A DC chopper-based fast active power output reduction scheme for DFIG wind turbine generators

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Abstract
Increasing penetration level of renewable energy results in unprecedented operational challenges of AC grids due to generation uncertainty and reduced inertia. In grid emergencies, Fast active Power output Reduction (FPR) is demanded to drop wind turbine generator (WTG) power outputs faster than usual. However, the power mismatch between WTG mechanical power input and reduced electrical power output resulted from FPR can lead to rotor overspeed, which cannot be timely nullified by slow-responding pitch control. Therefore, this paper proposes a novel FPR scheme for doubly-fed induction generator (DFIG)-based WTG through coordinated control of DC chopper and pitch angle. Specifically, the FPR command is executed by DFIG rotor-side converter control, while rotor overspeed is restricted by triggering the DC chopper to dissipate the mismatched power. The pitch angle is actuated at a maximal rate to eliminate the mismatched power and switch off the DC chopper. The effectiveness of the proposed FPR scheme is verified through comparative simulation studies under FPR command execution and a grid fault. It shows the proposed scheme can achieve FPR in tens of milliseconds, avoid rotor overspeed and provide low-voltage ride-through capability in a fully-controlled manner.

1 | INTRODUCTION

With environmental pollution challenges and energy crisis arising worldwide in the recent decades, wind power stands out from other various types of renewable energy. Global wind turbine generator (WTG) installed capacity sees a significant growth in recent years and is expected to increase by 50% from the present baseline capacity over the next 5 years [1]. For maximum utilization of wind power, WTGs are conventionally operated in the maximum power point tracking (MPPT) mode [2] regardless of the grid conditions, and at low penetration level this independent MPPT mode has negligible impact on grid operational security. However, large-scale integration and high penetration levels of wind power with the characteristics of high intermittency and fluctuation as well as reduced inertia contribution to the power grid can deteriorate the grid stability [3, 4].

This situation has led the academia and industry to re-evaluate power grids characteristics and adopt new grid code requirements for WTGs [5–7]. One of the new requirements is the Fast active Power output Reduction (FPR) capability of WTGs. The FPR can address grid operational challenges by fast reducing WTG power outputs under the following emergency conditions:

(1) Transmission network congestion: Transmission capacity is not planned to accommodate excessive wind power, leading to the grid thermal overloading [8]. To tackle the transmission
overloading issue, for example, the National Grid UK has
designed a new ancillary service of ‘transmission constraint
management’ for the WTG operators to decrease the amount
of power production with high ramp rate requirements [9];

(2) High-voltage direct current (HVDC) commutation failure: Tradi-
tional HVDC transmission systems planned for wind power
delivery are prone to grid faults, causing commutation failures
which can block the HVDC converter in the receiving end and
raise the grid frequency in the sending end to unacceptable levels [10]. To deal with the frequency stability, the National Grid
UK designed another new ancillary service of ‘enhanced fast
frequency response’ service, under which the total response
time delay of WTG frequency response must be as fast as
less than 1 s and the time delay for detection and instructing
response must be as short as less than 0.5 s [11];

(3) Grid low-voltage fault conditions: WTG transient rotor over-
current shall be suppressed by effective measure [12],
and WTGs are required to remain grid connected for reactive power
support by grid codes [13]. In particular, the UK grid code
requires WTGs to reduce their active power outputs to a level in
proportion to the retained grid voltage during voltage dips [14].

The common WTG FPR scheme is to modify the initial
MPPT power reference in rotor-side converter (RSC) control
according to the power command, and execute the pitch
control to limit the rotor speed variations [15, 16]. However, for
achieving the FPR, the pitch control with typical time con-
stant over 1 s is slow to offset the unbalanced active power
(between the mechanical power input from the prime mover
and the electrical power output). The unbalanced power acceler-
ates the rotor speed, causing rotor overspeed to potentially dam-
age the mechanical components or shut down the WTG system.

Extra energy storage systems (ESSs) are useful for the WTG
FPR to address the power dissipation issue. Different coordi-
nated control strategies between WTG and ESS are proposed in
[17–20]. However, ESS may be economically unsuitable for the
infrequent WTG FPR, and the state of art of ESS technology
still has implementation issues such as low power density,
low charging/discharging rate, low service life etc. [21, 22]. By
contrast, energy dissipation devices such as DC choppers are
less expensive than ESS. A DC chopper is comprised of a dump
resistor and a power electronic switch, and it is typically embed-
ded in the DC-link, which consists of a dump resistor
in the AC/DC conversion system of a WTG to prevent
DC-link overvoltage during low voltage ride-through (LVRT)
[23, 24].

A DC chopper can also be employed to achieve the FPR
and prevent rotor overspeed. However, the unbalanced energy
for FPR can be significant, so the aforementioned DC chopper
scheme may have significant energy handling burden which may
reduce the equipment lifespan of a DC chopper. Reference [22]
proposes a novel scheme for permanent magnetic synchronous
generator-based WTGs to employ a DC chopper and a pitch
angle control together for eliminating excessive power. How-

ever, the implementation of such a scheme in doubly fed induction
generator (DFIG) WTGs has not been reported.

