Enhanced Ride-Through Capability Under Rectifier-Side AC Fault for Series LCC-MMC Hybrid HVDC System

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ABSTRACT The series line-commutated converter (LCC) and modular multilevel converter (MMC) hybrid HVDC system provides a more economical and flexible alternative for UHVDC transmission. With the LCC DC voltage reduction, no current cut-off will occur under slight rectifier-side AC faults. However, with the limitation of the MMC voltage modulation ratio, when the rectifier-side AC fault is extremely acute, the current cut-off will unavoidably exist, resulting in enormous impacts on AC and DC systems. To reduce the risk of the current cut-off and improve fault recovery, this paper proposes an enhanced coordinated control strategy. First, under the varying severity of rectifier-side AC faults, the \textit{U-I} operation characteristics are meticulously analyzed. Then, the third harmonic voltage injection (THVI) and reactive power dynamic adjustment (RPDA) are introduced to expand the operation range of MMC DC voltage. Based on the enlarged operation range, a backup DC current control of MMC is proposed to adaptively regulate the MMC DC voltage relying on the fault severity. Finally, the feasibility and effectiveness of the proposed coordinated control strategy is verified through several simulation scenarios of varied fault severity on PSCAD/EMTDC. The simulation results show that, the proposed control enlarges the system operation range, improves the fault recovery, and significantly reduces the risk of current cut-off.

INDEX TERMS Line commutated converter (LCC), modular multilevel converter (MMC), current cut-off, third harmonic voltage injection (THVI), backup DC current control

I. INTRODUCTION

To fulfill the ever-growing energy demand, high-voltage direct current (HVDC) transmission technology has drawn an indispensable role on long-distance and bulk-capacity power transmission occasions, notably the vast-territory areas where the energy sources and load demands are distributed unevenly [1], [2]. Until now, two types of converters are mainly adopted by the power utility companies for HVDC projects: line commutated converter (LCC) and modular multilevel converter (MMC) [3].

LCC based HVDC has been applied in most of practical HVDC projects, due to its high technology maturity, small operation loss, low investment cost, and sufficient practical experience. However, LCC-HVDC introduces some inherent drawbacks, such as excessive consumption of reactive power, large footprint, incapability to connect weak AC systems. Moreover, with the wide application of LCC-HVDC, multi-infeed HVDC frame has been gradually formed in the China East and Guangdong power grid, resulting in several severe problems, such as simultaneous commutation failure, and devastation on AC system stability [4]. As an alternative, MMC based HVDC has many attractive features, such as no commutation failure, high control flexibility, potentially smaller footprint [5]. However, compared to LCC-HVDC, MMC-HVDC has several obstacles: higher installation cost, smaller power rating, and higher loss.

In order to take full use of the superiorities of both LCC and MMC, hybrid HVDC transmission technology has been paid increasing attention to the future power transmission [6]-[8]. Based on the various novel hybrid HVDC systems proposed by scholars, the hybrid HVDC system could be sorted into four categories: (1) pole-hybrid system (LCC and MMC applied in different poles) [9]; (3) station-hybrid system (LCC and MMC applied in different stations) [10]-
[12]; (3) series converter-hybrid system (LCC and MMC series in one pole) [13], [14]; (4) parallel converter-hybrid system (LCC and MMC connected in parallel to the same DC line) [15]-[16]. Among these schemes, a series converter-hybrid HVDC project called Baitahe-Jiangsu HVDC (BJ-HVDC) is under construction, where the rectifier are LCCs, and one LCC in series with three paralleled half-bridge submodules (HBSMs) based MMCs are adopted at inverter.

The BJ-HVDC project is planned to deliver the abundant hydropower from the Baitahe Hydropower Station to the Jiangsu power grid. With total transmission capability of ±800 kV/8000 MW, the following merits make the BJ-HVDC project fulfill the desires of ultra-high voltage, large capacity and flexible power transmission: (1) own the self-healing capability against DC faults, with the force retard of rectifier-side LCC and the unidirectional continuity of upper-valve LCC at the inverter; (2) maintain power transmission to a certain extent, and offer reactive power support, under AC faults at inverter, thus mitigating the multi-infeed HVDC problem; (3) realize the distributed supply of urban load centers, and improve the flexibility and reliability of HVDC system; (4) could be taken as an illustrative project for new HVDC projects or upgrade of the existing LCC-HVDCs.

