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Enhancing the HVRT Capability of DFIG-based Wind Farms Using Cooperative Rotor-Side SMES Considering Blocking Fault of LCC-HVDC System

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Abstract—Line-commutated converter based high voltage direct current (LCC-HVDC) has been applied for transferring bulk power from wind farms to load center through long distance in many countries. When the blocking fault of LCC-HVDC system occurs, the surplus reactive power accumulated at the sending end will lead to an overvoltage thus causing the disconnection of wind turbines. To maintain the reliable connection of wind turbines and ensure the stability of power system, this paper introduce one superconducting magnetic energy storage (SMES) unit to connect in parallel with the rotor side of doubly fed induction generator (DFIG). By controlling the energy side converter and rotor side converter to inject demagnetizing current and reactive current into the rotor, the proposed scheme can effectively stabilize key parameters of wind turbine and provide desirable reactive power support, showing a favorable high voltage ride through (HVRT) performance. Several cases based on PSCAD/EMTDC & MATLAB/Simulink co-simulation together with economic analysis are conducted to demonstrate the feasibility and superiority of the proposed scheme on enhancing HVRT capability of DFIG-based wind farms.

Index Terms—HVDC blocking fault, DFIG, superconducting magnetic energy storage, HVRT.

I. INTRODUCTION

Total capacity for wind energy globally in 2019 is over 651 GW, with an increase of 10 percent compared to 2018 [1]. However, most wind farms are located at remote areas and far away from load center. Line-commutated converter based high voltage direct current (LCC-HVDC) transmission system is considered as one of the best ways to economically transmit the bulk wind power through such long distance [2]-[4]. To ensure the normal operation of LCC-HVDC transmission system, the VAR compensators are needed as the converter station will consume a large of reactive power. When the LCC-HVDC blocking fault occurs, the long switch process causes the surplus reactive power capacity of the installed VAR compensators cannot be consumed timely, causing the overvoltage at sending AC system [5]. The overvoltage may cause the cascading trip-off of DFIG-based wind farm, leading to power system voltage instability [6]-[7]. In order to ensure voltage stability and evade critical incidents, DFIG-based wind farms are required to maintain reliable grid-connection under such overvoltage.

Numerous researches have been conducted aiming at meeting the high voltage ride through (HVRT) requirements for wind turbine and improving the stability of power system under LCC-HVDC blocking fault. Existing solutions for enhancing HVRT capability of DFIG connected to LCC-HVDC system can be divided into three categories: system side scheme, DFIG side scheme, and coordinated control scheme.

System side scheme try to mitigate the overvoltage at power system level. In [8], coordinated control strategy of generator shedding by stability control system and filters switched-off by pole control system is proposed to decrease the transient overvoltage caused by DC blocking. In [9], strategies such as improving short circuit capacity, strengthening grid structure, and improving voltage adaptability of wind farms are proposed to preventing cascading tripping of wind farms. However, this scheme cannot completely prevent wind farm from tripping off caused by transient overvoltage.

DFIG side scheme is to enhance the HVRT capability of DFIG itself by improving converter control. Resonance controller, virtual impedance control, enhanced hysteresis-based current regulator are proposed to improve the HVRT capability of wind farms in [10]-[12]. Demagnetization control is a well-known technique, which can reduce the rotor voltage by injecting demagnetizing current that opposite to the magnetic flux [13]. In [14], a P-Q coordination based HVRT strategy is proposed to suppress transient overvoltage, in which the Q-V control is coordinated with the P-V de-loading control to achieve the maximum reactive power capacity. However, DFIG will still face an overvoltage, together with decreased...
DFIG active power and high rotor voltage. Although the improved control scheme has a relatively low cost, the control ability is limited thus cannot ride through severe fault.

