Suppressing output power fluctuation and improving FRT Capability of DFIG-based wind energy conversion system with SMES and dual-mode protection scheme

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Abstract
As the grid codes of wind turbines note, doubly fed induction generator (DFIG)-based wind energy conversion system (WECS) should maintain uninterrupted operation during certain voltage faults. To meet the codes, a novel configuration of DFIG-based WECS is proposed in which a superconducting magnetic energy storage (SMES) and a series transformer are incorporated. The control strategies of the WECS are redesigned to smooth the output power fluctuations and ride through different levels of voltage faults. The grid-side converter (GSC) is controlled to smooth power fluctuations caused by random wind speeds under normal conditions. The GSC and protection circuit are controlled to switch into the series compensation mode to fully compensate the stator voltage during voltage swells and slight voltage sags. While under severe voltage sags, the protection circuit operates in the current limiting mode, which significantly limits the stator and rotor fault overcurrent, improves the stator voltage and suppresses fluctuations of the electromagnetic torque. The different faults are applied, the simulation results demonstrate that the presented scheme can effectively smooth output power fluctuations and strengthen the voltage fault ride-through capability (FRT) of WECS.

1 INTRODUCTION

In order to prevent environmental degradation and reduce fossil energy consumption, the total amount of renewable energy generation has been steadily increasing year by year. Among them, because of the mature development of wind power technology, DFIG-based wind turbines have been widely used around the world [1–3]. However, the fact that the stator is connected to the grid make the DFIG face the risk of over-voltage and over-current, which will even damage the converter in severe cases [4]. Therefore, it must be ensured that the DFIG has fault ride-through (FRT) capability under certain faults [5]. In addition, owing to the randomness and intermittence of wind speed, the wind speed fluctuations can affect the voltage and frequency stabilities of the grid, which is a key factor to restrict the high-power delivery of wind farms to the grid in practice operation [6].

Improving RSC and GSC’s control strategies is a low-cost way to promote FRT capability of the DFIG. The demagnetizing control proposed in [7] and the further improved double-loop control in [8] both result that the rotor current contains the current component of rotor speed frequency, causing electromagnetic torque oscillations. [9] Proposes a scaled current tracking control, however, it will cause reactive current absorption and rotor speed acceleration. Worse still, improved control is often limited by ratings of DFIG’s converters, making it unsuitable for severe faults.

Another kind of efficient method is to add the corresponding hardware protection device [10–19]. The combined method of crowbar and DC-chopper can effectively protect the DFIG converters [10]. Nevertheless, during the activation of the crowbar, the DFIG will turn into an asynchronous motor, absorbing the reactive power from the system and worsening the wind farm terminal voltage. In [11], the static synchronous
compensators (STATCOM) are adopted to output reactive power to increase the terminal voltage during faults. Besides, a dynamic voltage restorer (DVR) is introduced to remain the DFIG terminal voltage in [12]. Recently, a resistive superconducting fault current limiter (R-SFCL) and an inductive SFCL (L-SFCL) are designed in [13] and in [14], respectively. The R-SFCL and L-SFCL applied in the DFIG rotor side can apparently limit the overcurrent in [15] and [16] respectively. But as an energy consumption type current limiter, the R-SFCL needs a large amount of refrigeration power and cannot contribute to energy storage during faults [15]. And the latter will extend the decay process of transient flux [16]. A new FCL-DVR is introduced in [17] to compensate voltage variations and suppress short current. However, it does not help to smooth the output power and reduce DC-link fluctuations of the DFIG. And an additional converter still increases the system cost. In [18], the GSC is reconfigured as a DVR connected in series between the stator and the power grid under faults. However, owing to the low capacity of the GSC, if the stator voltage is to be fully compensated, the GSC capacity should be redesigned to be the same as the power rating of the DFIG.

Moreover, none of the above mentioned methods can smooth the output power of the DFIG under varying wind speed. Several methods have been proposed based on the energy storage device (ESD) to both have FRT capability and smooth output power. In [20], an ESD and an energy storage converter (ESC) are reconstructed as an auxiliary source connected in parallel with the RSC to inject required demagnetizing current and reactive current. However, as a result of the injection of a large amplitude of demagnetizing current, power and electromagnetic torque oscillations are greater. And the ESC is not utilised during normal conditions. [21] Proposes a new embedded topology of DFIG and DVR. Each converter performs a specific function, which can obtain ideal voltage fault ride-through performance. But its investment costs are high and the DVR adopts positive and negative sequence control loops based on PI controllers, resulting in computational burdens.