Due to the broad operation range of LCC DC voltage, no current cut-off will occur under slight rectifier-side AC faults, relying on the backup DC current control of LCC at inverter. However, with the limitation of the voltage modulation ratio, the adjustable operation range of HBSM-MMC DC voltage is badly restricted [17]. When the rectifier-side AC fault is extremely acute, the current cut-off will unavoidably exist, resulting in enormous impacts on AC and DC systems. Up to now, majority of literatures focuses on the current cut-off suppression of the station-hybrid systems [18], [19], while little research is carried out for the BJ-HVDC.

To reduce the risk of the current cut-off under rectifier-side AC fault, this paper proposes an enhanced coordinated control strategy for the BJ-HVDC. Firstly, the operation range of HBSM-MMC DC voltage is maximally expanded by employing the third harmonic voltage injection (THVI) and reactive power dynamic adjustment (RPDA). Then, a backup DC current control strategy for DC voltage adaptive regulation of the MMC is proposed. Finally, PSCAD/EMTDC simulation is carried out to verify the feasibility and effectiveness of the proposed coordinated strategy. The contributions of this paper are summarized as follows:

1) The paper analyzes the operation characteristics of the BJ-HVDC under the varying severity of AC faults occurred at rectifier.
2) The THVI and RPDA are adopted to expand the operation range of HBSM-MMC DC voltage.
3) The paper proposes a backup DC current control to adaptively regulate the MMC DC voltage for the ride-through under rectifier-side AC fault. The feasibility and effectiveness of the proposed coordinated control strategy is verified on PSCAD/EMTDC.

The outline of this paper is organized as follows. Section II describes the basic structure, control system and modelling of BJ-HVDC. Section III analyzes the operation characteristics under steady and rectifier-side AC faults. In Section IV, based on the expanded the operation range of MMC DC voltage, the MMC backup DC current control is proposed. The simulation verifications on PSCAD/EMTDC are studied in Section V. Section VI dawns the conclusion.

II. STRUCTURE, CONTROL AND MODELLING

A. STRUCTURE

The basic topology of the BJ-HVDC is depicted as in Fig. 1, and for simplicity, only the positive pole is presented. Here, the rectifier consists of two series 12-pulse LCCs to bear the ±800 kV DC voltage. For the inverter, a 12-pulse LCC at the upper valve is series with lower-valve MMCs to share the total 800 kV DC voltage, namely ±400 kV for each converter. The three identical HBSM-MMCs are connected in parallel to match the LCC capacity. Besides, the LCC and three MMCs at inverter are physically located at same location but connected to different AC systems.

B. Control System

The control system has been discussed minutely in [14], and will not be repeated here in full depth. The LCC at rectifier side adopts constant DC current control (CC) and minimum firing angle (5°) control (MFA). As illustrated in Fig. 2, the LCC at inverter side adopts constant DC voltage control (CV), and the backup extinction angle control (BEA) and the backup DC current control (BCC) are also adopted as auxiliary controls under fault conditions.
The vector current control is adopted for all MMCs. All three MMCs adopt constant DC voltage control and constant reactive power control. Besides, DC current balance control is applied to eliminate the unbalanced current distribution among MMCs.

C. SYSTEM MODELLING

1) LCC MODELLING

The DC voltages at rectifier and inverter of the LCC \( U_{dcR} \) and \( U_{dcI} \) are expressed as [20]:

\[
U_{dcR} = 4 \left( \frac{3\sqrt{2}}{\pi} \right) E_{in} \cos \alpha_d - d_{dc} I_{dc} \tag{1}
\]

\[
U_{dcI} = 2 \left( \frac{3\sqrt{2}}{\pi} \right) E_{in} \cos \beta_d + d_{dc} I_{dc} \tag{2}
\]

where, \( E_{in} \) and \( E_{dc} \) are the RMS values of line-to-line AC voltages at the LCC valve side of rectifier and inverter, respectively; \( I_{dc} \) is the DC current; \( \alpha_d \) is the firing angle of LCC at rectifier; \( \beta_d \) is the advance firing angle of LCC at inverter; \( d_{dcR} \) and \( d_{dcI} \) are the LCC equivalent commutation resistances at rectifier and inverter, respectively.

