Bidirectional speed range extension of DFIG-based WECS with dynamic minimum dc-bus voltage

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Abstract

Enlarging the speed range of wind turbines is an effective way to increase power production in low-frequency band wind which contains more energy and is very challenging for DFIG-based wind energy conversion system (WECS). The analysis shows that current controllability of the converter is the main factor limiting bidirectional speed range extension (BSRE). This problem can be solved by increasing dc-bus voltage, but a constant and high dc-bus voltage will increase the electrical stress and switching losses of the converter. This paper proposed a dynamic minimum dc-bus voltage (DMDCV) technique in which the dc-bus voltage can automatically adjust to enable the back-to-back voltage source converter to work in linear modulation mode at its minimum value, thus supporting BSRE while also achieving multiple goals including low electrical stress and low switching losses. Two implementation methods of DMDCV with and without modulation depth loop are proposed and discussed. The co-simulation results verified the feasibility of DMDCV and the advantages of BSRE in improving power generation.

1 INTRODUCTION

Wind power has experienced rapid development during the past decades\cite{1}. At the same time, it is an on-going goal to reduce the levelized cost of energy (LCOE) of wind energy conversion system (WECS), especially in the context of parity feed-in tariffs\cite{2}.

Increasing power production is one of the most effective ways to reduce LCOE. There are four basic kinds of maximum power point tracking (MPPT) schemes to operate the WECSs exactly on optimal operation point (OOP), i.e. perturb and observe control (also known as hill-climbing searching control), tip speed ratio (TSR) control, optimal torque control (OTC) and power signal feedback (PSF) control\cite{3,4}. The new research trends are advanced controls\cite{5–7}, intelligent algorithm\cite{8,9}, and MPPT with less parameter dependence\cite{10}. The comparison study in\cite{11} shows that OTC outperforms TSR in terms of power fluctuation and mechanical loads. Due to the simplicity and good performance, MW-scale WECS usually adopts OTC approach\cite{12}.

Another question is, how to keep the turbine operating on $\lambda_{\text{opt}}$ as much as possible. Two possible factors may cause the WECS to deviate from OOP. One is the huge moment of inertia $J$ of wind turbine (dynamic tracking problem); the other is the speed range limitation of WECS (static tracking problem). The huge $J$ leads to a poor tracking performance under fluctuating wind speed, so WECSs will inevitably deviate from $\lambda_{\text{opt}}$\cite{13,14}. To this end, $J$ is equivalently reduced through improved generator torque control\cite{15}. The dynamic tracking ability can be described by the transfer function $\Delta\omega(s)/\Delta\tau(s)$, and a constant MPPT bandwidth strategy is proposed in\cite{16}, which also reduces $J$ equivalently. These methods are theoretically effective but will introduce additional power fluctuations\cite{17}. Moreover, the actual effects are very limited when applied to MW-scale WECSs, the reason can be explained in Figure 1 in which the power spectrum of natural wind together with $\Delta\omega(s)/\Delta\tau(s)$ is plotted in frequency domain (the dotted line marked by ‘with enhanced tracking ability’ refers to $J$ and is equivalently reduced by 33.3\%). Note the typical $J$ of a MW-scale WECS is about 12 s ($J = 2HF$), and the Van der Hoven spectrum is quite universal, so Figure 1 has good versatility. It shows the tracking ability can only be enhanced effectively in the ‘poor tracking frequency band’, which is above 0.025 Hz, where the energy spectrum of natural wind is quite limited. So, this paper focuses more on

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low-frequency range below 0.025 Hz, where the wind component contains more energy, and the main problem is static tracking rather than dynamic tracking.