In our previous works, we have proposed that a parallel superconducting magnetic energy storage device (SMES) for balancing the output power can be appeared as FCL under faults, which ensures good transient performances during voltage sag period and recovery with modified controls [22]. But the superconducting coil (SC) may face the risk of overcharge or quench under sever faults in this system, and its performance under asymmetric voltage sags is not presented and the effect on voltage swells needs to be studied. It is worth noting that SMES is an electrochemical battery with the advantages of quick response speed, low pollution, and high-power density by comparison to other ESDs [23–25].

This paper proposes a new integrated configuration of DFIG-based WECS with SMES and dual-mode protection scheme for smoothing power fluctuations and enhancing voltage fault ride-through performance, which is making full use of DFIG’s components to reduce the investment cost of introducing hardware. First, under normal operation, the SMES can absorb or release power through the GSC to suppress the output power fluctuations. Under a voltage swell or a slight voltage sag, the GSC operating in the series compensation mode can fully compensate the stator voltage, and the WECS is not affected by the grid voltage disturbance. In severe faults, the protection scheme enters the current-limiting mode to limit the overcurrent, while improving the stator voltage.

The organization of this paper is as below. Section 2 shows the DFIG math model and its performance in case of a fault. The proposed configuration and operating principle are presented in Section 3. The proposed control strategies for this system are described in Section 4. The simulation results and discussion are provided in Section 5. The cost analysis is demonstrated in Section 6. Finally, the conclusion is summarized in Section 7.

### 2 MATH MODEL OF DFIG

The direction of the stator and rotor currents are both based on the motor convention. The voltage and flux equations in a static stator-oriented reference frame can be expressed as

\[
\vec{v}_s = R_s \vec{i}_s + \frac{d}{dt} \vec{\psi}_s \tag{1}
\]

\[
\vec{v}_r = R_r \vec{i}_r + \frac{d}{dt} \vec{\psi}_r - j \omega \vec{\psi}_s \tag{2}
\]

\[
\vec{\psi}_s = L_{ss} \vec{i}_s + L_{sr} \vec{i}_r \tag{3}
\]

\[
\vec{\psi}_r = L_{rs} \vec{i}_s + L_{rr} \vec{i}_r \tag{4}
\]

where \(v_s, i_s, \) and \(\psi_s\) are voltage, current and flux space vector. The subscripts “s” and “r” represent the stator and rotor reference frames, respectively. \(L_{ss}, L_{sr}, \) and \(L_{ss}, L_{rr}\) are stator, rotor and magnetizing inductance, respectively.

According to Equations (3) and (4), the rotor flux expressed by the stator flux and the rotor current can be obtained

\[
\vec{\psi}_r = \frac{L_{ss}}{L_{rs}} \vec{\psi}_s + \sigma L_{ss} \vec{i}_s \tag{5}
\]

where \(\sigma = 1 - L_{ss}^2 / L_{ss} L_{sr}\) is the leakage coefficient.

Substituting Equation (5) in (2), the rotor voltage can be computed by

\[
\vec{v}_r = \frac{L_{ss}}{L_{rs}} \cdot \frac{d}{dt} \vec{\psi}_s + (R_r + \sigma L_s \frac{d}{dt}) \cdot \vec{v}_s \tag{6}
\]

The rotor voltage consists of two terms. The first term of the right side of Equation (6) is the back-emf of the rotor induced by the change of the stator flux, which is also known as the rotor open-circuit voltage denoted as \(\vec{v}_s\). The second term represents the voltage drop of across the rotor transient impedance.
THE PROPOSED CONFIGURATION

3.1 Principle of operation

The dual operation modes of the protection circuit exist, as described below:

1. Series compensation mode: Under normal operation, the series transformer is bypassed by S3. When a voltage fault is detected, the switch S1 and S3 are opened, the switch S2 is closed. The GSC controller is switched to compensation control, and the compensation voltage is injected to keep the DFIG terminal voltage as the pre-fault value. Therefore, DFIG can maintain steady operation and supply power to the grid.