2) MMC MODELLING

The MMC DC-side circuit is equivalent as an equivalent capacitance \( C_q \) in parallel with a controlled current source, and is written as [21]:

\[
C_q \frac{dU_{dc(i)\beta}}{dt} = I_{dc(i)\beta} - I_{dc(i)\alpha} \tag{3}
\]

where, \( U_{dc(i)\beta} \) and \( I_{dc(i)\beta} \) are the DC voltage and DC current of the \( i \)th \( (i=1, 2, 3) \) MMC, respectively; \( I_{dc(i)\alpha} \) is the controlled current source of the \( i \)th MMC. As three MMCs are connected in parallel, the DC voltages of three MMCs are equal, namely, \( U_{dc(i)\beta} = U_{dc(i)\beta} = U_{dc(i)\beta} = U_{dc} \). Similarly, the DC currents of three MMCs are also equal, i.e., \( I_{dc(i)\beta} = I_{dc(i)\beta} = I_{dc(i)\beta} = I_{dc} \).

The MMC voltage modulation index \( m \) is defined as:

\[
m = \frac{2U_{dc(i)\alpha}}{U_{dc(i)\beta}} \tag{4}
\]

where, \( U_{dc(i)\alpha} \) is the amplitude of the fundamental differential-mode phase voltage of MMC. Generally, the index \( m \) of HBSM-MMC is about 0.85, and its maximum value is 1.

3) EQUIVALENT CIRCUIT

Later analysis is done only for positive pole, which is also valid for negative pole. Base on the above analysis, the DC-side equivalent circuit is depicted in Fig. 3. Here, the DC transmission line mode is simplified with a DC resistance \( R_L \).

As in Fig. 3, the basic characteristics of the BJ-HVDC system is derived as:

\[
\begin{align*}
U_{dcR} &= U_{dc} + R_L I_{dc} \\
U_{dcI} &= U_{dc} + U_{dc(i)\beta} - U_{dc(i)\alpha}
\end{align*}
\]

From (5), the DC current \( I_{dc} \) could be calculated as:

\[
I_{dc} = \frac{U_{dc} - (U_{dc(i)\beta} - U_{dc(i)\alpha})}{R_L}
\]

FIGURE 3. Equivalent circuit at DC side of the BJ-HVDC.

III. OPERATION CHARACTERISTICS

The \( U-I \) characteristics for rectifier-side AC faults of the BJ-HVDC is drawn in Fig. 4. Here, the DO segment adopts current deviation control (CD). It is noted that the voltage-dependent current order limit control (VDOL) is eliminated, for the reason that more power could be transmitted to the receiving AC system, thus minimizing the impact on the receiving AC system under rectifier-side AC faults [13]. The DC current increment between the CC and BCC controls is limited to a conservative value of 0.1 p.u. With the limitation of the voltage modulation ratio \( m \), the MMC voltages remain constant under the rectifier-side AC faults, corresponding to the voltage in-operatable area in Fig. 4.

FIGURE 4. \( U-I \) characteristics for rectifier-side AC faults.

Under normal operation, the system operates at point O. The rectifier LCC works at the CC control to regulate the DC current \( I_{dc} \) as 1.0 p.u. by adjusting the \( \alpha_d \) (normally 15°), while all inverter LCC and three MMCs work at the CV control to manage the DC voltage as 0.5 p.u. for each converter. The decrease of AC voltage \( E_{in} \) will cause the decline of the DC voltage \( U_{dcR} \), and the DC current \( I_{dc} \) will decrease subsequently until the current is cut-off.

According to the DC current decline, the severity of AC faults is classified into four grades. Grade 1, the DC current is remained as 1.0 p.u.; grade 2, the DC current is regulated as 0.9 ~ 1.0 p.u.; grade 3, the DC current operates passively as 0 ~ 0.9 p.u.; grade 4, the current is cut-off (0 p.u.).
A. GRADE 1
Under slight rectifier-side AC faults, the DC current $I_{dc}$ could be sustained as 1.0 p.u. by adjusting the $\alpha_{R}$, and the DC voltage $U_{dcr}$ are also remained. However, the CC control will lose the regulation ability when the $\alpha_{R}$ is micrified to the minimum 5°.

