A High Voltage Ride Through Strategy For DFIG Considering HVDC System Converter Blocking
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Abstract—This paper presents a P-Q coordination based high-voltage ride-through control (HVRT) strategy for double fed induction machines (DFIGs) based on a combined Q-V control and de-loading control. The effect of DFIG’s active/reactive power injection on transient overvoltage is firstly analyzed and the DFIG’s reactive power limit evaluation is then conducted. In the proposed strategy, the reactive power limit of DFIG can be flexibly extended during the transient process in coordination with DFIG’s rapid active power control, as a result the transient overvoltage caused by the DC bipolar block can be effectively suppressed. Moreover, the key outer loop parameters such as the Q-V control coefficients and the de-loading coefficient can be determined based on the voltage level and available DFIG power capacity. MATLAB/Simulink simulations can verify the effectiveness of the proposed control strategy.

Index Terms—transient overvoltage, reactive power absorption, active power de-loading control

I. INTRODUCTION

The past ten years have witnessed the rapid wind power development for the purpose of solving the worldwide energy and environmental crises [1]. Despite of wind turbine generator (WTG)’s inherent uncertainty and variability, the necessary converter interface for WTG integration has posed big challenges for power grid operation and control, such as additional reserve requirement and inertial reduction in weak connection [2].

In northwest China, many large-scale wind farms are located more than 1000-km away from the load center, with much more lower synchronous machines proportion than that in other power systems and forming a weak-grid integration [3]. For the de facto long-distance transmission of wind power, HVDC has been adopted to transfer 1000MW-level wind power. As the HVDC converter can consume large-amount reactive power (about 50%-60% of its active power), when DC bipolar block occurs caused by different types of faults in the AC system, the surplus reactive power existing in the
converter station will cause the transient overvoltage surge [4]. The transient overvoltage problem caused by the DC blocking has been investigated in many literatures. In [5], the overvoltage phenomena is observed in offshore wind farms following blocking of the HVDC converter by means of simulation. The mechanism of transient overvoltage caused by DC blocking and its influence factors are analyzed in [6] and an apparent increase in short circuit ratio index is proposed to measure the transient overvoltage level.

Fortunately, many efforts have been devoted to develop control strategies to suppress transient overvoltage. For example, methods of modification on the control of HVDC system and wind farm STATCOM as well as the wind converter are briefly introduced and compared in [7]. Three typical overvoltage conditions are investigated by theoretical analysis and simulation based on the actual control and protection strategy of Yunnan-Guangdong (YG) UHVDC transmission project in [8]. Moreover, a transient voltage control based active voltage compensator is introduced to improve the transient voltage stability of grid-connected wind farm with DFIGs in [9, 10].

However it’s occasionally overlooked that additional reactive power regulation capacity of DFIG can be achieved in emergency cases [11]. In this paper, a P-Q coordination method is proposed for emergency reactive power control to suppress transient overvoltage, in which a Q-V partition var control logic is developed for reactive power adjustment and a P-V partition de-loading control logic is presented for active power adjustment accordingly, as a result the reactive power supporting potential can be enlarged flexibly. Moreover, in the study, the key parameters such as the Q-V control coefficients and the de-loading coefficient can be determined based on a voltage partition rule considering the voltage level and the DFIG power capacity.

The rest of this paper is organized as follows: Section II analyzes the sending-end transient overvoltage and the effect of DFIG’s active/reactive power injection on transient overvoltage as well as DFIG’s reactive power limit evaluation. Section III introduces the proposed P-Q coordination based HVRT control strategy and the determination of key parameters. Section IV provides the case studies. Finally, conclusions are drawn in Section V.

II. TRANSIENT OVERVOLTAGE ANALYSIS

A. System Description

The DFIG wind farm integrated system in Fig. 1 represents a typical case of bulk wind power transmission from generation centers to load centers by means of HVDC transmission. An equivalent model consisting of the equivalent reactance \( X_e \) and voltage source \( V_s \) is used to represent the sending-end AC grid. For simplicity purposes, a single DFIG-based wind turbine is used to represent the aggregate behavior of the whole wind farm. The traditional double loop control structure is applied for DFIG converter control. Originally under normal operating condition, the conventional MPPT control is used for the RSC outer loop and the constant var/voltage control is used for the GSC outer loop to maintain the DC-link voltage. The outer loop will generate the reference signals for the inner current loop independently. The inner current control is carried out in the rotational framework (d-q) with stator flux orientation by the help of the phase-locked-loop (PLL). Basic PI controller is adopted in those inner control loops[12, 13]. Moreover, a group of static capacitor and filter is installed at the rectifier station to compensate for the reactive power consumption.