This paper proposes a novel FPR scheme for DFIG WTGs
through the coordinated control of a DC chopper and a pitch
angle control. Under the proposed scheme, the DC chopp-

per is triggered at the beginning of FPR to contain the ini-
tial rise of the rotor speed, and it can be switched off when
the slow-responding pitch control works. The proposed FPR
scheme offers more advantages than those aforementioned typ-
ical DFIG power control schemes as reported in [15, 16, 19,
20], as it makes full use of both the DC chopper and the pitch
angle control which function in different time scales for rotor
speed security.

The rest of the paper is organized as follows: Section 2 briefly
introduces the mathematical modelling and conventional con-
tral strategy of a DFIG WTG. Section 3 presents the detailed
design of the proposed FPR scheme. Section 4 optimizes the
FPR controller parameters and evaluates the robustness of the
proposed scheme through the small signal stability analysis
(SSSA) and the time-domain simulation analysis. To evaluate the
effectiveness and advantages of the proposed FPR scheme, Sec-
tion 5 compares the proposed FPR scheme with conventional
ones under FPR control command and voltage-dip fault condi-
tion in simulation case studies. Section 6 concludes the paper.

2 | MODELLING AND CONVENTIONAL
CONTROL OF DFIG WTG SYSTEM

Figure 1 illustrates the circuit and control schematics of a grid
connected DFIG WTG. The low-speed wind turbine drives the
high-speed generator rotor through a gearbox. The generator is
a wound-rotor DFIG, with its stator directly connected to the
grid and its rotor fed through a variable-frequency converter.
The voltage-sourced converter (VSC) power conversion system
consists of an RSC, a grid-side converter (GSC) and a DC-link
system, which is normally rated at a small fraction (25–30%) of
the total generator rated capacity [18]. A DC chopper can be
embedded in the DC-link, which consists of a dump resistor
and an insulated gate bipolar transistor (IGBT) in series. The
DFIG mathematical model and conventional control scheme
are presented in this section as a basis for the proposed FPR
scheme design.

2.1 | Modelling of a DFIG

A DFIG machine can be described by the following voltage rela-
tionships of (1) and (2) and the flux-linkage relationship of (3)
[2], where all the variables are expressed in per unit in a syn-
chronous d−q reference frame:

\[
\begin{bmatrix}
\dot{i}_{rd}
\\
\dot{i}_{rq}
\end{bmatrix}
=
\begin{bmatrix}
-R_r & 0 \\
0 & -R_q
\end{bmatrix}
\begin{bmatrix}
i_{rd}
\\
i_{rq}
\end{bmatrix}
+
\frac{1}{\omega_s}
\begin{bmatrix}
\psi_{rd}
\\
\psi_{rq}
\end{bmatrix}
+
\begin{bmatrix}
0 & -\omega_s
\\
\omega_s & 0
\end{bmatrix}
\begin{bmatrix}
\psi_{rd}
\\
\psi_{rq}
\end{bmatrix},
\]

(1)

\[
\begin{bmatrix}
\dot{\psi}_{rd}
\\
\dot{\psi}_{rq}
\end{bmatrix}
=
\begin{bmatrix}
R_r & 0 \\
0 & R_q
\end{bmatrix}
\begin{bmatrix}
\psi_{rd}
\\
\psi_{rq}
\end{bmatrix}
+
\frac{1}{\omega_s}
\begin{bmatrix}
\psi_{rd}
\\
\psi_{rq}
\end{bmatrix}
+
\begin{bmatrix}
0 & -\omega_{dip}
\\
\omega_{dip} & 0
\end{bmatrix}
\begin{bmatrix}
\psi_{rd}
\\
\psi_{rq}
\end{bmatrix},
\]

(2)

\[
\begin{bmatrix}
\psi_{rd}
\\
\psi_{rq}
\end{bmatrix}
=
\begin{bmatrix}
-X_r & 0 & X_{sr} & 0
\\
0 & -X_r & 0 & X_{qr}
\\
-X_m & 0 & X_r & 0
\\
0 & -X_m & 0 & X_r
\end{bmatrix}
\begin{bmatrix}
i_{rd}
\\
i_{rq}
\\
i_{sr}
\\
i_{qr}
\end{bmatrix},
\]

(3)
where \( \mathbf{v}_s = v_{sd} + jv_{sq} \) and \( \mathbf{v}_r = v_{rd} + jv_{rq} \) are the stator and rotor voltage vectors, respectively; \( \mathbf{i}_s = i_{sd} + ji_{sq} \) and \( \mathbf{i}_r = i_{rd} + ji_{rq} \) are the stator and rotor current vectors, respectively; \( \mathbf{\Psi}_s = \Psi_{sd} + j\Psi_{sq} \) and \( \mathbf{\Psi}_r = \Psi_{rd} + j\Psi_{rq} \) are the stator and rotor flux linkage vectors, respectively; \( R_s \) and \( R_r \) represent the stator and rotor resistances, respectively; \( X_{ls} = X_{ls} + Xm \), \( X_{lr} = X_{lr} + Xm \), where \( X_{ls} \) and \( X_{lr} \) are the stator and rotor leakage reactances, respectively, and \( Xm \) is the magnetizing reactance; \( \omega_b, \omega_s \) and \( \omega_r \) are the base, stator and rotor angular speeds respectively, and \( \omega_{sl} = \omega_s - \omega_r \).

