Research on Low Voltage Ride through Strategy for Power Electronic Transformer

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Abstract. In view of the operating characteristics for voltage sags of AC side of the power electronic transformer (PET), a low-voltage ride through (LVRT) strategy adapted to bidirectional power exchange of PET is proposed for the purposes of maintaining the system stability, assisting the system voltage recovery and protecting PET safety. During the asymmetric voltage sag, the negative sequence current of PET is eliminated to ensure the symmetry of the injected current. According to the degree of positive sequence voltage sag, the reactive current injection is provided to assist in voltage recovery. According to the PET active power condition before the voltage sag, the level and direction of which are maintained as far as possible without exceeding the limit, for which the disturbance to the AC and DC grids is reduced. Finally, the effectiveness of the proposed LVRT strategy is verified by simulation model.

1. Introduction

With the increase of grid-connected capacity of distributed energy and the growth of the demand for ‘plug and play’ of user-side load, DC power distribution technology has been gradually applied for pilot applications due to its outstanding power supply capability, strong controllability and good load compatibility [1,2]. And traditional AC distribution network is developing towards AC/DC hybrid distribution network. As a key equipment in AC/DC hybrid distribution network, power electronic transformer (PET) bears many tasks such as AC/DC system interconnection, voltage level conversion, power flow control, power quality adjustment, reactive power compensation and so on [3-5], the operating performance of which has a vital impact on the safe and stable operation of the power grid.

In the AC/DC hybrid distribution network, the main power supply is generally an AC power supply. When the AC grid is short-circuited and the voltage sags, PET should realize LVRT without off-grid to improve the stability of the grid operation and the reliability of the power supply. At present, there are a lot of researches on the normal operation control strategy of PET [6-9]. However, there are relatively few studies on LVRT strategies. In [10], aiming at the asymmetric short-circuit fault on AC side, the negative sequence voltage injection method is proposed to realize the DC voltage equalization between the bridge arms, but this measure will inject negative sequence current into the grid, which will adversely affect the operation of electrical equipment. In [11], the zero sequence voltage injection method is used for DC voltage equalization control, and the negative sequence current suppression is used to reduce the negative sequence current. However, the double-loop control
is still used during the LVRT, which slows down the system adjustment speed and affect the negative sequence current suppression effect. Reference [12] proposed a LVRT strategy for a cascaded H-bridge centralized photovoltaic grid-connected device, which injected reactive power into the grid during voltage sags, but the PV grid-connected device is a power unidirectional transmission device, for which this strategy does not accommodate power bidirectional transmission conditions.

According to the structural characteristics of PET, a LVRT strategy suitable for bidirectional power exchange of PET is proposed for the purpose of maintaining system stability, assisting system voltage recovery and ensuring PET operation safety, which can realize reactive power support and negative sequence current elimination in short-circuit fault of power grid, and effectively reduce active power fluctuations. The good performance of the proposed LVRT strategy is verified by the simulation results.

2. Topology of PET

PET can be divided into AC/AC type and AC/DC/AC type according to whether the intermediate conversion module has DC link. The latter has become the research focus because of its good controllability and high flexibility. AC/DC/AC type PET includes two basic structural forms: cascaded H-bridge type and MMC type [5,13]. Cascaded H-bridge PET has advantages of higher power density, and there is no bridge arm circulating current when three-phase star connection is connected, for which its research and application have received extensive attention. This paper will focus on the engineering practice and the LVRT strategy of cascaded H-bridge PET. The basic structure of the cascaded H-bridge four-port PET is shown in figure 1. The ports are AC 10kV, DC ±750V, AC 380V and DC ±375V respectively.

![Figure 1. Overall structure of PET.](image1)

![Figure 2. Pre-stage AC-DC module topology.](image2)

The AC-DC module in figure 1 implements the power conversion between AC10kV and DC±750V, which is a key component and bears the main function of the PET. The AC-DC module consists of two identical star cascaded units shown in figure 2.