Under the overvoltage operating condition after DC bipolar blocking described below, the following outer loops will be designed and applied: 1) two Q-V independent control loops are designed for the RSC power control and the GSC var/voltage control, respectively[14, 15]; 2) a P-V de-loading loop is designed to generate the power reference for active power control. The details will be elaborated in next section.

B. Effect of WTG’s Active/Reactive Power Injection

From Appendix A, when there a transient overvoltage occurs at the sending-end AC system, \( V_p \) satisfies the following relationship,

\[
aV_p^4 + bV_p^2 + c = 0
\]

where \( a = (1 - G_e X_e)^2 \), \( b = -1 - 2(1 - G_e X_e)Q_{DFIG} X_e \) and \( c = (P_{DFIG}^2 + Q_{DFIG}^2)X_e^2 \).

The sensitivity of the sending-end voltage at PCC \( V_p \) with respect to the DFIG active/reactive power output \( P_{DFIG} \), \( Q_{DFIG} \) can be formulated from (1) as,

\[
\frac{\partial V_p}{\partial P_{DFIG}} = \frac{1}{V_p} \frac{P_{DFIG} X_e^2}{\sqrt{b^2 - 4ac}}
\]

\[
\frac{\partial V_p}{\partial Q_{DFIG}} = \frac{1 - G_e X_e}{2aV_p} \frac{(1 + \sqrt{b^2 - 4ac})}{\sqrt{b^2 - 4ac}}
\]
It is obvious from (2) that $\frac{\partial V_p}{\partial P_{DFIG}} < 0$ when $P_{DFIG} > 0$. On the other hand, it can be found in Appendix A that $\frac{\partial V_p}{\partial Q_{DFIG}} > 0$ if the sending-end AC system has short-circuit ratio (SCR) greater than 0.6 (SCR>0.6). In other words, when overvoltage at PCC happens, the wind farm’s absorbing reactive power, i.e., in inductive operating mode, can help suppress the transient overvoltage.

It can be concluded from Appendix A that although the increase of absorbing reactive power and active power output of wind farm can both help suppress the transient overvoltage, the former method is more effective than the latter one in suppressing the transient overvoltage, which means it’s feasible to allow wind farm to absorb reactive power to help suppress the transient overvoltage and further increase the inductive reactive power limit of DFIG by de-loading control.

### C. Inductive Reactive Power Limit

1) Reactive power evaluation

The inductive reactive power of wind farm comes from two resources: DFIG stator by RSC control and GSC itself.

The stator reactive power limit is mainly determined by: (1) the maximum rotor current constraint in inequality (4)\cite{16}; (2) the generator capacity constraint in inequality (5)\cite{17, 18}. The details can be found in Appendix B.

\[
P_r^2 + (Q_r + \frac{3V_r^2}{2X_s})^2 \leq (\frac{3X_m}{2X_s}I_{r\text{max}})^2 \tag{4}
\]

\[
P_r^2 + Q_r^2 \leq S_v^2 \tag{5}
\]

where $X_s = X_{ls} + X_m$.

Therefore, the stator reactive power limit $Q_{s\text{max}}$ can be determined by the less value between a) the reactive power corresponding to the maximum rotor current limit $Q_{r\text{max}}$ and b) the maximum available reactive power $Q_{s\text{max}}$:

\[
\begin{align*}
Q_{r\text{max}} &= \frac{1.5V_r^2}{X_s} + \sqrt{(1.5X_mV_r^2/I_{r\text{max}}^2/X_s)} - P_r^2 \\
Q_{s\text{max}} &= \sqrt{S_v^2 - P_r^2} \\
Q_{s\text{max}} &= \min\{Q_{r\text{max}}, Q_{s\text{max}}\} \tag{6}
\end{align*}
\]

An illustration of the relationship between the stator reactive power limit $Q_{s\text{max}}$, and its active power $P_r$ is given in Fig. 2(a). It’s clear when $P_r$ is less than $P_{r\text{max}}$, $Q_{r\text{max}} = Q_{s\text{max}}$; otherwise $Q_{s\text{max}} = Q_{r\text{max}}$.