First, it is possible to get a wider wind region achievable of $\lambda_{\text{opt}}$ by replacing the look-up table control with variable-limit speed closed loop control [17, 18]. Then, the only way to further extend the MPPT region is to extend speed range, which, however, is often limited by mechanical and electrical systems. For PMSG-based WECS equipped with a full-scale converter, the generator stator voltage decreases with decreasing $\omega$, so it can operate at very low $\omega$ without influencing current controllability, and the rated speed can be extended with a dc–dc boost topology [19, 20] or the flux weakening technique [21, 22]. For WECS with a dual stator-winding induction generator, the dc-bus on the control-winding side and the dc-bus on the power-winding side are connected in parallel to further widen the speed range of the constant dc voltage output [23], and [24] adopts boost converter to increase the speed range. The speed range extension of DFIG-based WECS is more difficult, as the stator is connected to grid directly and the rotor voltage correlates to stator voltage and slip rate. In [25, 26], when the wind speed is low, the DFIG stator is disconnected from the grid and short-circuited, and all the power flows through the rotor and back-to-back converter, thus lower rotational speed and lower cut-in wind speeds can be achieved, but the mode switching may bring adverse effects. In [27], the flux-weakening technique of DFIG-based WECS is adopted for generator loss minimization and speed range extension, in which two single-primary single-secondary transformers are required to replace the conventional transformers. As can be seen, all of the above methods need to modify the main circuit topology, which is unrealistic for the commercial DFIG-based WECS that has been put into operation. In addition, the above-mentioned research can only extend the speed range towards low speed, whereas extension towards high speed is more effective since power is the cube of $v$.

As the main contribution, this article quantitatively analysed the constraints and expected effects of speed range extension of DFIG-based WECS. Then a dynamic minimum dc-bus voltage (DMDCV) technique is proposed which supports bidirectional speed range extension (BSRE) of DFIG-based WECS without modifying the main circuit topology. The proposed technique also features low electrical stress and low switching losses.

### 2.1 Expected effect of BSRE

As an important characteristic, $C_{p\text{max}}$ can only be obtained when the TSR $\lambda$ is kept on $\lambda_{\text{opt}}$. However, due to the limited speed range, it is not practical to maintain $\lambda_{\text{opt}}$ from cut-in wind $v_{\text{cutin}}$ all the way to rated wind $v_n$ [17]. In Figure 2a, $\omega_m$ is the permitted minimum speed, $\omega_n$ is the rated speed, $\omega_{\text{max}}$ is the safe speed. $\omega_{\text{max}}$ is usually set to 1.1 times of $\omega_n$ in order to reserve margin. Once exceeding $\omega_{\text{max}}$ will trigger emergency pitch action and emergency stop. The typical $\omega_n$ of commercial MW-scale DFIG-based WECS is 1.2 pu (the base speed is the synchronous speed of DFIG), and the safe speed $\omega_{\text{max}}$ is determined to be 1.32 pu. This safe speed is a rigid constraint of the mechanical system, and the BSRE in this paper will always be carried out within this speed constraint, even under extreme conditions. BSRE is to decrease $\omega_m$ and increase $\omega_n$, and the wind speed interval WECS can keep on $\lambda_{\text{opt}}$ and is extended from $[v_1, v_2]$ to $[v_{1\text{ext}}, v_{2\text{ext}}]$. As a result, $C_p$ can be improved in wind speed intervals $[v_{\text{cutin}}, v_1]$ and $[v_2, v_n]$ as $\omega$ is closer to the optimum speed $\omega_{\text{opt}}$, and $v_n$ can be slightly decreased to $v_{\text{next}}$, as shown in Figure 2a. Take a real 1.67 MW WECS as an example, when
the speed range (in pu) is extended from [0.75, 1.2] to [0.67, 1.25], the increment of active power is shown in Figure 2b.

Fit the line ‘relative increment of \( P_s \)’ to a function \( f(v) \), if the wind speed probability density is \( g(v) \), then the increase in average power generation (\%) can be derived

\[
\Delta \bar{P} = \int_{v_{\text{min}}}^{v_{\text{max}}} f(v)g(v) \, dv
\]  

Assuming that \( g(v) \) follows the Weibull distribution, and the average \( \bar{v} \) is set to be 5, 7, 9 m/s, respectively (represent wind resources of different quality), the calculated \( \Delta \bar{P} \) are 3.03\%, 2.18\% and 1.47\%, respectively. Note that this benefit corresponds to the increase in annual power generation, which is very impressive.