In order to achieve a full compensation of a 100% voltage sag, the voltage source converter (VSC) must be rated at the power of DFIG-based wind turbine according to [12]. Since part compensation of the line voltage will be more economical method. In practice, the rated power of the GSC is usually equal to the slip active power of the DFIG. Thus, $P_{GSC} = 0.3P_{DFIG}$ is defined here. Another advantage of selecting 30% rated capacity is that within the range of voltage swell specified in the guidelines [27], full compensation can be realized by relying on the GSC and transient switching of switches can be reduced. The proposed compensation mode can compensate not more than 30% of voltage sag or swell.

2. Fault current limiting mode: After a short-circuit fault occurs, the switch S3 and S2 are opened, and the S1 is closed simultaneously. The inductor element of this LC filter is series connected in the stator circuit by a coupling transformer, which both limits the fault overcurrent and increases the terminal voltage to ensure that DFIG can continue uninterrupted operation under a severe fault.

In this case, the equivalent series impedance induced in the stator terminal can be expressed by

$$Z_{eq} = R_f + j\omega_1 L_{eq}$$

$$= n^2 (R_f + j\omega_1 L_f)$$

where $n$ is the turn ratio of the series transformer. $L_f$ represents the inductance of the LC filter. $R_f$ denotes the internal resistance of the inductor of the LC filter.

The peak rotor current of DFIG is generally reached at $T/2$ since from a fault. Therefore, the maximum value of fault rotor phase current is considered as the sum of the maximum values of the components [19].

$$i_{r,max}(t) = \left[ i_{r0}(0) - \frac{1}{\sigma T} \right] V_f I_{sw} \left( 1 - j \frac{\tau}{1 + \tau^2 \omega_f^2} \right)^{-T/(2\pi)} e^{-T/(2\pi)}$$

$$+ \frac{V_f}{\sigma T} \left( 1 - j \frac{\tau}{1 + \tau^2 \omega_f^2} \right)^{-T/(2\pi)} e^{-T/(2\pi)}$$

$$+ \frac{1}{\sigma T} V_f I_{sw} \left( 1 - j \frac{\tau}{1 + \tau^2 \omega_f^2} \right)^{-T/(2\pi)} e^{-T/(2\pi)}$$

where $\sigma$ is the slip rate, $\omega_f$ is the rotor angular frequency, and $\omega_1$ is the synchronous angular frequency. $I_{sw}$ is the maximum amplitude of the stator current. $V_f$ is the grid phase voltage, and $T$ is the duration of the fault.
where

\[
\tau_s = \frac{L_s + L_{eq}}{R_s + R_{eq}}; \sigma' = 1 - \frac{L_s^2}{(L_s + L_{eq})L_r} \sigma = \frac{\tau_r}{R_r} \\
\tau = \frac{\tau_s \tau_r}{\tau_s - \tau_r}.
\]

It can be seen that the rotor overcurrent can be restrained. Therefore, the RSC will be effectively protected with the fault current limiting mode under serious short faults.

### 3.2 Switching sequence

The flowchart of the switching sequence of corresponding power electronic switches and the GSC control is depicted in Figure 2. The fast detection algorithm in [28] is used to obtain the positive-sequence component of PCC voltage. When the voltage detection algorithm detects that the PCC voltage \(U_{\text{PCC}}\) is between 0.7 and 0.95 pu or >1.05 pu, the GSC enters the series compensation mode. Switch 3 is open, switch 2 is closed, and switch 1 is opened. If the PCC voltage is below 0.7 pu caused by a short-circuit fault, the fault current limiting function of the series compensation device is enabled. Switches 1 and 2 maintain the switch state under normal operating conditions, switch 3 is open, and switch 4 is closed. When the fault is cleared, the PCC voltage fluctuates near its rated value. The GSC can enter the series compensation mode to accelerate the voltage recovery. While it returns to the rated voltage, the GSC restores normal operation.