Coordinated control scheme is to fulfill HVRT by coordinating DFIG and additional equipment. Many auxiliary hardware devices have been utilized for enhancing the HVRT capability of DFIG, including the series dynamic resistor, dynamic voltage restorer (DVR), STATCOM, unified power flow controller (UPFC), and SVC [15-19]. Zhang proposed a HVRT strategy in [20]. By coordinating the VAR compensators, DFIG-based wind farm, HVDC system converter, and synchronous compensator, the proposed scheme can restrain the overvoltage significantly. Similarly, Han proposed a collaborative control strategy by putting into static var compensators and cutting off the sending AC filters on the basis of different response times [21]. The HVRT control strategy based on the coordination of wind turbine with division of controllable domain and STATCOM is proposed in [22]. These schemes perform well when dealing with wind farm overvoltage problems caused by HVDC blocking, but they need the help of fast VAR compensators. Moreover, the fault ride through capability of DFIG itself has not been significantly improved.

Superconducting magnetic energy storage system (SMES) has the advantages of fast response speed, long service life, large power density, etc. Some researchers pointed out that the total investment cost of the compensation device based on SMES is relatively acceptable [23]-[24], and its applications in the fault ride-through problem of DFIG have been already proved to have practical value [25]-[27]. Considering the advantages of SMES and the drawbacks of existing HVRT schemes, this paper propose a cooperative strategy of SMES device and demagnetization control to enhance the HVRT capability of DFIG-based wind farms. One SMES unit integrated with the energy side converter (ESC) is introduced to connect in parallel with the rotor side of DFIG. By coordinating energy side converter with rotor side converter (RSC) to inject demagnetizing current and reactive current into rotor, the key parameters of wind turbine can be effectively stabilized and providing desirable reactive power support. Compared with the existing scheme, the proposed scheme has faster response speed due to the characteristics of SMES, stronger fault ride-through and reactive power support capability.

II. MECHANISM OF OVERVOLTAGE CAUSED BY HVDC BLOCKING FAULTS

The typical LCC-HVDC sending system configuration is shown in Fig. 1 [20]. An equivalent DFIG and a synchronous generator is used to represent the wind farm and sending AC system, respectively. The VAR compensators here are AC filters and fixed capacitor. To simplify the overvoltage analysis, the equivalent circuit shown in Fig. 2 is used.

There is no reactive power exchange between the AC system and the LCC-HVDC system normally as the reactive power that rectifier consumed is balanced by the VAR compensators. When the blocking fault occurs, the transmitted active power and the consumed reactive power become zero, but the VAR compensators are still generating reactive power due to their long switch process. The mismatched reactive power will lead to an overvoltage at the point of common coupling (PCC). The overvoltage makes the VAR compensators generate more reactive power. Consequently, the voltage will be even higher.

Typically, the switching process of the mechanical fixed capacitor mostly sustains 200 ms. For STATCOM, since the dual closed-loop control scheme is usually used, its dynamic reactive power response is relatively slow, which is about 100 ms. Therefore, the overvoltage under the LCC-HVDC blocking faults is inevitable and the wind generator would withstand a high voltage for at least 100–200 ms. When the fault is not cleared in time, the overvoltage may last longer.

$$\frac{U_p}{P_{dc}} = \frac{2Q_{dc}}{P_{dc}^2} \frac{1}{P_{dc}^2}$$

where $k$ is a coefficient which is 1 for bipolar blocking and 0.5 for mono-polar blocking. SCR is the short circuit ratio and $Q_{dc}$ is blocking capacity. According to (1), the maximum overvoltage caused by the mono-polar blocking and the bipolar blocking are 1.213 p.u. and 1.44 p.u. respectively [28].

Therefore, it is very necessary to enhance the high voltage ride through capability of DFIG, meet the grid code of wind farms and avoid the overvoltage affecting the safety and stability of the power system.

III. DFIG MODEL CONNECTED WITH SMES AND COOPERATIVE TRANSIENT CONTROL STRATEGY

A. DFIG model connected with rotor side SMES

As shown in Fig. 3, the stator of DFIG is directly connected to the grid via a step-up transformer, the rotor is connected to a back-to-back PWM converter, and the SMES is connected to the rotor of DFIG in parallel with the rotor-side converter. At steady state, the ESC capacitor is connected in parallel with the
DFIG DC bus, and the switch S is closed. In this case, the ESC reference signal is 0, and the ESC do not exchange power with rotor, reducing harmonic injection into the rotor winding. When the LCC-HVDC blocking fault occurs, the switch S which connected with the DC bus is quickly opened, and the SMES is connected in parallel with the RSC in this situation. The energy stored in the SMES generates demagnetizing current and reactive current through the ESC and cooperates with the demagnetizing and reactive current generated by the RSC injected into the rotor winding.