During grade 1, the DC current $I_{dc}$ and DC voltage $U_{dcr}$ remain unchanged under pre- and post-fault. When the $\alpha_{R}$ is micrified to 5°, (1) is rewritten as:

$$U_{dcr}=4\left(\frac{3\sqrt{2}}{\pi} E_{cr}^* \cos 5° - d_{\alpha R} I_{de}^* \right)$$

(7)

where, $E_{cr}^*$ is the post-fault critical AC voltage at rectifier side for grade 1, which is calculated as:

$$E_{cr}^* = E_{cr} \frac{\cos 15°}{\cos 5°} \approx 0.97 E_{cr}$$

(8)

From (8), $\alpha_{R}$ adjustment is a trivial measure to ride through the rectifier-side AC fault.

B. GRADE 2
Under grade 2, the DC voltage $U_{dcr}$ relies on the AC voltage $E_{cr}$, and is lower than the DC voltage $U_{dcl}$. In order to maintain the stable operation of the system, the inverter LCC is eventually switched into the BCC control between the AC and DC control, and the DC current is regulated as 0.9 p.u.

As in Fig. 4, correspondingly, the AB segment gradually moves down until it passes the critical operation point E. Suppose that the system operates at point X, the rectifier LCC works at the MFA control, the inverter LCC is switched into the BCC control, and the MMCs still keep the DC voltage $U_{dcl}$ as 0.5 p.u. At the point E, the $\beta_{L}$ is raised to 90°, and the BCC control loses the controllability. Equations (1) and (2) are rewritten as:

$$U_{dcr}^* = 4\left(\frac{3\sqrt{2}}{\pi} E_{cr}^* \cos 90° - d_{\alpha R} I_{de}^* \right)$$

(9)

$$U_{dcl}^* = 2\left(\frac{3\sqrt{2}}{\pi} E_{cr}^* \cos 90° + d_{\alpha L} I_{de}^* \right)$$

(10)

where, $U_{dcr}^*$ and $U_{dcl}^*$ are the critical DC voltages of the rectifier and inverter LCCs for grade 2, respectively; $I_{de}^*$ is the critical DC current (0.9 p.u.); $E_{cr}^*$ is the post-fault critical AC voltage at rectifier side for grade 2.

Substitute (9) and (10) into (5), and the $E_{cr}^*$ is deduced as:

$$E_{cr}^* = \frac{\sqrt{2}\pi}{24\cos 5°}\left[U_{dcr}^* + (4d_{\alpha R} + 2d_{\alpha L} + R_L) I_{de}^* \right]$$

(11)

C. GRADE 3
Under grade 3, the AB segment sequentially moves down until it passes the critical operation point Z. During this grade, the BCC control loses the controllability, and the DC voltage $U_{dcl}$ drops as in (10). The MMCs still keep the DC voltage $U_{dcl}$ as 0.5 p.u. The DC current $I_{dc}^*$ decreases passively, and is positively correlated with the post-fault AC voltage at rectifier side, which is derived as:

$$I_{dc}^* = \frac{12\sqrt{2}E_{cr}^* \cos 5° - \pi U_{dcl}}{4d_{\alpha R} + 2d_{\alpha L} + R_L}$$

(12)

where, $E_{cr}^*$ is the post-fault AC voltage at rectifier side for grade 3. At the critical operation point Z, the DC voltage $U_{dcl}$ is equal to the MMC DC voltage $U_{dcl}$, then the current cut-off occurs. The post-fault critical AC voltage at rectifier side for the current cut-off $E_{cr}^*$ is calculated as:

$$E_{cr}^* = \frac{\sqrt{2}\pi}{24\cos 5°}U_{dcl} = \frac{\sqrt{2}\pi U_{dcl}}{24\cos 5°} m$$

(13)

D. GRADE 4
Under grade 4, the DC voltage $U_{dcr}$ drops below the MMC DC voltage $U_{dcl}$. Due to the unidirectional continuity of the thyristor, the DC current $I_{dc}$ will drop to zero rapidly, and the power transmission will be interrupted.