### 2.2 Restrictions on speed range extension

The restrictions of BSRE may come from electrical and mechanical subsystems. For electrical subsystem, BSRE will increase the slip of DFIG, so the current controllability and capacity of RSC may be a problem. For mechanical subsystem, \( \omega_{\text{max}} \) should be strictly limited, but the margin between \( \omega_{\text{max}} \) and \( \omega_e \) will be reduced when BSRE is used, so the unexpected overspeed is more likely to occur in extreme wind conditions.

### 3 BSRE SOLUTIONS OF DFIG-BASED WECS

BSRE directly affects the slip rate \( s \) of DFIG and is coupled to the converter through rotor windings, so the impacts of BSRE on rotor voltage and current need to be analysed first.

#### 3.1 Impacts of BSRE on DFIG rotor

After determining a specific BSRE, the mapping between \( v \) and \( \omega_e \), and the \( C_p \) curve of WECS can be determined (Figure 2), so the total electric power, \( P_s \), can be obtained from \( v \). Then a one-to-one mapping between \( \omega_e \) and \( P_e \) can be established, and the active power of DFIG stator, \( P_s \), will be distributed naturally

\[
P_e = P_s / (1 - s)
\]

where \( s = 1 - \omega_e \). Then the reactive power of stator, \( Q_s \), can be calculated at a certain \( \cos \varphi_s \)

\[
Q_s = \sqrt{1 - \cos^2 \varphi_s} P_s / \cos \varphi_s
\]

Then the conjugate phasor of stator current, \( \dot{I}_s^* \), is

\[
\dot{I}_s^* = \frac{P_s + jQ_s}{3U_s}
\]

And the stator flux phasor,

\[
\dot{\psi}_s = \frac{U_s - R_s \dot{I}_s}{j\omega_s}
\]

The phasor (converted to the stator side) of rotor current, \( \dot{I}_r \), rotor flux, \( \dot{\psi}_r \), and rotor voltage, \( \dot{U}_r \), can be calculated,

\[
\begin{align*}
\dot{I}_r &= (\dot{\psi}_s - L_s \dot{I}_s) / I_m \\
\dot{\psi}_r &= L_m \dot{I}_s + L_r \dot{I}_r \\
\dot{U}_r &= R_s \dot{I}_s + j\omega_s \dot{\psi}_r
\end{align*}
\]

Then \( \dot{I}_r \) and \( \dot{U}_r \) can be converted back to the rotor side,

\[
\begin{align*}
\dot{I}_{r1} &= \dot{I}_r / k_{fs} \\
\dot{U}_{r1} &= k_{fs} \dot{U}_r
\end{align*}
\]

\( U_r \) and \( I_r \) can be derived from the amplitude of \( \dot{U}_{r1} \) and \( \dot{I}_{r1} \).

\[
U_r = |I| k_{fs} \sqrt{\left( \frac{L_s \dot{I}_s}{I_m} \right)^2 + \left( \frac{\dot{\psi}_s}{U_s} \right)^2 - \frac{2L_m \dot{I}_s \sin \varphi_s}{I_m}}
\]

\[
I_r = \frac{1}{k_{fs}} \sqrt{\left( \frac{\dot{\psi}_s}{U_s} \right)^2 + \left( \frac{\dot{I}_s}{\omega_s I_m} \right)^2 + \frac{2L_m \dot{I}_s \sin \varphi_s}{\omega_s I_m}}
\]

in which, \( g_1 = \omega_s P_s (L_m^2 - L_s I_n) / 3 \cos \varphi_s I_m \), \( g_2 = P_s I_n / 3 \cos \varphi_s I_m \).

\( U_s \) is the RMS voltage of stator phase voltage; \( L_m, I_r \) and \( I_m \) are the stator inductance, rotor inductance and mutual inductance, respectively; \( \omega_e \) is the angular frequency of the stator voltage; \( k_{fs} \) is the turns ratio of rotor and stator-windings.