One of the main problems that need to be solved in the practical application of cascaded H-bridge PET is how to achieve the equalization of the three-phase DC voltage when asymmetric voltage sags occur in the power grid to ensure the safe operation of the converter. References [10,11] proposes the use of zero sequence or negative sequence voltage injection strategies to achieve DC voltage equalization control, but it will lead to control complexity, and the time-delay effect of the control strategy will affect the equalization effect. In view of the above problems, this paper realizes the self-balancing of DC voltage between bridge arms through the optimization design of DC link topology, which is shown in figures 2 and 3. In figure 2, the sub-module of the cascaded bridge arm adopts a typical cascaded H-bridge structure on the AC side, and on the DC side all the three-phase sub-modules are uniformly connected in parallel to form a DC port; In figure 3, the sub-module of AC-DC module uses a resonant bidirectional DC-DC converter, and the double-sided H-bridge is connected through a high-frequency transformer with a resonant capacitor to achieve voltage level conversion and electrical isolation. The H-bridge on both sides modulate the DC voltage into a high-frequency square wave, and the power exchange is realized through the resonance link. When the operating frequency is near the resonant frequency, the DC-DC ratio of the converter is equal to the high-
frequency transformer ratio, and the performance of the converter is stable, and the load capacity of the converter is strong [14,15]. Adopting the above topology structure, when an asymmetric voltage sag occurs on the AC side, the DC side parallel modules can realize current self-balancing, thereby realizing the AC side series modules voltage self-balancing. Thus, there is no need to add the DC voltage balance control link, for which the device operating performance can be improved and the control system can be simplified.

![Figure 3](image-url)  
**Figure 3.** Sub-module topology of PET cascaded unit.

3. LVRT strategy of PET

3.1. Control objectives of LVRT

AC-DC module of PET generally uses a dual closed-loop control strategy during normal operation, as shown in figure 4. According to the working conditions and control objectives of PET, the outer loop can be controlled by constant DC voltage or constant power, the adjustment time of which is generally 40~100ms. The current inner loop adopts the $d$-axis voltage-oriented feedforward decoupling control strategy to quickly track the $d$-axis and $q$-axis current instruction values generated by the outer loop controller to improve the control performance, and the tracking time is 2~5ms.

![Figure 4](image-url)  
**Figure 4.** Steady state control schematic diagram of PET.

When the AC grid is short-circuited and the voltage sags, the PET should realize LVRT without off-grid to improve the stability of the grid operation and the reliability of the power supply. At present, although preliminary research has been carried out on the PET LVRT strategy, a unified understanding has not yet been formed. In this paper, for the purpose of maintaining stable operation of the power grid, assisting grid voltage recovery and ensuring the safety of PET itself, the basic control objectives of PET LVRT are proposed as follows:

1) When an asymmetric short circuit fault occurs in the power grid, the negative sequence current is eliminated by the negative sequence current suppression measures to ensure the symmetry of the current injected into the grid.

2) According to the degree of positive sequence voltage sag on the AC side, the reactive current injection is automatically adjusted to help the grid voltage recovery.

![Figure 5](image-url)  
**Figure 5.** Low-voltage ride through strategy of PET.
3) According to the active power condition before the voltage sag and the degree of positive sequence voltage sag on the AC side, the active transmission level and direction are maintained as far as possible under the premise of ensuring that the PET current does not exceed the limit, for which the disturbance to the AC/DC grid is reduced.

The block diagram of the LVRT strategy is shown in figure 5. In the figure, $\alpha$ is the positive sequence voltage sag degree, which is the ratio of the positive sequence voltage amplitude during voltage sag to the normal operation voltage amplitude, that is:

$$\alpha = \frac{u_{sd}}{u_{sd0}}$$  \hspace{1cm} (1)

When PET detects $\alpha < 0.9$, it is switched to LVRT control mode automatically. It is considered that the energy storage equipment is connected to the DC grid, for which the DC voltage can be maintained during the low voltage ride through operation. The current inner loop is directly used for control to improve the overall response speed by blocking the outer loop of the controller.