IV. FAULT RIDE-THROUGH COORDINATED CONTROL
According to the above analysis, during grievous rectifier-side AC faults, the risk of the current cut-off could be minified by diminishing the MMC DC voltage $U_{dcl}$. From (13), the DC voltage $U_{dcl}$ could be diminished by magnifying the index $m$ or minifying the $U_{dcl}$. Based on the existing researches, the THVI is a feasible way to magnify the index $m$ [22]. Besides, the RPDA can minify the $U_{dcl}$ by actively absorbing the reactive power form AC system. No over-modulation will appear induced by both approaches.

A. THIRD HARMONIC VOLTAGE INJECTION
Take a phase as an example. With the THVI, the AC phase voltage $u_{va}$ at the valve-side MMC is expressed as follows:

$$u_{va} = U_{dcl} \sin (\omega t) + \frac{1}{6} U_{dcl} \sin (3\omega t)$$

(14)

Additionally, the basic principle of the THVI is pictured in Fig. 5. With the THVI, the AC phase voltage wave is varied as the saddle-shaped wave.

FIGURE 5. Principle of THVI. (a) THVI process; (b) Wave comparison.
By inserting a third harmonic voltage component, whose magnitude is 1/6 of the voltage $U_{\text{diffm}}$, the peak of the AC phase voltage $u_{\text{ph}}$ is reduced to $\sqrt{3}/2$ of the voltage $U_{\text{diffm}}$ and the maximum modulation index is enlarged to $2/\sqrt{3}$ (≈1.1547) from 1.

The circulating current suppression control (CCSC) are usually applied to suppress the second-order harmonic circulating current [23]. However, the CCSC distorts the AC phase voltage $u_{\text{ph}}$ as in Fig. 5(b), resulting in an increscent peak of the voltage $u_{\text{ph}}$. Consequently, the maximum modulation index is narrowed to less than $2/\sqrt{3}$.

Thus, under rectifier-side AC faults, the THVI is applied, meanwhile the CCSC is prohibited to achieve the $u_{\text{ph}}$ peak minimum. Although the circulating current is raised, the current stresses of the power devices on arm may be minified due to the reduced DC component and the THVI.

**B. REACTIVE POWER DYNAMIC ADJUSTMENT**

The active power and reactive power controls of MMC are decoupled. By dynamically adjusting the reactive power absorbed by MMC, the $U_{\text{diffm}}$ could be minified. Nevertheless, the AC voltage should not be too low, otherwise it will threaten the stable operation of the AC system.

Thus, only for the index $m$ reaching its maximum, the RPDA is activated. Compared to the risk of current cut-off, the temporary low voltage operation is acceptable.

**C. ENHANCED CONTROL STRATEGY**

Based on two approaches discussed above, the operation range of HBSM-MMC DC voltage is maximally expanded. Then, referred as the BCC control of conventional LCC, the backup DC current control for MMC is proposed. This control adaptively regulates the MMC DC voltage according to the severity of rectifier-side AC fault, thus improving the power transmission.

The enhanced control strategy of MMC is illustrated as in Fig. 6. Here, the superscript “*” denotes reference value; the subscripts “d” and “q” are the dq axis components; the subscripts “p” and “n” represent the upper (positive) and lower (negative) arms, respectively; FD is the fault detection signal of rectifier-side AC fault. The output upper limit $U_{\text{anm}}$ of the BCC control is the MMC DC voltage reference for normal operation. The output upper limit $U_{\text{anm}}$ is calculated:

$$U_{\text{anm}} = \begin{cases} 2U_{\text{diffm}}, & m > m_{\text{max}} \\ 2\lambda U_{\text{diffm}}, & m = m_{\text{max}} \\ m_{\text{max}}, & m < m_{\text{max}} \end{cases}$$

where, $\lambda$ is the minimum acceptable operation voltage of AC system, which mainly depends on the AC system strength, such as 0.95; $m_{\text{max}}$ (≈1.1547) is the maximum modulation index with the THVI. $U_{\text{cm}}$ is the average voltage of SM capacitors, which is defined as [24]:

$$U_{\text{cm}} = \frac{1}{6N_{\text{CN}}} \sum_{j=a,b,c} \sum_{k=1}^{N} U_c(j,k,x)$$

where, $U_c(j,k,x)$ is the voltage of the $x$-th SM capacitor on $k$ arm in phase $j$; $N$ is the number of arm SMs; $N_{\text{CN}}$ represents the nominal voltage of SM capacitor.