The characteristic diagram of the stator reactive power limit with respect to $P_r$ and $V_s$ at the rated wind speed is plotted in Fig. 2(b) and it can be observed that both the immediate rise in DFIG stator voltage and the decrease of DFIG active power can simultaneously increase its reactive power limit.

On the other hand, the reactive power limit of GSC is determined by its apparent power capacity:

\[
Q_{G\text{max}} = \sqrt{S_m^2 - (sP_m)^2} \tag{7}
\]

In general, GSC is controlled to maintain the DC voltage and there is minor active power output. As a result, $Q_{G\text{max}}$ can be approximated to be $S_m$\cite{19, 20} and the total reactive power limit $Q_{G\text{max}}$ of a DFIG can absorb is determined by:

\[
Q_{G\text{max}} = Q_{s\text{max}} + Q_{G\text{max}} \tag{8}
\]

2) Active power de-loading

From Equality (6), it is clear that the reactive power limit can be extended by the decrease of DFIG active power, i.e., DFIG de-loading operation. The principle of DFIG de-loading is given in Fig. 3, in which the operating points are on the MPPT curve, but actively trace some de-loading curve defined in (9) so that part of available wind energy can be stored in form of rotating kinetic energy\cite{21}.

\[
P_r = P_{d\text{e}} = (1 - K_{d\text{e}})P_{MPPT}, \quad 0 \leq K_{d\text{e}} \leq K_{d\text{e\text{max}}} \tag{9}
\]

As far as DFIG is concerned, $K_{d\text{e\text{max}}}$ is about 0.1–0.2 \cite{11} and $K_{d\text{e\text{max}}} = 0.2$ is set in the study.

Further, the reactive power limit of DFIG with different wind speeds and de-loading coefficients is plotted in Fig. 2(c). It can be observed: (1) normally the reactive power limit will be reduced with the increase of wind speed and (2) the limit can be enlarged by means of active power de-loading, especially in high wind speed range (10-12m/s). Therefor the
power limit of the stator and DFIG under de-loading $Q_{Gd}^{\text{max}}, Q_{GD}^{\text{max}}$ can respectively be updated from (6)-(9) accordingly.

III. A P-Q COORDINATION BASED HVRT CONTROL

Since any DFIG converter capacity is limited, the main idea to capture additional reactive power capacity is by means of reactive power control and active power de-loading coordinately, which will be elaborated below.

A P-Q Coordination

The P-Q coordination includes two main logics: (1) Stator and GSC var absorption by RSC and GSC reactive control; (2) Var capacity enlargement by de-loading control. The main procedure of the P-Q coordination based HVRT control is illustrated in Fig. 4. When the overvoltage condition is detected, firstly the reactive power limit is evaluated and the outer loop parameters are determined according to the rules explained below; secondly, RSC and GSC var control is executed to absorb the surplus reactive power; thirdly the DFIG de-loading will be executed and the resultant reactive var capacity will be enlarged. The whole procedure will last until the PCC voltage is satisfied or the maximum de-loading is reached.

As of Q-V piecewise control in Fig. 5(a), the whole process corresponds to two stages:

1) Stage I: $V_{pOV}^{\text{ref}} < V_p \leq V_{O1}^{\text{ref}}$, the RSC and GSC reactive control is activated and the stator and GSC will absorb reactive power proportional to their reactive power limit along line AB. This process continues until the reactive power limit of DFIG is reached. The following reactive reference power setting is used:

$$
Q_{Q}^{ref} = \frac{Q_{G}^{max}}{Q_{G}^{max}} K_i (V_p - V_{pOV}^{\text{ref}}), \quad Q_{Q}^{ref} < 0
$$

(11)

2) Stage II: $V_{O1}^{\text{ref}} < V_p \leq V_{pOV}^{\text{max}}$, the reactive power limit of DFIG will be temporarily enlarged by active power de-loading control. This process continues until the maximum de-loading is reached. The reference power is set as follows:

$$
Q_{Q}^{ref} = \left\{ \begin{array}{ll}
Q_{Q}^{max} + K_i (V_p - V_{O1}^{\text{ref}}), & Q_{Q}^{ref} < 0 \\
Q_{Q}^{max}, & Q_{Q}^{ref} < 0
\end{array} \right.
$$