3.2. Implementation of LVRT

3.2.1. Inner loop design. The PET pre-stage AC-DC converter realizes the power conversion between AC and bipolar DC. The transformation modules of the two star cascaded structures are identical, so the mathematical model and control strategy are also identical. Therefore, this section only discusses the transformation module between the AC side and the unipolar DC. The mathematical model of the AC side of the AC-DC module of PET shown in figure 2 is

$$\begin{align*}
L_{arm} \frac{d}{dt} i_{dl}^{+} + R_{eq} i_{dl}^{+} &= u_{dl}^{+} - u_{dl}^{0} + \omega L_{arm} i_{ql}^{+} \\
L_{arm} \frac{d}{dt} i_{ql}^{+} + R_{eq} i_{ql}^{+} &= u_{ql}^{+} - u_{ql}^{0} - \omega L_{arm} i_{dl}^{+}
\end{align*}$$  \hspace{1cm} (2)

In equation (2), $L_{arm}$ is the bridge arm filter inductor, $R_{eq}$ is the series equivalent resistance of the IGBT turn-on resistors of cascaded H-bridge sub-module and filter inductor additional resistor. During voltage asymmetric sags, the system voltage and current will contain positive and negative sequence components. Performing positive and negative sequence decomposition on mathematical model shown in equation (2) in a double $dq$ coordinate system, and the AC side mathematical model of the AC-DC module of PET in the forward and the reverse rotation coordinate system can be obtained as equations (3) and (4).

$$\begin{align*}
L_{arm} \frac{d}{dt} i_{dq}^{+} + R_{eq} i_{dq}^{+} &= u_{dq}^{+} - u_{dq}^{0} + \omega L_{arm} i_{dq}^{+} \\
L_{arm} \frac{d}{dt} i_{dq}^{+} + R_{eq} i_{dq}^{+} &= u_{dq}^{+} - u_{dq}^{0} - \omega L_{arm} i_{dq}^{+} \\
L_{arm} \frac{d}{dt} i_{dq}^{-} + R_{eq} i_{dq}^{-} &= u_{dq}^{-} - u_{dq}^{0} - \omega L_{arm} i_{dq}^{-} \\
L_{arm} \frac{d}{dt} i_{dq}^{-} + R_{eq} i_{dq}^{-} &= u_{dq}^{-} - u_{dq}^{0} + \omega L_{arm} i_{dq}^{-}
\end{align*}$$  \hspace{1cm} (3, 4)

The ‘+’ in the lower corner of each variable in the equation represents the forward rotation coordinate system, and the ‘-’ represents the reverse rotation coordinate system. The ‘+’ in the upper corner indicates the positive sequence component, and the ‘-’ indicates the negative sequence component.
The PI controller is used for current regulation and current feedforward decoupling. According to the mathematical models shown in equations (3) and (4), the positive and negative sequence dq axis voltage instruction values can be obtained as equations (5) and (6), the corresponding LVRT block diagram is shown in figure 6.

\[
\begin{align*}
\mathbf{u}_d^* &= -\left[ k_p (i_{dq}^*-i_{dq}) + k_i \int (i_{dq}^*-i_{dq}) dt \right] + u_{sd}^* + \omega L_{sw} i_{dq}^* \\
\mathbf{u}_q^* &= -\left[ k_p (i_{dq}^*-i_{dq}) + k_i \int (i_{dq}^*-i_{dq}) dt \right] + u_{sq}^* - \omega L_{sw} i_{dq}^*
\end{align*}
\]  
\tag{5}
\]

\[
\begin{align*}
\mathbf{u}_d^- &= -\left[ k_p (i_{dq}^*-i_{dq}) + k_i \int (i_{dq}^*-i_{dq}) dt \right] + u_{sd}^- - \omega L_{sw} i_{dq}^* \\
\mathbf{u}_q^- &= -\left[ k_p (i_{dq}^*-i_{dq}) + k_i \int (i_{dq}^*-i_{dq}) dt \right] + u_{sq}^- + \omega L_{sw} i_{dq}^-
\end{align*}
\]  
\tag{6}
\]

**Figure 6(a).** Block diagram of positive sequence components.  
**Figure 6(b).** Block diagram of negative sequence components.  
**Figure 7.** Inner loop unified control block diagram.