Fig. 3 DFIG wind energy conversion system with rotor side SMES

B. Demagnetization control strategy

When the voltage swell occurs, the dc component of the stator flux linkage is generated, and it is accompanied by a negative sequence component in the case of asymmetric faults. Under the coupling effect between stator and rotor, these components of the stator flux linkage will induce a large electromotive force on the rotor side, that is, the rotor overvoltage. Because the rotor leakage resistance and resistance are relatively small, this overvoltage will produce an overcurrent. The overvoltage and overcurrent cause the RSC to lose the decoupling control of DFIG, which further aggravates the power imbalance of the converter, resulting in overvoltage and electromagnetic torque oscillation of the dc bus, and finally causing DFIG to trip-off. Therefore, the key to realize DFIG HVRT is to accelerate the decrease of the dc and negative sequence component of the stator flux, reduce the overvoltage and overcurrent of the rotor, and avoid the RSC losing control.

The positive sequence, negative sequence and dc components of the stator flux are generated in the case of voltage swell. The decrease of the dc and negative sequence components of the stator flux is accelerated by generating flux components that contrary to the dc and negative sequence component of the stator flux by controlling the rotor current.

\[
\begin{align*}
\psi_{rd} &= R_i j_{rd} + \sigma L_r \frac{di_{rd}}{dt} - \omega_m \psi_{rq} \\
\psi_{rq} &= R_i j_{rq} + \sigma L_r \frac{di_{rq}}{dt} + \omega_m \psi_{rd}
\end{align*}
\]

The rotor flux is defined as follows:

\[
\psi_r = \frac{L_m}{L_s} \psi_s + \sigma L_s (\psi_{s1} + \psi_{s2} + \psi_{s3}) + \sigma L_r i_r
\]

According to (5), the rotor induced electromotive force can be reduced by injecting flux components that contrary to the dc and negative sequence component of the stator flux by controlling the rotor current.

\[
i_{rd\text{demaref}} = i_{r2\text{ref}} + i_{r\text{ref}} = -\frac{\psi_{s2}}{\sigma L_r} - \frac{\psi_{sn}}{\sigma L_r}
\]

where, \(i_{rd\text{demaref}}\) is the reference value of total demagnetization current; \(i_{r2\text{ref}}\) is the reference value of negative sequence demagnetization current. \(i_{r\text{ref}}\) is the reference value of dc demagnetization current.

The SMES and RSC together provide the demagnetization current when the voltage swell occurs, i.e.

\[
i_{rd\text{demaref}} = i_{r\text{RSC}} + i_{r\text{ESC}}
\]

where, \(i_{r\text{RSC}}\) is the demagnetization current provided by the RSC, \(i_{r\text{ESC}}\) is the demagnetization current provided by the ESC, and the rotor closed-loop current control after adding the demagnetization current is:

\[
\begin{align*}
i_{rd}' &= i_{rd\text{demaref}} + i_{rd} \\
i_{rq}' &= i_{rq\text{demaref}} + i_{rq}
\end{align*}
\]

C. DFIG rotor-side converter control strategy

According to the German E.ON standard for HVRT, DFIG should also provide reactive power on the premise that it ride through the fault. Specifically, when the voltage rises to 1.1 or above, the DFIG is required to provide at least 2% reactive power once voltage increases by per 1% to compensate the grid voltage. The reactive current is provided equally by the RSC and SMES.

\[
\begin{align*}
i_{rQ} &= -2 \times (v_r - 1.1) I_r \\
i_{rQ} &= i_{rQ\text{RSC}} + i_{rQ\text{ESC}}
\end{align*}
\]

where \(i_{rQ}\) is the total reactive current injected into the rotor; \(i_{rQ\text{RSC}}\) is the reactive current provided by the RSC. \(i_{rQ\text{ESC}}\) is the reactive current provided by the ESC.