Under normal operation, the MMC adopts CV and constant reactive power controls, and the CCSC also works. The BCC control output $U_{\text{anm}}$ is equal to its upper limit $U_{\text{anm}}$. After the rectifier-side AC fault is detected, the MMC CV control is switched into constant average voltage control (CAV) of SM capacitors to maintain the capacitor voltage near the nominal voltage $U_{\text{CN}}$. Meanwhile, the THVI is activated and the CCSC output is set to zero. If the BCC control output reaches its lower limit $U_{\text{anm}}$, the RPDA is activated to further expand the voltage operation range, and the limit $U_{\text{anm}}$ is varied as in (15). The RPDA is realized by the constant AC voltage amplitude control.

**D. EFFECTIVENESS EVALUATION**

Based on the enhanced coordination control strategy, the improved $U$-$I$ characteristics for rectifier-side AC faults is redrawn in Fig. 7. With the THVI and RPDA, the MMC voltage in-operable area is narrowed. The operation range of grade 2 and grade 3 is magnified.
Under grade 2, at the DE segment, the BCC controls of both LCC and MMC jointly regulate the DC current as 0.9 p.u., which contributes to the even distribution of power transmission. At the EE’ segment, the BCC control of LCC loses the controllability ($\beta_l=90^\circ$), while only the BCC control of MMC works. For grade 3, the index reaches its maximum and the RPDA is activated.

According to (15), (13) is rewritten as:

$$E_{\text{min}}^\text{ext} = \frac{\sqrt{2\pi}U_{\text{dc,lim}}}{12\cos5^\circ m_{\text{max}}}$$  \hspace{1cm} (17)

Suppose the index $m$ is 0.85 and $\lambda$ is 0.95, the post-fault critical AC voltage at rectifier side for the current cut-off is reduced by 26.4%. In other words, the capability of fault ride-through is prominently improved.

V. SIMULATION VERIFICATION

In order to verify the effectiveness of the proposed ride-through coordinated control strategy under rectifier-side AC faults, the monopolar BJ-HVDC hybrid system in Fig. 1 is benchmarked on PSCAD/EMTDC. The main parameters are listed in Table 1. Under normal operation, the firing angle $\alpha_l$ of rectifier LCC is 15°, and the extinction angle $\gamma_l$ of inverter LCC is 17°; all MMCs adopt constant reactive power control, and the reference is 0 p.u.; the index $m$ is 0.8575.

For rectifier-side AC fault with different severity, two cases are simulated: case 1, without the proposed control strategy; case 2, with the proposed control strategy.

### TABLE I

| Items | Rectifier | Inverter |
|-------|-----------|----------|
| Nominal DC power (monopolar), MW | 4 000 | 4 000 |
| Nominal LCC DC voltage, kV | 800 | 380 |
| Nominal MMC DC voltage, kV | / | 380 |
| Nominal DC current, kA | 5.0 | 5.0 |
| Nominal AC system voltage (rms, L-L), kV | 525 | 510 |
| X/R | 8.66 | 8.66 |
| Smoothing reactor, mH | 150±2 | 150±2 |

### Parameters of a MMC unit

| Items | Values |
|-------|--------|
| Normal capacity, MVA | 1 000 |
| Normal active power, MW | 667 |
| Number of SMs on an arm | 200 |
| Normal Voltage of SM capacitor, kV | 2.0 |
| SM capacitance, $\mu$F | 16.67 |
| Arm reactance, mH | 25.33 |

### Transformer Parameters

| Items | Value |
|-------|-------|
| Normal capacity, MVA | 1 200 |
| Wiring mode | Y/0, Δ, Y/Δ, Y/0Y |
| Winding voltages (L-L), kV/kV | 525/179.75, 510/161.50 |
| Leakage reactance, % | 19, 18 |
| Normal capacity, MVA | / |
| Wiring mode | / |
| Winding voltages (L-L), kV/kV | / |
| Leakage reactance, % | / |

### DC Line Parameters

| Items | Values |
|-------|--------|
| Length, km | 2172 |
| $+ve$ Sequence R, $\Omega$/km | 0.00543 |
| $+ve$ Sequence L, mH/km | 0.8078 |
| $+ve$ Sequence C, $\mu$F/km | 0.01476 |

For all later scenarios, at time $t = 1.0$ s, a three-phase-to-ground fault is applied at rectifier-side, which is cleared after 0.4 s ($t=1.4$ s). Varied fault resistances are adopted to imitate the severity of rectifier-side AC faults.