2.2 Wind turbine aerodynamics

Wind power \( P_0 \), existing in the kinetic energy of wind crossing a surface \( S \) at a speed \( v_w \), is expressed by [2]

\[
P_0 = \frac{1}{2} \rho S v_w^3,
\]

where \( \rho \) is the air density.

Based on Betz' Law, only a part of the power \( P_0 \) can be captured by wind turbine as the mechanical power input \( P_m \):

\[
P_m = C_p(\lambda, \beta)P_0 = \frac{1}{2} \rho S C_p(\lambda, \beta) v_w^3,
\]

where the power coefficient \( C_p \) is a non-linear function of tip-speed ratio \( \lambda \) and pitch angle \( \beta \) [25]:

\[
C_p = \begin{cases} 
0.5176 \left(\frac{116}{\lambda} - 0.4\beta - 5\right) e^{-\frac{21}{\lambda}} + 0.0068\lambda, \\
\frac{1}{\lambda+0.08\beta} - \frac{0.035}{\beta^3+1}, 
\end{cases}
\]

where the tip-speed ratio \( \lambda \) is defined as the ratio between real-time turbine speed \( \omega_j \) (in per unit, with its base value \( \Omega_b \)) and the wind speed \( v_w \):

\[
\lambda = \frac{\Omega_b R_{WT}}{\omega_j v_w},
\]

where \( R_{WT} \) is the radius of the wind turbine.

According to (6) and (7), to capture the maximum power by wind turbine, the power coefficient \( C_p \) should track a maximum value \( C_{p\text{max}} \) by regulating pitch angle \( \beta \) to \( 0^\circ \) and keeping the tip-speed ratio at a constant optimal value \( \lambda_{opt} \). \( \lambda_{opt} \) can be achieved by maintaining turbine speed \( \omega_j \) at its optimal value \( \omega_{j\text{opt}} \), which shall vary in proportion to the instantaneous wind speed \( v_w \):

\[
\omega_{j\text{opt}} = \frac{\lambda_{opt}}{\Omega_b R_{WT}} v_w.
\]

2.3 DFIG conventional control

The control objective of the RSC is to conduct the MPPT, whereas the GSC aims to maintain the DC-link power balance by regulating the DC voltage. For the situation when the rotor speed is below its rated value, the pitch angle \( \beta \) is controlled at a fixed value of \( 0^\circ \), allowing the RSC to conduct the MPPT mode. When the rotor speed exceeds its rated value, the pitch angle is increased to reduce the mechanical power extracted from the wind to restrict the rotor overspeed. The vector control scheme for RSC and GSC employs two cascaded proportional-integral (PI) control loops in a synchronous \( d-q \) reference frame. The \( d \)-axis of the reference frame is aligned with the stator voltage vector \( v_s \) by a phase-locked loop (PLL), such that the \( d \) and \( q \) components of the three-phase balanced stator voltage in steady state are

\[
\begin{aligned}
ev_{sd} &= v_s, \\
ev_{sq} &= 0,
\end{aligned}
\]
The conventional DFIG control scheme as illustrated in Figure 1 is well presented in [2]. This section only introduces the RSC control, the GSC control and the pitch angle control which are relevant to the proposed FPR scheme.

2.3.1 RSC control

By combining (1), (3) and (9) and neglecting the stator flux derivatives and stator resistance in (1), it can be deduced that the $d$-axis stator and rotor currents are proportionally linked, $i_{sd} = i_{rd} X_s / X_r$. Accordingly, the stator active power $P_s$ is proportional to rotor current $i_{rd}$ as

$$P_s = v_{id} i_{rd} + v_{iq} i_{rq} = |v_s| X_s i_{rd}. \quad (10)$$

The optimal active power reference $P^{*}_s$ for RSC is obtained according to the instantaneous rotor speed, based on a pre-set MPPT curve. Based on (10), the stator active power control tracks $P^{*}_s$ by regulating rotor current $i_{rd}$. This is achieved by a PI controller in the RSC control to compute $d$-axis current reference $i_{rd}^*$ for the inner current control:

$$i_{rd}^* = \left( k_{pd} + \frac{k_{id}}{s} \right) (P^{*}_s - P_s), \quad (11)$$

where $k_{pd}$ and $k_{id}$ are the proportional and integral coefficients of the stator active power controller, respectively.