Considering both demagnetization current and reactive current, the rotor reference current is:

\[
\begin{align*}
i_{rd}' &= i_{rd} \\
i_{rq}' &= i_{rq} + i_{rQ}
\end{align*}
\]

Represent the rotor flux by stator voltage and rotor current:

\[
\begin{align*}
\psi_{rd} &= \sigma L_r i_{rd} \\
\psi_{rq} &= -\frac{L_m}{L_s} u_s + \sigma L_r i_{rq}
\end{align*}
\]

Substitute (10) and (11) into (4) to obtain the RSC closed-loop control equation. The control diagram is shown in Fig. 4.
According to Fig. 4, when the voltage swell occurs, the fault identification algorithm proposed in [29] is adopted to quickly and accurately calculate the positive and negative sequence component amplitude of the grid voltage, so as to generate the reference signal of injected reactive current. Flux sequence component separation algorithm is adopted to calculate the demagnetization reference current. The dq-axes rotor voltage references are got by two independent PI controller. Then generate the RSC switch signal by PWM modulator.

D. SMES power flow and its control strategy

The equivalent circuit diagram is shown in Fig. 5. The switch is equivalent to ideal switch $S_1$, $S_3$, and a series resistance $R_{on}$; The diode is equivalent to ideal diode $D_2$, $D_4$, a series equivalent resistance $R_d$ and a series equivalent voltage source $U_d$. During charging stage, the current path is $R_{on}$, $S_1$, $L_{SC}$, $R_{on}$, and $S_3$. During energy storage stage, the current path is $R_{on}$, $S_1$, $L_{SC}$, $D_4$, and $R_d$. During discharge stage, the current path is $R_d$, $D_2$, $L_{SC}$, $D_4$, and $R_d$, then injects demagnetization current and reactive current into the rotor through ESC.

Ignoring the loss of superconductor and refrigeration device, the current and voltage equation at steady state are:

$$\begin{align*}
\frac{di_d}{dt} + i_d(t)R_{on} + i_d(t)R_d + U_d &= 0 \\
L_{sc}\frac{di_d(t)}{dt} + i_L(t)R_{on} + i_L(t)R_d + U_d &= 0 \\
\end{align*}$$

(13)

where $i_d(t)$ is the equivalent DC output current, $i_c(t)$ is the working current of the DC capacitor, $i_L(t)$ is the initial voltage of the DC capacitor. $i_d(t)$ is the working current of the superconductor.

For energy transfer through chopper circuit, the reactive power exchanged between ESC and rotor is $Q_{ESC}$:

$$Q_{ESC} = \frac{u_r u_{u_{ESC}}}{jX_{LEC}} = \frac{u_r u_{u_{ESC}} \cos \delta - u_r^2}{X_{LEC}}$$

(19)

where, $u_{u_{ESC}}$ is the AC side voltage of the converter; $X_{LEC}$ is AC side inductance of the converter; $\delta$ is the phase difference between $u_{u_{ESC}}$ and $u_r$; When the ESC adopts PWM control, the voltage relationship between AC side and DC side is:

$$u_r = M \frac{u_{u_{ESC}} \cos \delta - u_r^2}{X_{LEC}}$$

(20)

where $M$ is modulation ratio. When adopting space vector PWM, its maximum value $M_{max} = 1.15$. Thus, (19) can be expressed as:

$$Q_{ESC} = M \left( 3 u_{u_{ESC}} \frac{u_r \cos \delta}{X_{LEC}} - u_r^2 \right)$$

(21)

Equation (21) indicate that the reactive power provided by SMES can be controlled by controlling the output voltage $u_{u_{ESC}}$ of the ESC. The inner current control of SMES is shown in Fig. 6. When voltage swell occurs, failure detection algorithm is applied to calculate the required reactive current. The flux sequence component separation algorithm is adopted to calculate the demagnetization current reference signal. The reactive current reference signal and the demagnetization
current signal are used to obtain voltage signals through two independent closed-loop controller. The ESC switch signal is generated by PMW, then ESC and RSC cooperated to complete DFIG HVRT.

![Control diagram of energy side converter](image)

**Fig. 6 Control diagram of energy side converter**

### IV. SIMULATION ANALYSIS

#### A. System parameters

In order to verify that the proposed scheme can enhance the HVRT capability of DFIG under LCC-HVDC blocking fault, a LCC-HVDC transmission system connected DFIG wind farm are built in PSCAD/EMTDC, and a 1.5 MW DFIG with rotor-side SMES is built in MATLAB / Simulink, respectively, as illustrated in Fig. 1 and Fig. 3. The VAR compensators here are 13th filter, 11th filter, and shunt capacitors. Their capacities are built in PSCAD/EMTDC, and a 1.5 MW DFIG with DFIG HVRT.

