Fault Characteristic on DC Pole-to-Pole Short-Circuit in Distribution Electronic Power Transformers

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Fault Characteristic on DC Pole-to-Pole Short-Circuit in Distribution Electronic Power Transformers

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Abstract. The analysis on fault characteristic of Distribution Electronic Power Transformer (D-EPT) can help design its operation and protection scheme, hence improve the reliability of the D-EPT as well as the distribution power grid. The DC pole-to-pole short-circuit fault at DC-Link is analyzed with R-L-C resonant mode and free-wheeling mode, and the theoretical analysis on the short-circuit voltage and current is based on several influence factors and relevant system parameters, which indicates that the fault characteristics are related to the configuration, operation and system parameters of D-EPT.

1. Introduction

Globe energy demand has risen rapidly due to the unprecedented human society development, which makes the utilization of distributed generation and renewable energy generation excellent solution for energy shortage problem and environment deterioration problem [1,2].

As the traditional electric power system can not release the full potential of the distributed energy, the Distribution Electronic Power Transformer (D-EPT) becomes the key component in future energy internet, in which can be taken as an energy router [3]. Comparing the traditional transformer with the D-EPT, the D-EPT is able to connect both AC ports and DC ports with different voltage levels, and achieve flexible regulation on the output power in all ports by adjusting control strategy of power electronic modules [4-7]. The energy router in energy internet requires ability to tolerant the fault during operation, unlike traditional transformer, the over voltage and over current in a system failure may cause damage to the power electronic components in the D-EPT [8,9]. To protect the switching components, the inner protection system is usually embedded to turn the corresponding power switches off.

Based on the fault characteristics of traditional power transformer, a protection scheme for EPT is proposed [10,11], however only for AC terminals. In [12], a protection scheme is proposed for DC terminal fault, without theoretical analysis. The fault characteristic analysis of EPT based on MMC in distribution network, and the fault types in the MMC based EPT have greater impact on EPT in distribution network [13]. As the traditional VSC-HVDC (voltage sourced converter-high voltage direct current) devices is different from D-EPT in structures [14], it is necessary to analyze the fault characteristic for DC terminals of D-EPT.

In this paper, the topology structures and operational principle of D-EPT are introduced in Section 2. The theoretical analysis on DC pole-to-pole short-circuit fault is given in Section 3. The bonding is built between fault characteristics with relevant parameters of D-EPT in Section 4, and conclusion is presented in Section 5.

2. Structures and Operation Principle of D-EPT

The regular structure of D-EPT is shown in Figure 1, which has been applied on a three phase 10kV/400V 500kVA D-EPT industrial prototype in Huazhong University of Science and Technology and other fields. There are 4 voltage levels in D-EPT, including 10kV AC as input voltage, 9kV DC as rectifier DC-link voltage, 375V DC as inverter DC-link voltage, and 380V AC as output voltage.

Consisted of rectifier part, DC-DC converter part and inverter part, the basic structure of D-EPT is shown in Figure 1.

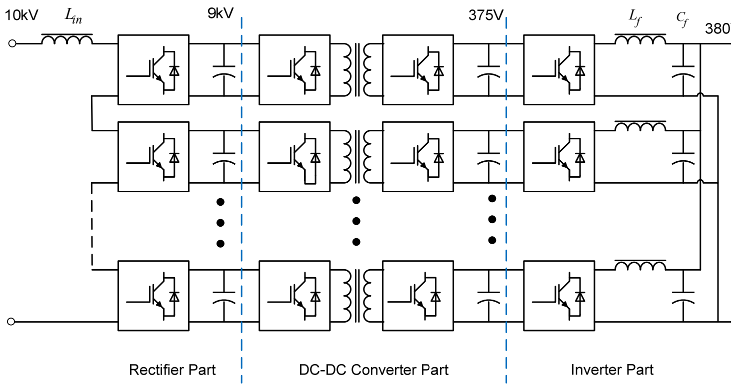

Figure 1. Structure of D-EPT

The rectifier part of D-EPT transfers the 10kV line voltage (5.77kV for one phase) of the grid to 9kV DC voltage for DC-DC converter part by cascaded H-bridges. Consisted of a H-bridge converter, a high frequency transformer (HFT) and diode bridge, the DC-DC converter part provides 375V DC voltage for inverter part of the EPT, which will then be inverted to 380V AC voltage in inverter part by a group of parallelled H-bridge inverters.

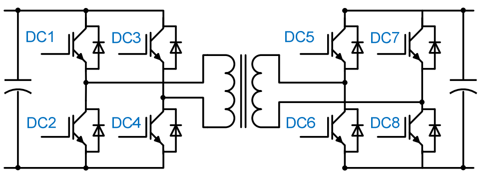

Figure 2. Structure of DC-DC part

Figure 2 shows the structure of the DC-DC part for a H-bridge power module, including a H-bridge converter at the primary side (high voltage) of the HFT, a HFT for isolation, and another H-bridge converter at the secondary side (low voltage) of the HFT.

The DC-link voltage of rectifier part is modulated to high frequency square wave by primary side H-bridge converteer including IGBT DC1 to DC4, then demodulated to secondary side H-bridge converter including IGBT DC5 to DC8, and in the end rectified to DC voltage in inverter part of the D-EPT.