#### 3.2 Requirements for converter capacity

The apparent power flows through rotor winding is

\[
S_r = 3U_r I_r
\]

Take \( P_s = P_n \) as the most severe case of Equation (2), the capacity demand of RSC (\( S_{hr} \)) imposed by BSRE can be obtained. It shows \( S_n \) is mainly dominated by rated speed \( \omega_{gn} \) and \( \cos \varphi_e \). The relationship between \( S_{hr} \) with \( s \) and \( Q_s \) is shown in Figure 3 (see DFIG parameters in Table A1). It shows \( S_{hr} \) should be improved along with \( |s| \), or the ability to output capacitive reactive power will be reduced. With \( s_{\text{max}} = -0.32 \) and \( Q_s = 0.25 \) pu (capacitive, \( P_s = 1/1.32 \) pu, \( \cos \varphi_s \approx 0.95 \)), the capacity demand of RSC is 35.37% \( S_n \). As the cost of converters decreases, DFIG-based WECS tends to use converters with larger capacity. Besides, for those \( S_{hr} < 30\% S_n \), it is possible to adopt a conservative BSRE strategy or appropriately reducing capacitive reactive power output.
3.3 Demands for current controllability of VSCs

DFIG-based WECS adopts the back-to-back converter, which consists of two voltage source converters (VSC), namely the grid side converter (GSC) and the rotor side converter (RSC). The VSC usually adopts cascaded double closed loop control to produce the magnitude and phase angle of its ac terminal voltage. The outer loop is power control loop (or dc-bus voltage control loop), the inner loop is current control loop. To keep the current controllable is of great importance, this means that the achievable ac voltage of VSC must match the voltage of ac source it connects.

The magnitude of VSC’s ac voltage can be expressed by

\[ U_{\text{vsc - rms}} = m k_{\text{dc}} u_{\text{dc}} / \sqrt{2} \]  \hspace{1cm} (11)

where \( m \) is the modulation depth, \( u_{\text{dc}} \) is the dc-bus voltage, \( k_{\text{dc}} \) is the utilization rate of dc-bus voltage. \( k_{\text{dc}} \) can be defined as \( U_{\text{pp}} / u_{\text{dc}} \), where \( U_{\text{pp}} \) is the peak value of the maximum phase voltage that can be reached. \( k_{\text{dc}} \) depends on the PWM methods, for SPWM, \( k_{\text{dc}} \) is 0.5; for SVPWM, \( k_{\text{dc}} \) is \( \sqrt{3}/3 \).

VSC can reach its maximum ac voltage when \( m = 1 \),

\[ U_{\text{vsc - rms}} = k_{\text{dc}} u_{\text{dc}} / \sqrt{2} \]  \hspace{1cm} (12)

For GSC, the ac source it connects is power grid, which has a relatively stable voltage. BSRE will not directly threaten the current controllability of GSC, and the designed \( u_{\text{dc}}^* \) can keep GSC works well. For RSC, the ac source it connects with is DFIG rotor. Equation (8) shows that \( U_{\text{r}} \) increase with increasing \( \abs{\dot{\omega}} \), so BSRE will threaten the current controllability of RSC from both sides.

Increasing \( u_{\text{dc}} \) is the most effective way to improve current controllability. Combining Equations (8) and (12), the demand for \( u_{\text{dc}} \) imposed by BSRE can be obtained, \( \frac{u_{\text{dc}}}{u_{\text{dc}}} = \frac{u_{\text{dc}}^*}{u_{\text{dc}}} \) mainly dominated by \( k_{r/s} \), \( \dot{P}_s \) and \( \cos \varphi_s \), in which \( P_s \) is the function of \( s \) and \( \omega \). \( \dot{P}_s \) can be also expressed as a unary function of \( s \) under any BSRE schemes. By taking \( \cos \varphi_s = 0.95 \) (capacitive), the impacts of BSRE on current controllability of RSC is shown in Figure 4. It shows: (1) \( k_{r/s} \) is an important parameter affecting BSRE. In this paper, \( k_{r/s} \) is 3.3, which is a large value in practice, so the analysis result is conservative. (2) BSRE calls for a higher \( u_{\text{dc}} \) from both \( \omega_{\text{min}} \) and \( \omega_{\text{max}} \). (3) \( \frac{u_{\text{dc}}^*}{u_{\text{dc}}} \) is quite sensitive to the extended rotational speed.

