed LVRT strategy.
The results show that the proposed LVRT strategy can achieve a better control performance under grid disturbances without increasing hardware costs.

Further research works on improving the LVRT capability of DFIG-based WGs are undergoing. On one hand, infinite SDC matrices exist for multivariable systems, which result in different control performance. To achieve better dynamic performance, approaches for finding the best SDC matrices is yet to be investigated. On the other hand, as the key part to practicality, computational efficiency is the most concerned, the main computational burden in implementing the SDRE technique is the repeated computation of the steady-state solution (in real time) of the ARE at each sampling instant, which demands more computational resources than conventional control algorithms. At present, hardware test of the proposed method is undergoing, and many approaches to improve the computational efficiency have emerged, such as Newton method [38], Taylor series method [39] etc. These methods can provide guidance for the real-time application of the proposed comprehensive LVRT strategy.

ACKNOWLEDGMENTS

This work was supported by National Natural Science Foundation of China (U1766215, 51707147) and Science and technology project of State Grid Corporation of China (Control Strategy Optimization Technology for Large-Scale Photovoltaic Power Generation on the sending-end and receiving-end of DC power system). The authors are with State Key Laboratory of Electrical Insulation and Power Equipment, and school of Electrical Engineering, Xi’an Jiaotong University, Xi’an 710049, Shaanxi Province, China.

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How to cite this article: Qin B., Zhang R., Li H, Ding T, Liu W. Disturbance attenuation control for LVRT capability enhancement of doubly fed wind generators. IET Gener Transm Distrib 2021; 1–11. https://doi.org/10.1049/gtd2.12200.