2.3.2 GSC control

The dynamics of DC-link voltage $V_{dc}$ is determined by the difference between the active power flowing into GSC $P_g$ and the one flowing into the rotor $P_r$ as illustrated in Figure 1:

$$C V_{dc} \frac{d V_{dc}}{dt} = P_g - P_r. \quad (12)$$

The GSC active power $P_g$ is proportional to the GSC $d$-axis current $i_{gd}$:

$$P_g = v_{gd} i_{gd} + v_{gq} i_{gq} = |v_g| i_{gd}, \quad (13)$$

where $i_{gd}$ and $i_{gq}$ refers to the GSC $d$- and $q$-axis currents, respectively.

Based on (12) and (13), the DC-link voltage $V_{dc}$ can be maintained at a reference value $V^{*}_{dc}$ by regulating $i_{gd}$ expressed as

$$i_{gd}^* = \left( k_{pd} + \frac{k_{id}}{s} \right) (V^{*}_{dc} - V_{dc}), \quad (14)$$

where $k_{pd}$ and $k_{id}$ are the proportional and integral coefficients of the DC voltage controller, respectively.

2.3.3 Pitch angle control

With a PI controller, the pitch command $\beta^{cmd}$ is calculated as

$$\beta^{cmd} = \left( k_{pg} + \frac{k_{ig}}{s} \right) (\omega - \omega_{max}), 0 \leq \beta^{cmd} \leq \beta_{max}, \quad (15)$$

where $k_{pg}$ and $k_{ig}$ are the proportional and integral coefficients of the pitch controller, respectively; and $\omega_{max}$ is the rated value of the rotor speed.

The pitch angle control is executed by actuating a non-linear mechanical servo with a limited rate of change. Thus, the FPR power imbalance issue as discussed earlier may not be addressed sufficiently fast solely by the pitch angle control, requiring a power electronics-controlled DC chopper in a faster time scale to restrict the initial rotor speed rise. This entire design will be discussed in the next section.

3 PROPOSED FPR SCHEME

An FPR scheme for DFIG WTG is proposed in this section to achieve DFIG fast active power reduction directly by controlling RSC and secure the rotor speed by employing a DC chopper and a pitch angle control in different time scales. The FPR scheme is designed in the following four modifications to the conventional control scheme as illustrated in Figure 1 in blue colour: (1) the MPPT mode in RSC is replaced by an RSC direct active power control to conduct FPR commands; (2) the GSC constant DC-link voltage regulation is replaced by a GSC DC-link voltage/rotor speed droop control, to vary the DC-link voltage in proportion to rotor speed variations; (3) a DC chopper control can be switched on at a pre-set DC voltage threshold to dissipate the unbalanced power for restricting rotor overspeed and (4) the traditional pitch control is replaced by a fast pitch control to set the desired pitch angle at the beginning of FPR to promote the pitch control response speed.

3.1 RSC direct active power control

To enable the direct execution of an FPR, a direct active power control is proposed in the active power control loop to change the MPPT mode.

The total active power output $P_t$ is obtained as the sum of the stator active power $P_s$ and the GSC active power $P_g$ as given in (10) and (13), respectively, which is expressed as (16) and shown in the right half part of Figure 2.

$$P_t = P_s - P_g = |v_s| X_s i_{rd} - |v_g| i_{gd}. \quad (16)$$

As observed from (16), $P_t$ can be controlled by regulating the reference of $i_{rd}$ for conventional inner current loop through
a PI controller, but it is also strongly coupled with the GSC d-axis current $i_{gd}$. As $i_{gd}$ can vary significantly with the dynamical current of the DC chopper, this can cause disturbances in the total DFIG active power output $P_e$. To eliminate this negative impact, a feedforward decoupling term $K$ is introduced in the proposed control loop, as shown in the left half part of Figure 2. As illustrated in Figure 2, the coupling effect of $P_g$ can be offset by setting $K$ as

$$K = \frac{X_s}{X_m} i_{gd}.$$

(17)

Therefore, the direct active power control loop for RSC is designed as

$$i_{rd}^* = \left( k_{p1} + \frac{k_{i1}}{s} \right) (P_e^* - P_e) + \frac{X_s}{X_m} i_{gd},$$

(18)

where $k_{p1}$ and $k_{i1}$ are the proportional and integral coefficients of the direct active power controller, respectively.

### 3.2 GSC DC voltage/rotor speed droop control

As the RSC direct active power control allows the control of total DFIG electrical power output as discussed before, the unbalanced electrical and mechanical power for FPR actions can raise the rotor speed. A DC-link voltage/rotor speed droop control is designed as seen in Figure 1 to co-relate the rotor speed rise with the DC-link voltage as

$$V_{dc}^* = V_{dc} + k (\omega_r - \omega_{opt}), \quad V_{dc} \leq V_{dc}^* \leq V_{dc\text{max}}$$

(19)

where $V_{dc}$ is the rated DC voltage, $V_{dc\text{max}}$ is the maximum allowable DC voltage and $k$ is the droop coefficient of the DC voltage/rotor speed droop control.