3.4 Control requirements for mechanical systems

Aiming at the problem that BSRE may reduce the safety speed margin, a combination of two improved controls will be used to solve this problem. First, increase the speed loop control bandwidth of generator torque control and pitch control. This allows the generator and the pitch system to respond more quickly to speed fluctuations, so the speed fluctuations around \( \omega_n \) will be reduced effectively. Second, when the speed exceeds a pre-set value \( \omega_{\text{preset}} \), the PI control will be replaced by non-linear PID control. The lead action provided by the derivative control enables the pitch system to respond quickly when necessary. And the non-linearity lies in that the derivative control only works when the speed change rate is greater than zero, which increases the ability to resist overspeeding.

4 THE DMDCV CONTROL

The designed \( u_{\text{dc}}^* \) must meet the requirements of all possible operating points, but such a high \( u_{\text{dc}}^* \) is not always necessary.
If a constant and high $u_{dc}^*$ is used at all operating points, the electrical stress of the IGBTs will be increased. The switching process of IGBT is shown in Figure 5, and the switching loss is

$$E_{sw} = \int_{t_1}^{t_2} v_{CE}i_C dt + \int_{t_3}^{t_4} v_{CE}i_C dt \quad (13)$$

The collector current is mainly determined by the operating point, and $v_{CE} = n_{dc}$ for a two-level VSC, so the switching loss will also increase with increasing $u_{dc}$. Here the DMDCV control is proposed in which $u_{dc}$ can be kept at the lowest value at different working points.

### 4.1 DMDCV with modulation depth loop

$U_{vsc}$ is determined by the closed loop control, or in other words $U_{vsc}$ is determined by external factors, including the references and the ac source it connects. Equation (11) shows once $k_{dc}$ is determined by the selected PMW method, the term ‘$m$x$n_{dc}$’ will be determined by external factors. The existing control adopts a constant reference $n_{dc}$, and the rapid control makes the error between $n_{dc}$ and $u_{dc}^*$ negligible. So when $n_{dc}$ is fixed, $m$ changes with external factors. Conversely, $u_{dc}^*$ can be dynamically adjusted to obtain a constant $m$. This can be automatically done with a modulation depth loop.

As long as $m$ is less than 1, VSC can work in the linear modulation state. A modulation depth control loop with a $m_{set}$ equal to 1 (or slightly lower, such as $m_{set} = 0.98$) is added to produce the lowest $u_{dc}^*$ that the VSC can operate in linear modulation state, thus the goals of low switching loss and low electrical stress can be achieved at the same time.

Since $u_{dc}$ is shared by RSC and GSC, both the modulation depth of RSC ($m_r$) and the modulation depth of GSC ($m_g$) should be lower than 1. So, the larger one of $m_r$ and $m_g$ will be compared with $m_{set}$ and then tuned by a PI regulator to generate the dynamic minimum $n_{dc}^*$, as shown in Figure 6a. The parameters of the PI regulator should be selected to decouple with the dc-bus voltage loop in which, $m_c$ can be calculated by

$$m_c = \sqrt{2U_c/k_{dc}n_{dc}} \quad (14)$$

where $U_c$ can be calculated from Equation (8). And by ignoring the voltage drop on GSC’s filter, $m_c$ can be calculated by

$$m_g = \frac{\sqrt{2U_{gsc}}}{k_{dc}n_{dc}} \quad (15)$$

Combined with Figure 4, it is not difficult to find that when $|s|$ is small, $u_{dc}^*$ will be mainly controlled by $m_g$; when $|s|$ is large, $u_{dc}^*$ will be mainly controlled by $m_r$.

The controller of GSC and RSC will produce the amplitude and phase of the three-phase voltage reference value, in which $\phi$ and $\phi_f$ are obtained from the angle between the $d$-axis voltage reference value and the $q$-axis reference value (fixed value in steady state) plus the phase angle of the phase-locked loop output (varying with a specific angular frequency).