### 4 CONTROL STRATEGY

#### 4.1 Control strategy of RSC

As demonstrated in Figure 3, during normal conditions, the RSC control scheme adopts the most employed dual loops vector control with PI controllers. For the outer loop, the stator active and reactive power references \((P_s, Q_s)\) and their actual values \((P_s, Q_s)\) determine the rotor current references. The differences between the \(dq\)-axis rotor reference currents and the actual rotor currents are controlled by PI controllers to obtain the RSC output reference voltage.

However, it is critical to take into account the dynamic reactive current support of the DFIG under a voltage fault [5]. Because the bandwidth of current inner loop is designed to be apparently larger than that of power outer loop, the response speed of the current loop is much faster than the power outer loop. Therefore, in order to promote the RSC control performance during a fault, when the protection circuit turns into fault current limiting mode, the power outer loop is disconnected and the current loop control operation is used. According to the E.ON guidelines [5], the additional reactive current that DFIG needs to output is

\[
I_{sq} \geq \begin{cases} 
-2 \Delta U_s/U_{sn}, & -0.5 \leq \Delta U_s/U_{sn} \leq -0.1 \\
0, & 0.5 \leq \Delta U_s/U_{sn} < -0.5 \\
1, & 1 \leq \Delta U_s/U_{sn} < 1.5 
\end{cases} \tag{12}
\]

Then according to the relationship between stator and rotor currents, the \(q\)-axis reference of the rotor current should be set to

\[
I_{rq,ref} = -\frac{L_s}{L_m} (1 - U_s) - \frac{U_s}{\omega_1 L_m} \tag{13}
\]

Based on the reference \(I_{rd,ref}^*\) of the maximum power tracking control, the active current can be set as

\[
I_{rd,ref} = \min \left\{ I_{rd,ref}^*, \sqrt{I_{rm}^2 - I_{rq,ref}^2} \right\} \tag{14}
\]

where \(I_{rm}\) is the continuous current threshold of the RSC.

#### 4.2 Control strategy of GSC

Under the help of the DC-link parallel energy storage device, the GSC can utilize cascaded vectors to control active and
reactive powers rather than adjusting the DC voltage under normal conditions. The stator voltage is oriented on the \(d\)-axis, that is \(U_{sd} = 0\). The power outputs can be controlled through adjusting the line current \(I_g\) shown in the following dynamics:

\[
I_{gd\_ref} = (K_p + \frac{1}{K_i \cdot s}) \cdot (P_g - P_{gref})
\]
\[
I_{gq\_ref} = (K_p + \frac{1}{K_i \cdot s}) \cdot (Q_g - Q_{gref})
\]

The inner current control loop generates the GSC grid-side reference voltage, which is consistent with conventional vector control of GSC as shown in Figure 3.

In practice, the reference reactive power \(Q_{g\_ref}\) is usually set to be zero. The reference active power \(P_{g\_ref}\) of the GSC can be set according to two situations to eliminate power fluctuations.

1. When the WECS outputs the required power \(P_{out\_ref}\) from the wind farm control centre, the reference active power can be given by

\[
P_{g\_ref} = P_{out\_ref} - P_{WT}
\]

where \(P_{WT}\) represents the mechanical power of the DFIG.

2. When the WECS output power is not specified, the power fluctuations can be reduced through low-pass filtering method, the reference active power is obtained by

\[
P_{g\_ref} = P_{WT} - \frac{1}{1 + T_{SMES}} P_{WT}
\]

where \(T_{SMES}\) is the filter time constant.

### 4.3 Series compensation of GSC

During the faults, the GSC is reconnected in series with the stator side and the series compensation mode of the VSC is active, which controls a compensation voltage to maintain the stator voltage. And asymmetric faults are more common in power system than symmetric faults. Thus, the GSC is required to be able to generate a negative sequence compensation voltage to prevent the asymmetric stator voltage. The voltage and current cascade control structure is adopted in [21]. However, the DFIG output current flows directly through the series transformer, the current control is unsuitable in here [12]. Therefore, a single closed-loop voltage control is adopted in transient control of the GSC without an inner current controller. The transient strategy of the GSC under the faults is shown in Figure 3. The controller is composed of a PI controller and a reduced-order vector integrator (ROVI) controller. The ROVI is only activated at \(-2\omega_1\) as a single-side resonant controller, which has a leading response within the allowed frequency offset [29].