(12)

2) P-V de-loading control logic

For the de-loading control logic in Fig. 5(b), a piecewise P-V power control rule is used:

$$
P_{\text{DFIG}} = \begin{cases} 
P_{\text{MPPT}} & V_p \leq V_{O1}^{\text{ref}} \\
(1 - K_{\text{de}}) P_{\text{MPPT}} & V_p > V_{O1}^{\text{ref}}
\end{cases}
$$

(13)

Normally, DFIG will operate at MPPT state when $V_p \leq V_{O1}^{\text{ref}}$. Otherwise, the de-loading control will be activated and DFIG will trace the de-loading DE curve until the maximum limit is reached.
The power outer loops corresponding to above Q-V control and P-V de-loading control logic are illustrated in Fig. 6, in which the outer loop parameters will be discussed below.

![Diagram](image)

**B Determination of Outer Loop Parameters**

1) The Q-V control coefficients $K_1$, $K_2$

As the control coefficients represent the slopes of piecewise Q-V curve in Fig. 5(a), they can be easily obtained:

$$
K_1 = \frac{Q_{\text{ref}} - Q_{\text{ref}}^\text{G}}{V_{\text{OV1}} - V_{\text{OV}}^\text{G}}
$$

and

$$
K_2 = \frac{Q_{\text{ref}} - Q_{\text{ref}}^\text{R}}{V_{\text{OV1}} - V_{\text{OV}}^\text{R}}
$$

(14)

where $Q_{\text{ref}}^\text{G}$ and $Q_{\text{ref}}^\text{R}$ are the reactive power limits of DFIG under MPPT and de-loading control in last section, respectively and $V_{\text{OV1}}$ is the de-loading triggering voltage.

2) The de-loading coefficient $K_{de}$

The de-loading logic in the power outer loop is illustrated in Fig. 6(c). Once $Q_{\text{ref}}$ is given in (11)-(12), the de-loading reference power $P_{\text{ref}}^\text{de}$ can be determined by

$$
P_{\text{ref}}^\text{de} = \min\left\{P_{\text{ref}}^\text{G}, P_{\text{ref}}^\text{R}\right\}
$$

(15)

where the two active power values are compared: a) the active power corresponding to the maximum rotor current limit:

$$
P_{\text{ref}}^\text{G} = \sqrt{\left(1.5X_sV_{\text{ref}}^\text{G}I_{\text{ref}}^\text{G}\right)^2 - (Q_{\text{ref}}^\text{G} - 1.5V_{\text{ref}}^\text{G}I_{\text{ref}}^\text{G})^2}
$$

(16)

and b) the maximum stator power limit in (17):

$$
P_{\text{ref}}^\text{R} = \sqrt{S_{\text{ref}}^2 - (Q_{\text{ref}}^\text{R})^2}
$$

(17)

Accordingly, the de-loading coefficient $K_{de}$ is

$$
K_{de} = 1 - \frac{P_{\text{ref}}^\text{de}}{P_{\text{ref}}^\text{GPT}}
$$

(18)

With the typical parameters in Table 1-Table 3, snapshot of the de-loading P-V trajectory $P_{\text{ref}}^\text{de}$ is plotted in Fig. 5(c) and it can be found that during the de-loading process, the maximum stator power limit will become the de-loading reference power.

IV. CASE STUDIES

A System Description

Fig. 7 shows the studied system of DFIG-based wind farm integrated into the AC power grid 2 by means of HVDC transmission. DFIG operates at the unit power factor under rated wind speed 12m/s initially and the block occurs at $t = 0.5x$. The system parameters and the DFIG PI controller parameters are given in Table 1 and Table 2. Simulations are conducted in MATLAB/Simulink.

![Diagram](image)

**Table 2 Parameters of DFIG PI controllers**

| PI controller | $K_s$ | $K_i$ |
|---------------|-------|-------|
| RSC active power control | 2/20  |       |
| RSC reactive power control | 1/20  |       |
| RSC current control | 0.6/100 |       |
| GSC DC voltage control | 8/400  |       |
| GSC reactive power control | 2/20  |       |
| GSC current control | 0.83/100 |       |

With system parameters available in Table 1, the control parameters of DFIG on the initial steady state condition where $v_p = 1.0$ can be obtained as listed in Table 3.