### 4.2 DMDCV without modulation depth loop

To generate $u_{dc}^*$ with an additional modulation depth loop is reasonable and clear. However, the PI regulators of cascade control will be increased to 4 (the PI in PLL is included). As a certain level difference of control bandwidth [28] (recommended 4 times or more) should be maintained between the inner loop and outer loop, it is hard to design the mutually restrictive control parameters for DMDCV.

It can be seen from Figure 6a that the tracking target of the modulation depth loop is an algebraic formula; therefore, there is no need to use an additional PI regulator to generate $u_{dc}^*$. Equation (12) can be understood in another way, i.e. the demanded minimum dc-bus voltage of a VSC (when $m = 1$) is

$$u_{dc}^{min} = \sqrt{2U_{vsc}^{dmd}/k_{dc}} \quad (16)$$

in which $U_{vsc}^{dmd}$ is the demanded ac voltage of VSC. The demanded minimum dc-bus voltage of RSC and GSC can be calculated separately, then the larger one should be chosen as the demanded minimum dc-bus voltage of the back-to-back converter, and DMDCV can be realized without modulation depth loop. As shown in Figure 6b $U_{vsc}^{dmd}$ can be calculated directly from

$$\begin{align*}
U_{vsc}^{dmd} &= \sqrt{u_{dr}^2 + u_{dq}^2} \\
U_{gsc}^{dmd} &= \sqrt{u_{dg}^2 + u_{dq}^2}
\end{align*} \quad (17)$$

where $u_{dr}^*$ and $u_{dq}^*$ are the output of the current loop, and if there are feedforward terms and decoupling terms, include these terms. So

$$u_{dc}^* = \sqrt{2 \max\{\sqrt{u_{dr}^* + u_{dq}^*}, \sqrt{u_{dg}^* + u_{dq}^*}\}/k_{dc}} \quad (18)$$
Equation (18) provides a general method to calculate the DMDCV for back-to-back converter, and all the calculations are finished within the converter controller and no extra parameters are needed. This advantage makes DMDCV also to be directly applied to full power conversion WECSs that are based on PMSG or SCIG.

4.3 The decision-making unit

A decision-making unit will determine whether to adopt BSRE and DMDCV or not. If the average wind speed is much higher than the rated wind speed, the WECS is already at full load state, so there is no need to enable BSRE. This article uses the same MPPT control as the actual WECSs [29], and when BSRE is disabled, the two speed commands keep its original value; when BSRE is enabled, the two speed commands of MPPT control extend upward and downward, respectively.

When DMDCV is disabled, set $u_{UL} = u_{LL} = 1100$ V, thus the modulation-depth control is bypassed; when DMDCV is enabled, set $u_{UL} = 1168$ V and $u_{LL} = 900$ V. The advantages of DMDCV are obvious. Case 1: there is no need for BSRE, the DMDCV will benefit the converter efficiency and the voltage stress of IGBTs. Case 2: there is a need for BSRE, the DMDCV will support speed range extension with the best condition.

5 SIMULATION VERIFICATIONS

5.1 Simulation settings

The simulation is done on the HIL co-simulation platform based on RTDS and Bladed (Figure 7), which can simulate detailed dynamics of WECS, including the interaction of aerodynamics, structural dynamics, electromagnetics, and control system [29]. This platform can be used to verify the feasibility of...
BSRE and DMDCV, and figure out the possible impacts on the mechanical system.

The detailed model of a 1.67 MW DFIG-based WECS was established, the rotor radius is 42.8 m and the rated wind is 10 m/s. The gearbox ratio is 104.5, the generator inertia and turbine inertia are 123.5 kg m² and 6.54 × 10⁶ kg m², respectively. A snubber circuit in parallel with the valve (IGBT) was used to consider the switching losses, which consists of a resistor in series with a capacitor, 20 Ω and 0.2 μF, respectively. The on/off state resistance of the valve is 0.5 mΩ and 10⁶ Ω, respectively.

Up to four groups of simulations are designed, among which ‘conventional’ does not adopt any improved control, the terms ‘DMDCV-PI’ and ‘DMDCV’, respectively, indicate DMDCV with and without modulation depth loop. ‘BSRE’ indicates that the speed range is extended from [0.75, 1.2] to [0.67, 1.25]. The speed loop PI parameters of RSC are listed in Table 1 [17], the speed loop parameters of RSC and GSC. The waveforms are also in line with expectations.