The unified control block diagram model is shown in figure 7 by decoupling the current inner loop, in which \(x^i\) and \(x\) represent the current instruction values and actual values in figure 6(a) and (b) respectively. The design principle of the current inner loop PI controller in figure 7 is the same with that of the steady-state control strategy because the control block diagram is consistent. The current inner loop can be guaranteed to have good tracking performance by optimizing the regulator parameters. The current inner loop controller parameters are set in the light of the typical I-type system, for which the current inner loop can be equivalent to the first-order inertia unit [16], and its time constant is 2~5ms.

3.2.2. Negative sequence current elimination. During the asymmetric voltage sag of the grid voltage, negative sequence current is eliminated in order to ensure the symmetry of the three-phase current injected into the grid to reduce the impact on the grid, as shown in equation (7). The negative sequence current dq axis components instruction value in the reverse rotation coordinate system shown in figure 6(b) is given as zero, and the negative sequence current dq axis component will quickly follow the instruction value shown in equation (7) to achieve the function of negative sequence current elimination.

\[
\begin{align*}
i_{dq}^- &= 0 \\
i_{dq}^+ &= 0
\end{align*}
\]  
\tag{7}
\]

3.2.3. Reactive power injection. Equation (8) is the \(q\)-axis positive sequence current instruction value. In the case of a voltage sag of less than 10%, PET can operate stably according to the normal control strategy, at this time \(i_{dq}^+=0\), to achieve unit power factor operation. When the voltage sags by more than 10%, for every 10% sag, PET provides 15% reactive power compensation to the AC grid, supporting the PCC voltage of the grid to help restore the grid voltage. The maximum compensation capacity of PET is 1.2 times the rated current.
3.2.4. Active power maintenance. During the grid voltage sag, the active power absorbed by PET from the grid is shown in equation (9).

\[ p = u_{d+}^* i_{d+}^* + u_{q+}^* i_{q+}^* + u_{d-}^* i_{d-}^* + u_{q-}^* i_{q-}^* \]  

(9)

When the positive sequence \( d \)-axis voltage orientation is adopted, \( u_{sq+} = 0 \). During LVRT operation, the negative sequence current can quickly track the instruction value of equation (7), that is, \( i_{d-} = i_{q-} = 0 \). The positive sequence \( d \)-axis current is also able to quickly track its instruction value. So the PET absorption power during the voltage sag can be obtained as shown in the equation (10).

\[ p = u_{d+}^* i_{d+}^* \]  

(10)

The power absorbed by PET from the grid before the grid voltage sags is

\[ p_0 = u_{ad0} i_{d0}^* \]  

(11)

PET transmission loss is neglected. It can be seen from the combination of equations (1), (10) and (11) that during the voltage sag, in order to make the active transmission level not change, it must be

\[ i_{d+}^* = i_{d0}^* / \alpha \]  

(12)

Therefore, the \( d \)-axis positive sequence current instruction value represented can be obtained as shown in the equation (13) In the equation (13), \( \text{sign} \) is a symbol function, for which the transmission direction of the active power before the voltage sag is extracted, so that the LVRT strategy can adapt to the characteristics of the PET bidirectional power transmission. \( \sqrt{1.2^2 - i_{q+}^{*2}} \) is the maximum allowable active current instruction value after reactive compensation according to equation (8).

\[ i_{d+}^* = \text{sign}(i_{d0}^*) \times \min \left\{ i_{d0}^*/\alpha, \sqrt{1.2^2 - i_{q+}^{*2}} \right\} \]  

(13)