**Table 3 Control parameters of DFIG on initial condition**

| Parameters | Values | Parameters | Values |
|------------|--------|------------|--------|
| $Q_{\text{ref}}^\text{pm}$ | 0.48 p.u. | $Q_{\text{ref}}^\text{pm}$ | 0.25 p.u. |
| $Q_{\text{ref}}^\text{pm}$ | 0.73 p.u. | $Q_{\text{ref}}^\text{pm}$ | 1.02 p.u. |
| $V_{\text{OV1}}$ | 1.15 p.u. | $K_s$ | $K_i$ 9.6/3.6 |

B Method Comparison Study

In this section, a comparison study is conducted among three methods: (1) the proposed P-Q coordination based HVRT control (PQ-HVRT); (2) a constant Q control with $Q_{\text{ref}} = 0.2p.u$ under rated wind speed (CVAR); and (3) the unit power factor control without any var control (UPF).

![Diagram](image)
Further, the effect of the de-loading triggering voltage $V_{OV1}$ setting on PQ-HVRT is investigated and it is found that the lower $V_{OV1}$ is, the lower steady voltage at PCC exhibits in Fig. 10, as lower $V_{OV1}$ means faster de-loading control is taken action in PQ-HVRT.

![Fig. 10 Transient PCC voltage with different de-loading triggering voltage](image)

V. CONCLUSION

This paper proposes a P-Q coordination based HVRT control strategy for DFIG by means of a combined Q-V control and de-loading control to suppress PCC overvoltage. In the strategy, the reactive power capacity can be flexibly enlarged during the transient process in coordination with DFIG’s rapid active power control through the rotor speed control to achieve the de-loading operation. Simulations verify that the proposed HVRT strategy has better effect on PCC overvoltage suppression to avoid DFIG islanding compared with two other methods.

![Fig. A1 Phasor diagram of the sending-end AC voltage](image)

**APPENDIX A**

An illustration of the voltage relationship between $\hat{V}_p$ and $V_e$ is presented in Fig. A1(a) and is obtained as,  
\[
\hat{V}_p = V_e - \Delta V = V_e - jX_p I_p
\]  
\[
P_w + jQ_w = V_p(I_p)
\]  
\[\text{(A1)}\]

Under normal case where $V_e$ is at its rated voltage in Fig. A1(a), the AC system will inject reactive power for HVDC var consumption. When the HVDC system converter is blocked due to some malfunction like continuous commutation failure, the surplus reactive power will be reversely injected into the sending end, resulting in a transient overvoltage surge at PCC, i.e., $V_p$ will be increased to even greater than $V_e$, as illustrated in Fig. A1(b), in this case we have:
\[
P_w = -P_{DFIG}
\]
\[
Q_w = -Q_{DFIG} - Q_e = -Q_{DFIG} - V_e^2 G_e
\]  
\[
\hat{V}_p \text{ can further become (A3) by combining (A1) and (A2):}
\]

![Fig. A1(b) Overvoltage case](image)

**C Parameter Effect Study**

In Fig. 9 the comparison study at three typical wind speed 10m/s, 11m/s and 12m/s shows that at lower speed DFIG can absorb more reactive power and has better overvoltage suppression effect.
The following relationship can be easily obtained from (A3)
\[ aV_p^4 + bV_p^2 + c = 0 \]  
(A4)
where \( a = (1-G,X_e)^2 \), \( b = -1-2(1-G,X_e)Q_{DFIG}X_e \) and \( c = (P_{DFIG}^2 + Q_{DFIG}^2)X_e^2 \), and \( V_e = 1 \) is set in (A3).

Considering real voltage profile, \( V_p \) can be deduced:
\[ V_p = \sqrt{\frac{-b + \sqrt{b^2 - 4ac}}{2a}} \]  
(A5)
Accordingly, the derivative \( \frac{\partial V_p}{\partial Q_{DFIG}} \) and \( \frac{\partial V_p}{\partial P_{DFIG}} \) can be obtained as follows,
\[ \frac{\partial V_p}{\partial Q_{DFIG}} = \frac{(1-G,X_e)X_e(1+\sqrt{b^2 - 4ac})}{2aV_p\sqrt{b^2 - 4ac}} \]  
\[ \frac{\partial V_p}{\partial P_{DFIG}} = -\frac{P_{DFIG}X_e^2}{V_p\sqrt{b^2 - 4ac}} \]  
(A6)
where it is obvious that \( \frac{\partial V_p}{\partial Q_{DFIG}} < 0 \) if \( P_{DFIG} > 0 \).