TABLE 1 Speed loop control parameters of RSC

| Simulation group | Torque control | Pitch control |
|------------------|---------------|--------------|
|                  | Kp  | Ki  | Kp | ki | kd |
| Conventional     | 5   | 0.5 | 80 | 10 | –  |
| BSRE             | 20  | 2   | 240 | 16.67 | 60 |

FIGURE 7 The co-simulation platform with controller hardware-in-loop

5.2 Simulation results

First, the feasibility of the proposed control strategy will be verified under extreme wind conditions (\( \bar{v} = 15 \) m/s), as shown in Figure 8. Figure 8a shows, when adopting BSRE, the WECS operates stably at a higher speed. The improved torque control and pitch control ensure that the speed is within the safe range by limiting speed fluctuations. The speed of WECS will not be affected by DMDCV. For the converter, \( \nu_{dc} \) changes dynamically after DMDCV is adopted, \( m_e \) and \( m_t \) are always less than or equal to 1, so the converter works in the linear modulation area; At any time, one of \( m_e \) and \( m_t \) is equal to 1, which means that \( \nu_{dc} \) operates at the minimum value dynamically.

Comparing ‘BSRE&DMDCV-PI’ to ‘BSRE&DMDCV’, due to the level difference requirements, the control bandwidth of the modulation loop in ‘BSRE&DMDCV-PI’ should not be too high, so the actual dynamic performance of the modulation depth is limited. In practical applications, \( m_{ext} \) is set to 0.98 to preserve the margin to avoid over-modulation. It can be seen that the \( \nu_{dc} \) of ‘BSRE&DMDCV’ is lower, and the ability to maintain \( m = 1 \) under both static and dynamic conditions are better, so the follow-up simulations will use this scheme.

From another perspective, due to the lower control bandwidth of the modulation loop, the \( \nu_{dc} \) of ‘BSRE&DMDCV-PI’ is smoother.

Figure 8b shows the power loss and energy loss of converter under ‘conventional’ and ‘DMDCV’. Since the average wind speed far exceeds \( v_{ext} \), the four groups of simulations are always at full power. It shows when adopting DMDCV, the power loss of back-to-back converter (calculated by \( P_{dc}u \)) is reduced by about 2 kW, and the energy loss is reduced by 358 kJ (8.87%).

Figure 8c shows that three-phase current of generator stator and rotor are symmetrical and sinusoidal while \( \nu_{dc} \) is dynamically adjusted. The unity power factor control is applied for both RSC and GSC. The waveforms are also in line with expectations.

Figure 9a is simulated under low wind speed (\( \bar{v} = 4 \) m/s). As the only difference, ‘BSRE&DMDCV-PI’ and ‘BSRE-2&DMDCV’ use different \( \omega_{min}^{ext} \), 0.67 pu and 0.69 pu, respectively. The excessive low \( \omega \) in ‘BSRE&DMDCV’ makes \( \nu_{dc} \) exceed 1.1 kV most of the time, the speed fluctuations may even cause \( m_t \) to be slightly greater than 1 around 226 s and 303 s, indicating a slight over-modulation. As a compromise, ‘BSRE-2&DMDCV’ slightly increase \( \omega_{min}^{ext} \) and most of the time \( \nu_{dc} \) is less than or equal to 1.1 kV, and \( m_t \) always remains at 1. The increased power production (\( \Delta E \), in kWh, which is integral of increased \( P_{dc} \) of the two groups are 1.71 kW (4.42%) and 1.408 kW (3.63%), respectively).

Figure 9b is simulated under medium-high wind speed (\( \bar{v} = 9 \) m/s). In this wind condition, as the WECS is slightly far from the safe speed \( \omega_{max} \) (\( \nu_{min}^{dc} \) is very sensitive to slip), the dynamic dc-bus voltage \( \nu_{dc} \) is always lower than the conventional 1.1 kV. At any time, one of \( m_e \) and \( m_t \) is equal to 1, indicating that \( \nu_{dc} \) is the lower limit of the back-to-back converter. The \( \Delta E \) within 300 s is 4.182 kW, a relative increase of 1.928%.