The transfer function of the ROVI is given by

\[
G_{ROVI}(s) = \frac{K_{r1} + K_{r2}s}{s + j 2\omega_1 + 2\omega_c}
\]

where \(K_{r1}\) and \(K_{r2}\) are resonance coefficients, \(\omega_c\) is the cut-off frequency, which can reduce the sensitivity of the controller for frequency variations.

The converter reference voltage can be obtained by

\[
V_{ref}(t) = u_c(t) + G_{Vc+ROVI}(s) \cdot (u_{ref}(t) - u_c(t))
\]

where \(u_{ref}\) and \(u_c\) are the filter capacitor reference voltage and the capacitor measured voltage, respectively.
4.4 | DC/DC converter

As a power type energy storage unit, the SMES can quickly absorb or release energy by the DC/DC converter to keep the DC-link voltage constant. The control block diagram of the DC/DC converter is depicted in Figure 3. The deviation between the DC voltage reference $V_{dc(ref)}$ and the actual value $V_{dc}$ is used as the input of the PI controller to generate an adjustable duty cycle $\Delta D \in [-0.5, +0.5]$. And the duty cycle $D$ of the IGBTs is obtained by adding the basic value 0.5 to the adjustable duty cycle $\Delta D$.

5 | PERFORMANCE EVALUATION

A 1.5MW DFIG-based WECS model is built in Matlab-Simulink, and the slip rate $s = -0.2$. The maximum allowable value of rotor current is 2.0 pu. The simulation conditions are set as follows:

Case 1: steady operation with random varying wind speed;
Case 2: 30% symmetrical voltage swell;
Case 3: 3LG fault with rated wind speed.

5.1 | Case 1: Behaviours under varying wind speed

The total output power of WECS is set to be 0.9 pu, in which the base power is 1.5/0.9 MVA. Figure 4(a) shows random time-varying wind speed for 100 s. The stator output power will fluctuate in the range of 0.81–0.99 pu, as seen from Figure 4(b). However, the overall output power can be maintained at 0.9 pu under the power control of the GSC. And Figure 4(c) shows that the DC-link voltage ($V_{dc}$) also stays 1.0 pu by the SMES. Furthermore, the stored energy of the SMES is within 0.113–0.872 MJ which is below the maximum energy capacity, as shown in Figure 4(d).

5.2 | Case 2: Behaviours under 30% voltage swell

The stator positive-sequence components of stator voltage are depicted in Figure 5. The German guideline (Verband Deutscher Elektro, VDE) requires wind turbines to remain connected to the grid for at least 100 ms when the voltage reaches the 130% of rated value [30]. With the proposed strategy, the stator voltage is maintained at 1 pu. From Figure 5(b), it can be seen that the rotor voltage can still keep the pre-fault value under a low voltage fault of 0.3 pu lasting 700 ms. The voltage and power responses under a 30% voltage swell are illustrated in Figure 6. During the fault, the DFIG stator voltage rises to 1.3x of the rated voltage without protection, which threatens insulation of the stator windings. Under the proposed scheme, the GSC operates in series compensation mode once the fault is detected, which injects the compensation voltage. According to Figure 6(b), the stator voltage $U_s$ can maintain the pre-fault value. The DFIG behaves large fluctuations of active and reactive powers under no protection after the fault occurrence, as shown in Figure 6(c, d). With the proposed scheme, the output power has no fluctuations.

As illustrated in Figure 7(a), at the instant of fault occurrence, the peak value of the rotor voltage is 0.628 pu. As can be seen from Figure 7(b–d), there is a large transient component of the rotor current, which causes significant fluctuations in the electromagnetic torque ($T_{em}$) of the generator. It will reduce the quality of the grid-connected current and have an impact on the mechanical driving parts. With the proposed scheme, the rotor current basically has no fluctuations, and the oscillations of $T_{em}$ are significantly suppressed, as shown in Figure 7(b–d). Moreover, the proposed scheme has better effect on the DC voltage suppression. From Figure 8, the stored energy of the SMES is within its capacity.