The sign of \( \frac{\partial V_p}{\partial Q_{DFIG}} \) is analyzed below. Since the short-circuit ratio (SCR) of the sending-end AC is defined as
\[ SCR = \frac{S_n}{P_{dc}} = \frac{V_{ph}^2}{X_pP_{dc}} = \frac{1}{X_e} \]  
(A7)
where \( S_n \) is the short circuit capacity of the AC system, \( P_{dc} \) is the rated HVDC power, \( V_{ph} \) and \( P_{dc} \) are the base voltage and base power specified in per-unit analysis, respectively.

As the reactive compensation capacity \( Q_r \) at a HVDC converter station can concisely be expressed as
\[ Q_r = \frac{V_{ph}^2}{G} \]  
(A8)
where \( G \) denotes the capacitive susceptance. For HVDC, \( Q_r \) usually approximates to [0.4-0.6] \( P_{dc} \), thus \( G \leq 0.6 \).

From (A6), it can be found that \( \frac{\partial V_p}{\partial Q_{DFIG}} > 0 \) only if \( SCR > G \), that is \( SCR > 0.6 \).

In summary, when \( V_p > V_e \), the following statement can be concluded: 1) if \( P_{DFIG} > 0 \), \( \frac{\partial V_p}{\partial P_{DFIG}} < 0 \); 2) if \( SCR > 0.6 \), \( \frac{\partial V_p}{\partial Q_{DFIG}} > 0 \), which means the increase of reactive power absorption and active power output can both suppress the transient overvoltage; c) The latter is more effective than the former in suppressing the transient overvoltage.

**APPENDIX B**

The constrain of the reactive power limit of the stator side of DFIG considering the maximum endurable current of RSC is calculated as below.

The voltage, flux and power equation of the stator are listed as (B1)-(B3) by method of decoupling control with DQ axis.

\[ u_{sd} = R_i i_{sd} - \omega \psi_q + \frac{d}{dt} \psi_{sd} \]  
(B1)
\[ u_{sq} = R_i i_{sq} - \omega \psi_q + \frac{d}{dt} \psi_{sq} \]  
(B2)
\[ \psi_{sd} = L_s i_{sd} + L_m i_{d} \]  
\[ \psi_{sq} = L_s i_{sq} + L_m i_{q} \]  
(B3)

Adopting the stator flux d-axis directional control and neglecting the voltage drop in the stator winding, there is
\[ \psi_{sd} = \psi \]  
\[ \psi_{sq} = 0 \]  
(B4)

Consider the maximum endurable current of RSC as
\[ i_{sd}^2 + i_{sq}^2 \leq i_{rms}^2 \]  
(B5)

From Equality (B1)-(B6), the constrain of the reactive power limit of the stator side of DFIG is obtained as follows:
\[ P_r^2 + (Q_r + \frac{3i_{rms}^2}{2X_f})^2 \leq \frac{3X_f}{2X_f} V_s^2 i_{rms}^2 \]  
(B7)

**REFERENCES**

[1] Global Wind Energy Council (GWEC). “Global Wind Report 2009-2016,” 2017; http://gwec.net/publications/global-wind-report-2/.

[2] R. Piwko, P. Meibom, H. Holttinen et al., “Penetrating insights: lessons learned from large-scale wind power integration,” IEEE Power and Energy Magazine, vol. 10, no. 2, pp. 44-52, 2012.

[3] S. Wang, J. Hu, and X. Yuan, “Virtual synchronous control for grid-connected DFIG-based wind turbines,” IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 3, no. 4, pp. 932-944, 2015.

[4] J. Arrillaga, High Voltage Direct Current Transmission, 2nd ed., London: The Institution of Electrical Engineers, 1998.

[5] I. Erlich, B. Paz, M. K. Zadeh et al., “Overvoltage phenomena in offshore wind farms following blocking of the HVDC converter,” in 2016 IEEE Power and Energy Society General Meeting (PESGM), 2016, pp. 1-5.