Under the DC voltage/rotor speed droop control, the DC-link voltage is regulated in proportional to the rotor speed rise. In this manner, any rotor overspeed can raise the DC-link voltage, which will in turn trigger the DC chopper to dissipate the excessive energy by a DC-link voltage threshold as designed in the next subsection.

### 3.3 DC chopper control

A threshold $V_{dc\text{th}}$ (higher than the rated DC voltage $V_{dcb}$) is applied to the DC chopper control. This threshold sets a criterion on whether to trigger the DC chopper in connection with the DC voltage/rotor speed droop control. At any instantaneous DC voltage $V_{dc}$ higher than the threshold $V_{dc\text{th}}$, the DC chopper control turns on the dump resistor by regulating the duty cycle $D$ of the IGBT switch, as illustrated in Figure 1:

$$D = \left( k_{pc} + \frac{k_{ic}}{s} \right) \left( V_{dc} - V_{dc\text{th}} \right), \quad 0 \leq D \leq 1,$$

(20)

where $k_{pc}$ and $k_{ic}$ are the proportional and integral coefficients of the DC chopper controller, respectively.

### 3.4 Fast pitch angle control

As introduced before, the conventional pitch angle control has a slow response to secure the rotor speed. Given that an FPR action has a clear active power reference for the DFIG, the pitch angle control can be actuated at the beginning of the FPR by directly assigning a correct pitch angle reference. This is anticipated to be faster than the conventional pitch angle control which executes the pitch control only at the rotor speed out-of-limit.

The proposed fast pitch control calculates the pitch reference $\beta_0$ in two steps: Step 1 calculates the expected optimal power coefficient $C_{P0}$ at the FPR commanded active power $P_e^*$ aiming in the final steady state the mechanical power input $P_m$ is equal to $P_e^*$

$$C_{P0} = \frac{P_e^*}{P_0},$$

(21)

where the wind power $P_0$ is determined by the instantaneous wind speed $v_w$ as defined in (4). Step 2 looks up for $\beta_0$ in correspondence to the optimal $C_{P0}$ based on the lookup table shown in Figure 3. The lookup table is obtained from the aerodynamic characteristics of a DFIG in (6).
Furthermore, to regulate the rotor speed at the optimal \( \omega_{opt} \) following an FPR action, a minor compensation term \( \hat{\beta}_c \) is added to the initial value \( \beta_0 \), which is generated from a PI controller limited by a very small output margins \( [-\Delta \beta_{max}, \Delta \beta_{max}] \) as expressed in (22).

\[
\hat{\beta}_c = \left( \frac{k_p \hat{\beta}_c}{s} + k_i \beta_0 \right) (\omega - \omega_{opt}), |\beta_c| \leq \Delta \beta_{max},
\]

where \( k_p \hat{\beta}_c \) and \( k_i \beta_0 \) are the proportional and integral coefficients of the pitch angle compensator, respectively. Pitch angle margin \( \Delta \beta_{max} = 0.3^\circ \) is adopted in this paper.

As shown in Figure 1, the final pitch command \( \beta_{cmd} \) is obtained as the sum of the FPR commanded pitch angle reference \( \beta_0 \) and the compensated pitch angle reference \( \hat{\beta}_c \):

\[
\beta_{cmd} = \beta_0 + \hat{\beta}_c,
\]

The proposed fast pitch angle control can drive the pitch angle at a maximal rate at the beginning of FPR to assist the fast-responding DC chopper in suppressing rotor overspeed. In such a way, the power imbalance as resulted by the FPR action can be eliminated so that the DC chopper can be eventually switched off. Moreover, with the help of the compensation term \( \hat{\beta}_c \), the rotor speed can be restored to the optimal MPPT value.

### 3.5 Overall FPR scheme implementation

Figure 4 presents a flowchart which illustrates the overall operation procedure of the proposed FPR scheme. At the reception of an FPR command from system operators, the DFIG control mode is switched from the conventional mode to the proposed FPR scheme by applying the simultaneous FPR control signal switches as shown in yellow background in Figure 1.

The FPR action is executed by the RSC direct active power controller. The mechanical and electrical power imbalance drives the DFIG rotor speed to high values, and with the GSC DC voltage/rotor speed droop control the DC voltage rises with the rotor speed. This high DC voltage triggers the pre-set threshold in the DC chopper control and the excessive power is dissipated by the dump resistor of the DC chopper, preventing rotor overspeed. Meanwhile, the fast pitch control looks up the final optimal pitch angle at the beginning of the FPR, reducing the captured wind power and switching off the DC chopper in a faster speed than the conventional pitch control. In this way, the DC chopper and pitch angle control can jointly ensure rotor speed security for the FPR.

Compared to the conventional control scheme without DC chopper, the proposed FPR scheme avoids the complete reliance on the slow-responding pitch control. Compared to the power control schemes as reported in [19, 20] solely using the DC chopper, the proposed FPR employs both the power regulation capability of the pitch angle control and the DC chopper.