DFIG generated by PMW, then ESC and RSC cooperated to complete DFIG HVRT capability of DFIG under LCC-HVDC blocking fault, a independent closed-loop controller. The ESC switch signal is current signal are used to obtain voltage signals through two independent closed-loop controller. The ESC switch signal is generated by PMW, then ESC and RSC cooperated to complete DFIG HVRT.

#### B. Comparison of DFIG response

In this section, a comparison study is conducted among the following three cases: 1) without protection; 2): demagnetization control, and 3) proposed cooperative scheme. The simulation results are illustrated in Fig. 8.

![Simulation results](image)

**Fig. 8 Simulation results. (a) Electromagnetic torque. (b) Voltage of DC link. (c) Active power of DFIG. (d) Reactive power of DFIG. (g) Stator flux dq components. (h) Superconducting coil current. (i) Active power of ESC. (j) Reactive power of ESC.**

It can be observed from Fig. 8 that when the blocking fault occurs: 1) both electromagnetic torque and voltage of DC link experience an oscillation and have a peak value, proposed scheme has the best performance in mitigating the oscillation and the peak values; 2) the rotor voltage increases to 0.5242 p.u.
without protection during the fault, and proposed scheme can reduce the voltage to 0.4201 p.u., while demagnetization can only limit the voltage to 0.4815 p.u.; 3) rotor speed changes very little in all three cases, the proposed scheme has a certain effect in suppressing the rotor speed oscillation while demagnetization control performs best. 4) Stator flux dq components continuous oscillate during the fault, causing electromagnetic torque oscillation and DC bus overvoltage. Both case 2 and case 3 can mitigate the stator flux oscillation; 5) DFIG active power drop to 0.5881 p.u. under proposed scheme. For case 1 and 2, the value is 0.7551 and 0.669, respectively. Therefore, the proposed scheme can reduce more reactive power to reduce the PCC voltage than the other two schemes. 6) Stator flux oscillation is weakened under both case 2 and 3.

The SMES behaviors during the fault is shown in Fig. 8 (h) to (j). Since the stator flux is oscillated during the fault, superconducting coil current, active power, and reactive power provided by SMES are oscillated continuously, but their consistent trend is to provide demagnetization current and reactive current to help DFIG ride through the fault. Voltage at PCC is shown in Fig. 9. It shows that the proposed scheme can decrease the transient overvoltage at PCC, and more DFIGs, better performance. The peak value under these scenes are shown in Table III. Compared with Spain HVRT codes, when the fault sustain less than 250 ms, 2×1.5 MW DFIGs equipped with SMES can meet the grid code. For the fault longer than 250 ms, more than 7 DFIGs equipped with SMES are needed to meet the requirements. In summary, proposed scheme has the best performance in stabilizing key parameters of wind turbine and can effectively suppress transient overvoltage to help DFIG ride through the high voltage process under HVDC blocking fault.

![Fig. 9 Transient voltage at PCC under different scenes.](image)

<table>
<thead>
<tr>
<th>Scene</th>
<th>Overvoltage (pu)</th>
<th>Scene</th>
<th>Overvoltage (pu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.345</td>
<td>4</td>
<td>1.2970</td>
</tr>
<tr>
<td>2</td>
<td>1.3386</td>
<td>5</td>
<td>1.2515</td>
</tr>
<tr>
<td>3</td>
<td>1.3232</td>
<td>6</td>
<td>1.1993</td>
</tr>
</tbody>
</table>

V. DISCUSSIONS ON FEASIBILITY & ECONOMICS OF SMES

Among various energy storage system, SMES have outstanding advantages of high efficiency, high power density, fast response, and long life cycle [33]-[34]. SMES stores energy in the form of electromagnetic energy in a superconducting magnet wound by superconducting tape and releases it through a power conditioning system (PCS) when needed. The zero resistance characteristic of superconducting tapes determines that SMES has the advantages of high efficiency; the high current density of superconducting tapes determines the high power density of SMES; It store power in the form of electromagnetic energy determines that SMES has the advantage of fast response, which typically in millisecond class; SMES has no electrochemical reactions and mechanical wear during operation, so it has long life cycle. Therefore, SMES is very suitable for the applications of high power exchange and transient power compensation, such as fault ride through [35].