5.3 | Case 3: Behaviours under 3LG fault

As shown in Figure 1, a 3LG fault at bus 2 happens within 0.1–0.3s, causing the terminal voltage to drop by 90%. As a traditional protection circuit, the combinational method of a
crowbar and a dc chopper (scheme A) is adopted for comparative analysis. As the maximum rotor current increases to 2.0 pu, the crowbar circuit is activated to consume excess energy. Meanwhile, the RSC is blocked. And the LVRT scheme based on an energy storage device (ESD) in [20] is carried out for comparison, as the scheme B. And the proposed scheme is referred to as scheme C.

Figure 9 shows the stator voltage under a three-phases grounded fault with different protection schemes. As seen from Figure 9, the scheme A has an adverse effect on the stator voltage, which consumes reactive current from the grid to establish field excitation. Relying on the reactive output of DFIG in scheme B, the voltage is raised to 0.15 pu. Under the scheme C, the positive sequence stator voltage rises from 0.1 to 0.80 pu because of the rapid increase of equivalent impedance of the stator winding after the fault occurs.

Under the scheme A, the RSC is blocked during the crowbar operation and can be effectively protected. It can be seen from Figure 10(a) that when there is no protection, the active power instantly increases to 2.23 pu after the fault clearance due to the release of the DC capacitor charging energy. And
the reactive power sharply reduces to $-2.06$ pu with no protection and $-2.01$ pu with scheme A after the fault clearance in Figure 10(b). According to Figure 10(a, b), the scheme C can guarantee a smoother power transition. Moreover, during the activation of the crowbar, the DFIG consumes reactive power which further deteriorates the grid voltage. Especially after the fault elimination, the absorption of reactive power is more obvious, as seen from Figure 10(b). With the scheme C, 0.75 pu of required reactive power can be generated by the DFIG to improve fault voltage.

And with no protection, the DC-link voltage rises to 2.14 pu. From Figure 10(c), $V_{dc}$ can be constrained near the rated value in both schemes. With only crowbar, although the DC voltage rise can be suppressed, the DC-link voltage will still exceed its safety threshold. When the energy storage device is applied alone, it can stabilize the DC voltage, but cannot suppress the DFIG overcurrent and overvoltage. While it increases to 1.16 pu and then decreases to 0.91 pu in the early stage of the fault in scheme B. The peak-to-peak values of $V_{dc}$ fluctuations is only 0.12 pu. And the $V_{dc}$ deviation of the scheme C is the smallest among all schemes. In addition, the peak-to-peak values of $T_{em}$ at the fault occurrence and clearance are 3.982 and 3.334 pu without protection, respectively. As seen from Figure 10(d), their values are 3.397 and 3.346 pu with the scheme A. Because the scheme A cannot maintain the normal operation of the RSC, the electromagnetic torque is uncontrollable. It can be seen that the existence of the large demagnetization current of the scheme B of speed frequency cannot reduce the torque oscillation compared to the method without protection. While the peak-to-peak values of $T_{em}$ decline to 1.764 and 1.419 pu in the scheme B when the fault occurs and is cleared.

According to Figure 11, the stored energy of the SMES increases during the fault, whereas it is still below its capacity. Figure 12 depicts the stator and rotor current behaviours under the scheme B and C. When no protection is executed, the peak values of stator and rotor currents are 4.61 and 4.55 pu, respectively. And as shown in Figure 12(a, b), their peak values are 3.44 and 3.51 pu at the moment of fault occurrence with scheme A, which indicates that the stator fault currents cannot be limited. With the help of the parallel rotor-side converter in Scheme B, the current of RSC is less than the total rotor current, indicating that the RSC can be well protected. By contrast, the corresponding peak values with the scheme C are restricted to 1.55 and 1.74 pu, whose limitation rates are 33.6% and 38.2%, as seen from Figure 12(c, d). Therefore, the scheme C has better performance in fault current limitation. Meanwhile, the transient
components of stator and rotor currents decay faster by contrast with scheme B.

6 | COST ANALYSIS

The cost of this solution can be divided into the cost of energy storage device and the cost of fault ride-through device. In comparison with other ESDs, the SMES has the advantages of high-power density, quick response and long life. Moreover, the important factor to be considered in the application of energy storage devices to DFIG is capital cost, which includes energy costs, power costs, and per cycle cost. As shown in Table 1, in this study the inductance and rated current of the SMES coil are designed as 2 H and 1000 A, respectively. The rated power of SMES is selected generally according to 20–30% of active power rating of the DFIG.