These advantages will be further verified through the simulation case studies in Section 5.

Moreover, FPR cannot only execute the active power reduction commands from remote system operators but can also automatically adjust DFIG active power outputs in response to various grid events such as short-circuit fault or frequency excursion. For example, for the DFIG to provide the LVRT capability usually compulsory by grid codes, as shown in Figure 4, an active power/voltage magnitude droop control can be added in the FPR scheme to automatically generate the power command \( P_r^\ast \) for RSC direct active power control when the grid voltage falls below a preset threshold \( V_{ac,th} \). The DFIG active power output will then be reduced proportionally with the stator voltage magnitude \( |v_s| \), which is also the grid voltage at the point of common coupling (PCC):

\[
P_r^\ast = P_0 + k_{llv} (|v_s| - V_0), |v_s| < V_{ac,th}
\]

where \( P_0 \) and \( V_0 \) are the initial setpoint of active power output and stator voltage magnitude, respectively; and \( k_{llv} \) represents the droop coefficient.

The LVRT performances of the proposed FPR scheme will be evaluated and compared with the traditional control schemes in Section 5.
CONTROL PERFORMANCE OPTIMIZATION AND EVALUATION

To ensure a satisfactory performance of the proposed FPR scheme under various operating conditions, it is necessary to optimize the PI controller parameters of the FPR scheme and evaluate its robustness through both SSSA and time-domain simulation analysis.

The DFIG machine of (1)–(3), the two-mass shaft system as presented in [26], the wind turbine aerodynamics of (5)–(7), the VSC DC-link dynamics of (12) and the proposed FPR scheme of (16)–(23) are established in a system state-space matrix and linearized into the following form:

\[ \Delta \dot{x} = A \Delta x, \]  

where \( x \) is the state column vector and \( A \) is the state matrix. The system parameters are listed in the Appendix Table A1. The SSSA is conducted by analysing the eigenvalues of the state matrix \( A \).

4.1 Parameters tuning for control optimization

In the SSSA, the eigenvalue trajectories of \( k_{pl} \) and \( k_{1} \) of the RSC direct active power controller, and \( k_{pd} \) and \( k_{dc} \) of the GSC DC voltage controller are analysed with results shown in Figures 5(a)–(d), respectively.

As seen in Figure 5(a), as \( k_{pl} \) increases, a pair of eigenvalues with the imaginary value around \( \pm 4000 \text{ s}^{-1} \) shifts towards the imaginary axis, until they reach the right half plane at \( k_{pl} \) of 3 indicating an instability.

Figure 5(b) presents that with the increase of \( k_{1} \), the damping ratio of a pair of conjugate complex poles is slightly reduced, and a real pole moves left which indicates the active power response becomes faster. The real pole is almost fixed at \( -53.45 \text{ s}^{-1} \) and cannot move further left when \( k_{1} \) is larger than 100, meaning the fastest response time of the designed RSC direct active power control is limited at \( 3/53.45 \text{ s} = 56 \text{ ms} \).

Figure 5(c) shows that with the increase of \( k_{pd} \), a pair of real poles first move towards each other and then become a pair of conjugate complex poles at \( k_{pd} \) of 4.5. The damping ratio of the conjugate poles starts to decrease with further increase of \( k_{pd} \), indicating a deteriorated DC voltage stability.

Figure 5(d) shows that with the increase of \( k_{dc} \) from 0 to a large value 4000, a pair of conjugate complex poles move right and the damping ratio is reduced from 0.7 to 0.44, and a real pole moves left indicating a faster DC voltage response. However, when \( k_{dc} \) exceeds 1000, the time constants of dominant poles in all cases are less than 5 ms—a very fast responding speed. It can be concluded that the change of \( k_{dc} \) has trivial impact on the system stability.

Based on the above analytical results, the optimal values for the above parameters are identified as \( k_{pl} = 0.5 \), \( k_{1} = 100 \), \( k_{pd} = 8 \) and \( k_{dc} = 1000 \), which are presented in the Appendix Table A1 and adopted in simulation case studies in Section 5.

To verify the correctness of the state-space model as well as the effectiveness of parameters tuning on improving system stability, a 10 MW-rated DFIG WTG time-domain model is developed and simulated by SimPowerSystems in MATLAB/Simulink environment. The GSC is rated at 50% of the DFIG nominal rating. The DFIG WTG is connected to a 25-kV grid through a 575 V/25 kV step-up transformer and a 30-km line as shown in Figure 6. All the same parameters are presented in Appendix Table A1 and Table A2. The DFIG WTG is initially working in MPPT mode at wind speed 11 m/s and a total active power output of 1.06 pu.