No matter in terms of power or capacity, there is no technical bottleneck for the development of SMES. Existing technology has been able to support the research and development of 100MW/1GJ level SMES. The obstacle that restricts the widespread use of SMES is cost, it is still relatively high nowadays. The price of second-generation high temperature superconducting (HTS) tape (YBCO) is about 10 times of copper wire [33].

<table>
<thead>
<tr>
<th>Scene 6: 10.5MW cooperative control</th>
<th>Scene 5: 6 MW cooperative control</th>
<th>Scene 4: 3 MW cooperative control</th>
<th>Scene 3: 1.5MW cooperative control</th>
<th>Scene 2: Demagnetization</th>
<th>Scene 1: Without protection</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.9</td>
<td>1.0</td>
<td>1.1</td>
<td>1.2</td>
<td>1.3</td>
<td>1.4</td>
</tr>
<tr>
<td>V (pu)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time (s)</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

The SMES equipment costs contain four major parts: cold components costs (mainly are HTS magnet tapes costs), refrigeration costs, PCS costs, and operating costs.

The price of HTS tapes in the past years is shown in Table IV. Scholars from China predicted the potential costs change of SMES in [36]. With the development of manufacturing technology, the average tape price is expected to decline by 5-10% annually. According to the improvement in refrigerator efficiency and life cycle, the refrigeration costs are assumed to drop about 4.5% every year. Since PCS manufacturing is relatively mature, the PCS costs are assumed to reduce by 10% annually. Operating costs are generally 5% of investment costs. In general, the SMES costs is showing a downward trend.

According to the statistics in [37], the total installed cost of 1.5 MW DFIG is about $1473 K in 2019. While the cost of the 0.3H/1750A SMES adopted in this paper is about $271.4 K. According to these estimations, the cost of SMES unit is about 12.28% of the 1.5 MW DFIG. As the SMES used still has a large margin, with the increase in the capacity of a single wind turbine [37], the ratio of SMES cost will be further greatly reduced. Besides, the ratio will continue to decline with the potential SMES cost reduction.

Several real projects on large-scale SMES have been put into operation. China has developed a 10 kV/1MVA/1MJ superconducting fault current limiter-magnetic energy storage system to improve the power output stability and the low voltage ride through capability of DFIG wind farms, which has been implemented in Gansu Province, China, showed excellent performance [38]. The successful implementation of this
project further proved the feasibility and effectiveness of SMES in renewable energy application.

The cost of SMES is still relatively high at present and SMES cannot be commercialized right now. However, considering the extremely attractive advantages of SMES and the future cost reduction, the application of SMES in the field of renewable energy has good prospects.

VI. CONCLUSION

In this paper, a cooperative strategy of SMES device and demagnetization control is proposed to enhance HVRT capability of DFIG-based wind farm under blocking fault of LCC-HVDC system. The main findings and contributions could be summarized as follows:

1) The proposed scheme coordinates the SMES with rotor side converter of DFIG to provide demagnetizing current to suppress key parameters of DFIG, as well as reactive current to mitigate the PCC overvoltage. Thus, the overall HVRT requirement of grid code can be completely satisfied.

2) The proposed scheme has been tested and demonstrated through several cases. The results have revealed that the proposed scheme can always maintain an acceptable level of electromagnetic torque and DC bus voltage. In converse, DC bus overvoltage and severe electromagnetic torque oscillation will occur in DFIG if any protection is not adopted.

3) Compared to the traditional demagnetization control, the main benefit of the proposed scheme is to provide more demagnetizing current and reactive current, due to the additional assistance of SMES. Consequently, better suppressing capability of DFIG parameters and PCC overvoltage can be obtained thus providing a favorable HVRT enhancement.

4) SMES costs is still relatively high nowadays but acceptable. Considering its extremely attractive advantages and the future cost reduction, the application of SMES in the field of renewable energy shows good prospects.

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