Figure 10 shows the impacts of BSRE on the mechanical load. Considering that the mechanical load of WECS reaches its maximum value near \( \nu_{ext} \), the average wind speed is set to 12 m/s. It shows the low-speed shaft torque of the drive train is reduced effectively as the generator speed increases. The peak value of axial thrust is slightly increased, and the effect on the torque of the nacelle is negligible. Overall, BSRE benefits the torsion
FIGURE 8  Test on BSRE and DMDCV under extreme wind. (a) Feasibility test. (b) Converter loss. (c) Instantaneous currents of ‘BSRE & DMDCV’ from 142.5 to 142.6 s.

FIGURE 9  Evaluation of BSRE&DMDCV. (a) Power generation improvement in low wind speed. (b) Power generation improvement in medium-high wind speed.
mechanical components of WECS, and has very limited negative impact on non-torsion components.

6 | CONCLUSION

The proposed DMDCV control is able to keep the linear modulation state of RSC and GSC with the minimum dc-bus voltage, so as to achieve lower converter loss and lower electrical stress while supporting BSRE. The comprehensive measures can well solve the problem of reduced speed margin caused by the increase in rated speed. DMDCV without modulation depth loop is superior to DMDCV with modulation depth loop in terms of dynamic performance and parameter design flexibility. It is worth pointing out that because \( u_{\text{dc}}^\text{min} \) in DFIG-based WECS is very sensitive to \( s \), a large enough \( |s| \) only occurs in a few extreme wind conditions. Therefore, when BSRE and DMDVC are used reasonably, \( u_{\text{dc}} \) is lower than the conventional constant value most of the time.

The proposed control strategy has good practicability, and is easy to extend on the classic control method, and the feedback variables can be easily extracted without additional sensing signals. The co-simulation results show it can effectively improve wind energy capture efficiency and reduce converter switching losses, thus bringing considerable benefits to annual power production.

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NOMENCLATURE

- \( J \): moment of inertia of WECS
- \( k_{\text{dc}} \): utilization rate of dc-bus voltage
- \( m \): modulation depth of voltage source converter
- \( P_e \): active power of generator (stator and rotor)
- \( P_{\text{s}}, Q_{\text{s}} \): active/reactive power of generator stator
- \( s \): slip of DFIG
- \( u_{\text{dc}} \): dc-bus voltage of back-to-back converter
- \( U_r, I_r \): voltage/current of generator rotor
- \( U_s, I_s \): voltage/current of generator stator
- \( U_{\text{vsc}} \): AC port voltage of voltage source converter
- \( v \): wind speed
- \( \beta \): pitch angle of wind turbine
- \( \lambda \): tip speed ratio of wind turbine
- \( \lambda_{\text{opt}} \): optimum tip speed ratio of wind turbine
- \( \omega \): rotational speed of wind turbine

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APPENDIX A

TABLE A1 Parameters of DFIG

| Parameters       | Value       | Parameters       | Value       |
|------------------|-------------|------------------|-------------|
| Stator connection| Star        | Rotor connection| Star        |
| Rated L-L voltage| 690 V       | Rated power      | 1.67 MVA    |
| Rotor resistance | 1.3 mΩ      | Stator resistance| 1.0 mΩ     |
| Rated frequency  | 50 Hz       | Magnetizing reactance | 3.766 mH |
| Pair of poles    | 2           | Stator leakage inductance | 90.75 μH |
| Turns ratio $k_{r/s}$ | 3.3       | Rotor leakage inductance | 78.04 μH |

TABLE A2 Control parameters of GSC

| Control loops     | BSRE&DMDCV-PI | Remaining groups |
|-------------------|--------------|-----------------|
| Kp                | 160          | 50              |
| ki                | 900          | 900             |
| Current loop      | 40           | 2               |
| Udc & Qg loop     | 10           | 0.4             |
| Modulation loop   | 2.5          | 71.43           |
|                  | 0.25         |                 |

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