[6] Q. Guo, M. Yoon, C. Kim et al., “Commutation failure and voltage sensitivity analysis in a hybrid multi-infeed HVDC system containing modular multilevel converter,” International Transactions on Electrical Energy Systems, vol. 26, no. 10, pp. 2259-2271, 2016.

[7] C. Tong, A. Mats, and X. Haijian, “Methods for transient AC overvoltage reduction at wind farm terminal,” in 2016 China International Conference on Electricity Distribution (CICED), 2016, pp. 1-6.

[8] F. Wang, H. Li, J. Liu et al., “Analysis of UHVDC transient overvoltage based on the actual control and protection strategy,” in 2014 IEEPEP Asia-Pacific Power and Energy Engineering Conference (APPEEC), 2014, pp. 1-4.

[9] P. Ou, X. Xiao, Z. Zou et al., “Cooperative control of SFCL and reactive power for improving the transient voltage stability of grid-connected wind farm with DFIGs,” IEEE Transactions on Applied Superconductivity, vol. 26, no. 7, pp. 1-6, 2016.

[10] I. Ngamroo, and T. Karaipoom, “Cooperative control of SFCL and SMES for enhancing fault ride through capability and smoothing power fluctuation of DFIG wind farm,” IEEE Transactions on Applied Superconductivity, vol. 24, no. 5, pp. 1-4, 2014.
[11] M. Wang-Hansen, R. Josefsson, and H. Mehmedovic, “Frequency controlling wind power modeling of control strategies,” *IEEE Transactions on Sustainable Energy*, vol. 4, no. 4, pp. 954-959, 2013.

[12] J. Kim, E. Muljadi, J. Park et al., “Adaptive hierarchical voltage control of a DFIG-based wind power plant for a grid fault,” *IEEE Transactions on Smart Grid*, vol. 7, no. 6, pp. 2980-2990, 2016.

[13] M. S. Marhaba, S. Farhangi, H. Iman-Eini et al., “Reactive power sharing improvement of droop-controlled DFIG wind turbines in a microgrid,” *IET Generation, Transmission & Distribution*, vol. 12, no. 4, pp. 842-849, 2018.

[14] J. Kim, J. Seok, E. Muljadi et al., “Adaptive Q–V scheme for the voltage control of a DFIG-based wind power plant,” *IEEE Transactions on Power Electronics*, vol. 31, no. 5, pp. 3586-3599, 2016.

[15] J. Kim, E. Muljadi, J. Park et al., “Flexible h_{2}–V scheme of a DFIG for rapid voltage regulation of a wind power plant,” *IEEE Transactions on Industrial Electronics*, vol. 64, no. 11, pp. 8832-8842, 2017.

[16] X. Zou, D. Zhu, J. Hu et al., “Mechanism analysis of the required rotor current and voltage for DFIG-based WTs to ride-through severe symmetrical grid faults,” *IEEE Transactions on Power Electronics*, vol. 33, no. 9, pp. 7300-7304, 2018.

[17] M. Z. Sujod, I. Erlich, and S. Engelhardt, “Improving the reactive power capability of the DFIG-based wind turbine during operation around the synchronous speed,” *IEEE Transactions on Energy Conversion*, vol. 28, no. 3, pp. 736-745, 2013.

[18] S. Mondal, and D. Kastha, “Maximum active and reactive power capability of a matrix converter-fed DFIG-based wind energy conversion system,” *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 5, no. 3, pp. 1322-1333, 2017.

[19] M. Rahimi, “Coordinated control of rotor and grid sides converters in DFIG based wind turbines for providing optimal reactive power support and voltage regulation,” *Sustainable Energy Technologies and Assessments*, vol. 20, pp. 47-57, 2017/04/01, 2017.

[20] Y. Cui, L. Peng, W. Zhong et al., “Coordinated strategy of reactive power control on wind farms based doubly fed induction generator,” in *Proceedings of the Csee*, 2015, pp. 4300-4307.

[21] Z. Lu, Z. Wang, H. Xin et al., “Small signal stability analysis of a synchronized control-based microgrid under multiple operating conditions,” *Journal of Modern Power Systems and Clean Energy*, vol. 2, no. 3, pp. 244-255, 2014/09/01, 2014.

[22] China Electric Power Research Institute, "Test procedure of wind turbine high voltage ride through capability," National Standard NB/T 31111-2017, C. N. E. Administration, 2017.