A large FPR command to drop the DFIG active power to 0.1 pu is applied at \( t = 0.02 \text{ s} \). Figure 7 compares the results of the established small signal model and the time-domain model. As observed in Figure 7, the responses of DFIG active power output in the state-space model (dashed curve) and the time-domain model (solid curve) are almost identical, with minor difference in the enlarged zone with high-frequency oscillations, which confirms the accuracy of the state-space model. Furthermore, the active power gradually diverges after the FPR with the untuned parameters at the oscillation frequency 4833 rad/s from \( t = 0.12 \text{ s} \) as shown in the red curves of Figure 7. This phenomenon is consistent with the eigenvalue analysis as
different FPR commands as all the poles lie in the left plane of the root loci chart.

The FPR performance is further verified in the time-domain simulations of Figures 9 and 10. Figure 9(a) presents the DFIG active powers can be reduced to as low as 0.1 pu at different wind speeds and consequently different initial active power points, without significant rotor speed variations as seen in Figure 9(b). Note that at the high wind speed of 11 m/s the rotor speed security can still be guaranteed within the magnitude of 1.2 pu.

Figure 10(a) presents the simulation results for various FPR commands ranging from 0.1 to 0.9 pu. It can be seen the FPR can be achieved without noticeable delay and the rotor speed can be robustly secured as shown in Figure 10(b).

5 | CASE STUDIES

To evaluate the performance of the proposed FPR scheme, two case studies, using the same system parameters as Section 4 and presented in the Appendix are conducted to compare the FPR with the other historically reported control schemes: (1) an FPR command instructed from local or remote system operator and (2) a short-circuit fault at the DFIG PCC.

5.1 | FPR command execution

The proposed FPR scheme denoted as ‘FPR’ in Figure 11 is compared against the other two typical DFIG power control schemes:

(1) The modified conventional control scheme as reported in [15] and [16], which directly sets the RSC active power reference
The performance of the 'Pitch' scheme, the 'chopper' scheme and the 'FPR' scheme at various FPR commands based on the FPR commanded value and only employs the pitch angle control to restrict the rotor speed variation. This scheme is denoted as 'Pitch' in Figure 11.

(2) The coordinated active power control scheme as proposed in [19] and [20] with a DC chopper, where the RSC maintains the MPPT function, the GSC executes the FPR by controlling the total active power output and the DC chopper regulates the DC voltage. This scheme is denoted as 'Chopper' in Figure 11. Note that in the case study this scheme has the same resistance of the dump resistor for the DC chopper as the proposed FPR scheme.

The wind speed is set to constant 11 m/s, thus the DFIG has an active power output of 1.06 pu initially under the MPPT control mode for all the three schemes. The large FPR command which orders the DFIG active power to drop to 0.1 pu is applied at \( t = 5 \) s. The FPR command lasts for a period of 25 s and the MPPT mode is resumed at \( t = 30 \) s.

As observed in Figure 11(a), both the ‘Pitch’ and ‘FPR’ schemes can reduce the DFIG active power outputs instantly to 0.1 pu. By contrast, the active power output of the ‘Chopper’ scheme is reduced to 0.46 pu at best, failing to track the FPR command, as the GSC power rating 0.5 pu and the slip power 0.1 pu from the rotor windings restrict the amount of the power which can be dissipated by the DC chopper at 0.6 pu, as shown in Figure 11(c).

As observed in Figure 11(b), the DFIG WTG under the ‘Pitch’ scheme experiences rotor speed variations with a higher magnitude and longer duration, exceeding the limit of 1.2 pu for over 6 s (for clear demonstration, the protections such as brakes are removed), as there is no energy dissipation component and the power balancing only relies on the conventional slow-responding pitch angle control. As a result, the pitch angle of the ‘Pitch’ scheme is varied significantly as shown in Figure 11(d) compare to the other two schemes.

As observed in Figure 11(c), significant amount of energy (power times time) under the ‘Chopper’ scheme is continuously dissipated by the DC chopper. In comparison, the proposed FPR scheme has less amount of energy dissipation by the DC chopper, as it engages the pitch control to coordinately balance the power mismatch as seen in Figure 11(d).

In general, the proposed FPR scheme combines the respective advantages of the ‘Chopper’ and ‘Pitch’ schemes through the coordinated control of DC chopper and pitch angle which effectively function in different time scales, preventing the rotor speed from the hazardous overspeed.

5.2 LVRT performance

Figure 12 demonstrates the LVRT performance of the proposed FPR scheme and compares that with the conventional crowbar protection scheme. The principle of the crowbar protection is to short circuit the DFIG rotor windings at grid fault contingencies via a resistor connected to the ground [12]. The crowbar protection scheme is denoted ‘crowbar’ in Figure 12.

The wind speed is set to 10 m/s and the initial DFIG active power output is 0.8 pu. For the FPR scheme, the parameters of the LVRT active power/voltage magnitude droop control as proposed in (24) are set to \( P_0 = 1 \) pu, \( V_0 = 1 \) pu, \( k_LV = 1 \), \( V_{th} = 0.8 \) pu. For the rotor crowbar scheme, the triggering current threshold is set to 2 pu [27].