Substituting equation (8) into equation (13), the relationship between the positive sequence active current instruction value upper limit and the positive sequence active current instruction demand value for maintaining the active level before voltage sag and the voltage sag depth is shown in figure 8. The solid line in the figure is the maximum allowable active current after reactive power compensation, that is, the upper limit of active current. As the voltage sag depth deepens, the reactive power demand gradually increases, and the active power upper limit gradually decreases. The dotted clusters in the figure represent the amount of active output required to maintain the active level before and after the voltage sag. The dotted line from bottom to top respectively indicates that the PET is from no load to full load before the voltage sag, and the interval is 0.1p.u. It can be seen from figure 8 that the requirement of maintaining the active level before the voltage sag can be achieved according to the equation (13). Taking the active current instruction value of 0.6 before the voltage sag as an example, as shown in figure 9, the horizontal dotted line in the figure is the active current before the voltage sag. Under the condition that the voltage sag is not less than 55%, the control strategy can ensure the active before and after the voltage sag. The transmission level and direction remain constant.
4. Simulation results

A four-port PET simulation model was built in PSCAD/EMTDC in order to verify the effectiveness of the PET LVRT strategy proposed in this paper. The simulation model is shown in figure 9. The PET is connected to the AC grid through a line-frequency transformer, and the DC side is incorporated with a ±750V DC bus with distributed generators and DC loads. The low voltage DC and AC ports supply power to the DC and AC loads respectively. When the symmetric and the asymmetric short circuits occur at point f, the voltage symmetry and asymmetry sag at the 10kV bus are adjusted by adjusting the fault resistance to verify the PET LVRT strategy proposed in this paper. The main simulation parameters are shown in Table 1.

Table 1. PET simulation parameters.

| Parameter                              | Value       |
|----------------------------------------|-------------|
| PET rated capacity (MVA)               | 3           |
| PET equivalent resistance (Ω)          | 0.01        |
| PET rated AC voltage (kV)              | 10          |
| Transformer ratio                       | 35/10.5     |
| PET rated DC voltage (kV)              | ±0.75       |
| Transformer capacity (MVA)             | 30          |
| PET filter inductor (H)                | 0.02        |
| Leakage resistance (p.u.)              | 0.1         |

4.1. Voltage symmetric sag

Symmetric sag of three-phase voltage occurs at the connection bus of PET, the sag moment is t=0.3s, the degree of sag is α=0.4. The PET is set to operate in unit power factor of P*=0.375 and Q*=−0.375 before the voltage sag. The current instruction values obtained according to equations (7), (8) and (13) are shown in Table 2.

Table 2. Low voltage ride through parameters of voltage symmetric sag.

| P (i_d0) | Q (i_q0) | P_0 | Q_0 | i_d* | i_q* | P | Q |
|----------|----------|-----|-----|------|------|---|---|
| 0.375    | 0        | 0.375 | 0 | 0.937 | 0.75 | 0.375 | -0.3 |
| -0.375   | 0        | -0.375 | 0 | -0.937 | 0.75 | -0.375 | -0.3 |

Figures 10-15 is simulation waveforms of the two operating conditions shown in Table 2 in the case of voltage symmetric sag. Figures 10 and 11 are voltage and current waveforms of phase A.

Figures 8 and 9. Schematic diagram of active current compensation capability.

**Figure 8.** Schematic diagram of active current compensation capability.

**Figure 9.** Simulation system model of PET.

**Figure 10.** Voltage and current of Phase A in rectified state before voltage sag.

**Figure 11.** Voltage and current of Phase A in inverted state before voltage sag.
**Figure 12.** dq-axis current in rectified state before voltage sag.

Figures 12 and 13 show the dq-axis current instruction value and actual value waveforms. It is considered that there is 5ms adjustment delay of the phase-locked loop (PLL), the outer loop of the controller is blocked within 5ms after detecting that the positive sequence voltage sags, and the dq current reference value before the voltage sag is used as the inner loop instruction value. This method can prevent the power fluctuation caused by the adjustment of PLL, as well as the influence of the control system and PET for the output jitter of PLL caused by the voltage flicker on the normal operation.