Taking the vanadium redox battery (VRB) used in [21] as a comparison, VRB is a high energy capacity and low power density ESD with discharge time of seconds-10 h. From the perspective of technical performance, VRB is more suitable for large-scale energy integration. The high-power density of SMES makes its discharge milliseconds-8 s, which suggests that its smaller size is easier to be integrated in the DFIG and it is able to quickly balance power fluctuations within seconds. In terms of cost, as shown in Table 2 [31], the cost range of a 1 MJ / 575 kW VRB can be calculated as $345,042–862,778, while the cost of SMES with the same capacity is $115,278–232,778. Therefore, a lower power cost of SMES can make it show certain economic advantages when it is integrated into DFIG with low energy capacity and high power. In addition, it should be noted that the life of VRB is only between 5–10 years, and it needs to be replaced during the entire DFIG operation. The replacement cost and the cost of the new device will cause the overall cost to increase greatly. SMES has a long life of > 20 years as can be known from [31], thereby making it practically applied to protection of the entire life operation of DFIG for about 25 years. Therefore, the overall cost of SMES is more economical. To sum up, SMES is selected as embedded energy device for the DFIG, which can show advantages in cost and performance.

Moreover, it is worth noting that, compared with those ride-through methods based on additional converters or DVR, the proposed method does not require new converters. According to the cost estimation algorithm of the wind turbine converters in [32], the initial cost of the 1.5 MW SiC-based converter that only considers semiconductor devices and cooling systems can be estimated as $38,458. If the energy consumption cost is considered, the total cost will be multiplied several dozen times. Based on the above, the method presented in this paper demonstrates economic advantages while improving DFIG performance.

7 | CONCLUSION

In this paper, a new DFIG protection scheme is proposed to smooth power output and improve voltage FRT performance. The system construction, switching sequence and control strategy are designed under normal conditions and different levels of voltage fault. The proposed scheme makes full use of the components of the conventional DFIG system. Since it does not need to add a new converter or increase the rated capacity of the converter of conventional system, ensuring its economy. Under normal conditions, the GSC is controlled to suppress output power fluctuations of the DFIG. In the range of voltage swell and light voltage sag, the GSC is used to compensate the terminal voltage through a series transformer to maintain the pre-fault value, and the RSC still can operate in steady conditions and the key parameters keep unchanged. Under severe voltage sags, the fault current limiting mode of the protection circuit can be triggered to limit rotor fault current, reduce DC-link voltage and electromagnetic torque fluctuations. The maximum values of the stator and rotor currents are decreased from 4.61 and 4.55 pu to 1.55 and 1.74 pu, and their limitation rates are 33.6% and 38.2%, respectively. The peak-to-peak values of electromagnetic torque and DC voltage fluctuations are restricted to 1.76 and 0.12 pu. And the DFIG can generate specified reactive current and remain grid-connected operation. The simulation results verify the effectiveness of the proposed method under varying wind speed condition, voltage swells and voltage sags at different levels.

ACKNOWLEDGEMENT
This work was supported by the National Natural Science Foundation of China under Grant No. 51907134.

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APPENDIX A
See Table A1

| Parameters | Value |
|-----------|-------|
| Rated power | 1.5 MW |
| Nominal stator voltage | 575 V |
| Slip | −0.2 |
| Pole of pairs | 3 |
| Turn ratio | 2.5 |
| Stator/rotor resistance | 0.007 pu, 0.005 pu |
| Stator/rotor leakage inductance | 0.171 pu, 0.156 pu |
| Magnetising inductance | 2.9 pu |
| Rated DC-link voltage | 1150 V |
| Rated torque | 0.83 pu |

How to cite this article: Du, K-J, et al.: Suppressing output power fluctuation and improving FRT Capability of DFIG-based wind energy conversion system with SMES and dual-mode protection scheme. IET Gener Transm Distrib. 15, 1820–1829 (2021). https://doi.org/10.1049/gtd2.12137

TABLE A1 Parameters of the DFIG system