A. VOLTAGE DECREASES TO 65%

As depicted in Fig. 8, when AC bus at rectifier LCC suffers a non-serious fault, case 1 and case 2 operate at the DE segments in Fig. 4 and Fig. 7. The BCC controls of LCC in both cases can regulate the DC current as 0.9 p.u. by diminishing the advance firing angles $\beta_l$. The BCC control of MMC is also involved to the current regulation, and the MMC DC voltage $U_{\text{dc,MM}}$ is adaptively adjusted to about 0.459 p.u. in case 2. Due to the decreased $U_{\text{dc,MM}}$, the advance firing angle $\beta_l$ in case 2 is larger than that in case 1. As in Fig. 8(f), the AC voltage at grid-side MMC is undistorted. After 0.4 s, the AC-side fault is cleared, and the system gradually restores to the original rated state.

B. VOLTAGE DECREASES TO 50%

Fig. 9 illustrates the simulation results under AC voltage decreased to 50% due to the sever AC fault. During fault period, the DC current in case 2 is maintained at 0.9 p.u., superior to the 0.6 p.u. in case 1. Further, after fault clearance, the case 2 show significantly faster current recovery.

After AC fault occurs, the system in case 1 has to operate at ZE segment in Fig. 4. As the BCC control of LCC loses the controllability ($\beta_l=90^\circ$), the DC current is compelled to about 0.6 p.u.

While the system in case 2 operates at the EE’ segment in Fig. 7. Although the BCC control of LCC in case 2 also loses its controllability, depending on the enlarged operation range of MMC DC voltage, the DC current is still managed as 0.9 p.u. by the BCC control of MMC. The DC voltage $U_{\text{MM}}$ drops to about 0.355 p.u., and the corresponding modulation index $m$ is close to its maximum.
It is noted that the DC voltage of inverter LCC in case 2 is greater than that in case 1. This result can be revealed as in (10). For this scenario, the DC voltage $U_{dcll}$ is the voltage drop of the commutation resistance. Thus, the DC voltage $U_{dcll}$ only relies on the DC current. As in Fig. 9(f), the RPDA is de-activated, and the AC voltage at grid-side MMC is undistorted.

FIGURE 9. Response for rectifier-side AC fault when voltage decreases to 50%. (a) DC current; (b) the advance firing angle of the inverter LCC; (c) MMC DC voltage; (d) DC voltage of the inverter LCC; (e) modulation index; (f) a phase voltage at the grid-side MMC.

C. VOLTAGE DECREASES TO 40%

As in Fig. 10, both cases operate the voltage in-operatable area. Due to the narrower area, the DC current in case 2 is relatively large. The DC current in case 1 is dropped to near zero, and the system may suffer the current cut-off. Thus, it is identified that the proposed control strategy can significantly reduce the risk of current cut-off. As in Fig. 10(f), the RPDA is activated to regulate the AC voltage at grid-side MMC as 0.95 p.u., while it is still undistorted.

FIGURE 10. Response for rectifier-side AC fault when voltage drops to 40%. (a) DC current; (b) the advance firing angle of the inverter LCC; (c) MMC DC voltage; (d) DC voltage of the inverter LCC; (e) modulation index; (f) a phase voltage at the grid-side MMC.

VII. CONCLUSION

The paper first meticulously analyzes the U-I operation characteristics of the BJ-HVDC under the varying severity of AC faults occurred at rectifier. Then, a coordinated control strategy is proposed based on the THVI and the RPDA. Finally, three severities of rectifier-side AC fault are studied on PSCAD/EMTDC, and the results with and without the proposed control are compared and analyzed. Several conclusions through case studies are summarized as follows:

1) The THVI and the RPDA can maximally expand the operation range of MMC DC voltage. Further, no over-modulation appears.

2) The proposed BCC control effectively regulates the DC current by adaptively adjusting the MMC DC voltage, according to the severity of the rectifier-side AC fault.

3) The proposed control enlarges the system operation range, improves the fault recovery, and significantly reduce the risk of current cut-off.

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