**Figure 13.** dq-axis current in inverted state before voltage sag.

**Figure 14.** Power waveform in rectified state before voltage sag.

Figures 14 and 15 show the waveform of PET absorption power. After the voltage sags, PET can inject reactive power into the AC system according to the voltage sag depth to help the AC system voltage recovery. And can maintain the active transmission level before the fault.

**Figure 15.** Power waveform in inverted state before voltage sag.

4.2. Voltage asymmetric sag

The A-phase voltage at the connection bus of PET is unchanged, and the amplitude of BC two-phase voltage sags to 40% of the original value. According to the symmetrical components method, the positive sequence voltage sag depth can be obtained as $\alpha=0.6$. Under this condition, the simulation is verified for the cases of no-load and full-load operation before the voltage sag. The current instruction value under different operating conditions of voltage asymmetric sag can be calculated by equations (7), (8) and (13), as shown in table 3.

| $P^*(i_{d0}^*)$ | $Q^*(i_{q0}^*)$ | $i_{d+}^*$ | $i_{q+}^*$ | $i_{d-}^*$ | $i_{q-}^*$ |
|-----------------|-----------------|-------------|-------------|-------------|-------------|
| 0               | 0               | 0           | 0.45        | 0           | 0           |
| 1               | 0               | 1.112       | 0.45        | 0           | 0           |
| -1              | 0               | -1.112      | 0.45        | 0           | 0           |

4.2.1. PET no load before voltage sag. Figure 16 shows the waveforms of the positive sequence current dq axis component in the forward rotation coordinate system, which runs at no load before the voltage asymmetric sags. The current inner loop can quickly and accurately track the inner loop
current instruction value within 5ms, and can adjust the q-axis current to inject reactive power into the grid. The corresponding three-phase current waveform is shown in Figure 17. Because of the negative sequence current elimination, the three-phase current can be injected symmetrically into the grid and reduce the impact on the grid.

Figure 16. Positive sequence $dq$-axis current without load before voltage sag.

Figure 17. Three-phase grid-connected current without load before voltage sag.

4.2.2. PET full load before voltage sag. As shown in Table 3, the PET in full load condition before the voltage asymmetry sag is simulated according to the power transmission direction. Figures 18 and 19 are waveforms of positive and negative sequence current $dq$ axis components in the forward and reverse coordinate systems in the case where PET absorbs active power. It can be seen that the positive sequence current can quickly follow the instruction value change within 5ms, and the negative sequence current inner loop can quickly eliminate the negative sequence current after the voltage sags.

Figure 18. Positive sequence $dq$-axis current fully loaded before voltage sag.

Figure 19. Negative sequence $dq$-axis current fully loaded before voltage sag.

Figures 20 and 21 are three-phase current waveforms and power waveforms in the case where PET injects active power into the AC system. It can be seen that the negative sequence flow elimination control strategy can ensure the symmetry of the current injected into the grid under the condition of asymmetric voltage sag. PET can perform reactive power compensation to the grid to assist the grid voltage recovery, maintain the active power level as far as possible to reduce the disturbance to the grid.

Figure 20. Three-phase grid-connected current fully loaded before voltage sag.

Figure 21. PET power waveform fully loaded before voltage sag.
5. Conclusion
In this paper, a LVRT strategy that is suitable for power bidirectional transmission of PET is proposed, the effectiveness of which under voltage symmetric and asymmetric sag conditions is verified by simulation model. This strategy mainly implements the following functions:

1) During the voltage sag of the PET AC side, the power or voltage outer loop is blocked, and the current inner loop instruction value is given directly, which can improve the overall response speed of the system.

2) During the voltage asymmetric sag, the negative sequence current is eliminated to ensure the symmetry of the current injected into the grid.

3) According to the degree of positive sequence voltage sag, the corresponding reactive current injection is performed to help the grid voltage recover.

4) According to the active power condition before the voltage sag, the level and direction of active power are maintained as far as possible within the upper limit of the current-carrying, and the disturbance to the AC and DC grids is reduced.

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