A temporary three-phase fault which lasts for 625 ms is applied at busbar B2 at \( t = 0.5 \) s, causing an 80% voltage dip at the PCC as shown in Figure 12(a). As observed from Figure 12(c), when the rotor current under the ‘crowbar’ scheme reaches the triggering threshold of 2 pu, the DFIG active power control is interrupted by the short-circuited crowbar as shown in Figure 12(b), with apparent active power and current transients as observed from Figures 12(b) and (c), respectively. By contrast, the ‘FPR’ scheme can steadily regulate the active power output as seen in Figure 12(b) and suppress the rotor current overshoot to the magnitude less than 1.5 pu. It is also
worth notice that the proposed FPR scheme can ensure a stable voltage restoration process by its full controllability after the fault is cleared, as seen in Figure 12(a). It allows the DFIG WTG to ride through the fault, without the need of crowbar protection which may generate disturbances to the DFIG WTG operations.

More importantly, for the protection of the DFIG rotor speed, the proposed FPR scheme can better restrict the rotor speed variation during and after the fault as observed in Figure 12(d), compared to the crowbar scheme. This is because the DC chopper can be fast and flexibly executed and the pitch angle control is also activated to eliminate the power imbalance.

According to the above comparisons, the proposed FPR scheme can keep the DFIG WTG grid-connected, provide uninterruptible active power controllability for LVRT and effectively secure the rotor speed, without the employment of the crowbar protection.

6 CONCLUSION

This paper proposes a novel FPR scheme for DFIG WTG using a DC chopper in the AC–DC conversion system, in effort to avoid rotor overspeed. This FPR scheme is implemented through four parts of modifications to the conventional DFIG control scheme: an RSC direct active power control, a DC voltage/rotor speed droop control loop, a DC chopper control and a fast pitch control.

The control performances of the proposed FPR scheme are optimized and its robustness under various wind speeds and FPR command values is verified, by both SSSA and time-domain simulation analysis. The case studies demonstrate that the proposed FPR scheme can take advantages of both the DC chopper control and the pitch angle control in different time scales to achieve the FPR and effectively restrict rotor overspeed. In addition, under grid fault conditions, the proposed FPR scheme employs the fully and flexibly controlled DC chopper and provides superior LVRT capability, compared to the conventional rotor crowbar protection scheme.

The proposed FPR scheme is likely to be an important measure to enhance the control flexibility and ensure the operation stability in future power electronic converter dominated grids. The design approach can also be expanded to the other types of power electronic interfaced sources such as photovoltaic power generation.

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APPENDIX A

## TABLE A1  DFIG system parameters

| Item                        | Value       |
|-----------------------------|-------------|
| Rated capacity $S_e$        | 10 MVA      |
| Rated stator voltage $V_{s}$| 575 V       |
| Nominal angular frequency $\omega_b$ | $2\pi \times 60$ rad/s |
| Maximum rate of pitch angle change | 5°/s        |
| Maximum pitch angle         | 30°         |
| Rated rotor speed $\omega_{max}$ | 1.1 pu     |
| Shaft mutual damping $D_{s6}$ | 1.5         |
| Shaft stiffness $K_{s6}$    | 0.15 pu/°   |
| Wind turbine inertia $H_t$  | 4.29 s      |
| Rotor inertia $H_r$         | 0.9 s       |
| Stator resistance $R_s$     | 0.023 pu    |
| Stator leakage reactance $X_{s6}$ | 0.18 pu   |
| Rotor resistance $R_r$      | 0.016 pu    |
| Rotor leakage reactance $X_r$ | 0.16 pu    |
| Magnetizing reactance $X_m$ | 2.9 pu      |
| Rated DC voltage $V_{dc}$   | 1150 V      |
| DC-link capacitance $C$     | 84 mF       |
| DC chopper dump resistance $R_c$ | 0.26 Ω    |
| DC chopper switching frequency | 1 kHz      |
| RSC direct active power PI controller coefficients $(k_{p1}, k_{i1})$ | (0.5, 100) |
| RSC inner current PI controller coefficients | (5, 200) |
| GSC DC voltage PI controller coefficients $(k_{p6}, k_{i6})$ | (8, 10000) |
| GSC inner current PI controller coefficients | (2, 200) |
| GSC DC voltage/rotor speed droop coefficient $k$ | 10        |
| DC chopper PI controller coefficients | (10, 10000) |
| Pitch angle PI compensator coefficients | (100, 500) |
| Pitch angle PI compensator limit $\Delta \beta_{max}$ | 0.3°       |

## TABLE A2  PCC transformer and transmission line parameters

| Item                        | Value       |
|-----------------------------|-------------|
| Transformer ratio           | 575 V/25 kV |
| Transformer base capacity   | 10.5 MVA    |
| Transformer leakage inductance | 0.05 pu    |
| Line length                 | 30 km       |
| Line resistance             | 0.1153 Ω/km|
| Line inductance             | 1.05 mH/km  |