3. Theoretical Analysis on DC Pole-to-Pole Short-Circuit Fault

The short-circuit fault detection and protection of D-EPT are based on a hardware fault detection circuit which is embedded in each IGBT driver. When the short-circuit fault is detected, the IGBT driver will turn the corresponding IGBT off immediately, preventing the consequent damages to the D-EPT.

Figure 3 illustrates the circuit diagram of a basic H-bridge power module, including output capacitor C_{HB}, the voltage across the capacitor V_{dc}, the output inductor L_{HB}, short circuit current though inductor I_{dc}, and the equivalent resistor R_k during the pole-to-pole short circuit fault.

To simplify the analysis of fault characteristics on pole-to-pole short circuit, assumptions are listed below:

1. Assuming the basic H-bridge power module includes only one H-bridge;
2. The basic H-bridge power module works in the no-load condition before the failure;
3. The bolted fault happens at the output of H-bridge power module;
4. The fault detection and protection is very fast, hence the time between failure and IGBT turning off is very short.

According to the assumption mentioned above, the DC pole-to-pole short-circuit fault can be divided into two modes, including R-L-C resonant mode and inductor free-wheeling mode. In the R-L-C resonant mode, the energy stored in the capacitor will be transferred to the inductor; and in the inductor free-wheeling mode, the inductor will keep discharging until the short-circuit current decrease to zero.

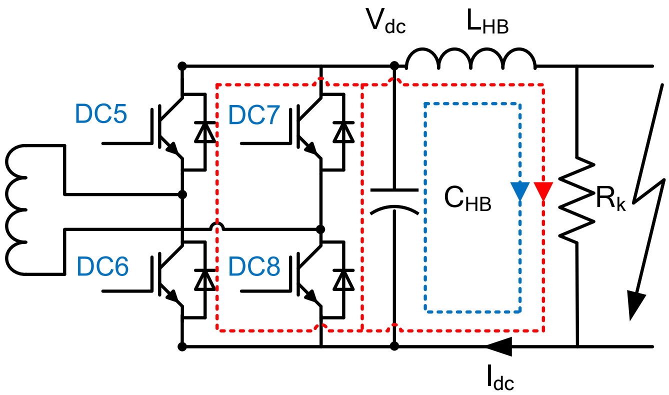

Figure 3. Pole-to-pole short circuit fault on a typical H-bridge power module

3.1. R-L-C resonant mode

When the short-circuit fault happens, the circuit is being excited by the energy initially stored in the capacitor and inductor, and the second-order differential equation can be given by:

$$L_{HB}C_{HB}\frac{d^2V_{dc}}{dt^2}+R_kC_{HB}\frac{dV_{dc}}{dt}+V_{dc}=0 \tag{1}$$

From equation (1), the capacitor voltage V_{dc} can be deduced as:

$$V_{dc}(t)=K_1e^{s_1t}+K_2e^{s_2t} \tag{2}$$

where, K_1 and K_2 are constants to be determined.

The two roots of the equation can be described as:

$$\begin{cases} s_1=-\alpha+\sqrt{\alpha^2-\omega_0^2} \\ s_2=-\alpha-\sqrt{\alpha^2-\omega_0^2} \end{cases} \tag{3}$$

where, $\alpha=\dfrac{R_k}{2L_{HB}}$, and $\omega_0=\dfrac{1}{\sqrt{L_{HB}C_{HB}}}$.

As the initial value of the capacitor voltage and inductor current are V_{dc} and 0 according to the no-load working condition,, the constants K_1 and K_2 can be described as:

$$\begin{cases} V_{dc}(0^+) = K_1 + K_2 = V_{dc} \\ \dfrac{dV_{dc}}{dt}(0^+) = K_1 s_1 + K_2 s_2 = 0 \end{cases} \tag{4}$$

And equation (2) can then be modified to:

$$V_{dc}(t) = \frac{V_{dc}}{s_2 - s_1}(s_2 e^{s_1 t} - s_1 e^{s_2 t}) \tag{5}$$

The assumption of bolted fault gives that:

$$R_k < 2\sqrt{\frac{L_{HB}}{C_{HB}}} \tag{6}$$

Hence, the loop is an underdamped system, and the capacitor voltage can be described as:

$$V_{dc}(t) = V_{dc}\frac{\omega_0}{\omega_d} e^{-\alpha t}\cos(\omega_d t - \theta) \tag{7}$$

where, $\omega_0 = \sqrt{\omega_0^2 - \alpha^2}$, and $\theta = \arctan\dfrac{\alpha}{\omega_d}$.

From (7), the inductor current can be deduced as:

$$I_{dc}(t) = \frac{V_{dc}}{\omega_d L_{HB}} e^{-\alpha t}\sin(\omega_d t) \tag{8}$$

Equation (6) indicates the critical condition the underdamped response for R-L-C resonant mode with no-load, and the capacitor voltage only decrease to zero with underdamped condition. Equation (7) indicates that the capacitor begins to discharge after the fault, and the anti-parallel diodes of the IGBTs will conduct when the capacitor voltage decreases to zero, and the H-bridge power module works in a inductor free-wheeling mode then. As a result, the time interval for R-L-C resonant mode can be expressed as:

$$t_1 = \frac{\theta + \dfrac{\pi}{2}}{\omega_d} \tag{9}$$

The maximum value of short-circuit current can be given by:

$$I_{dc\max} = I_{dc}(t_1) = \frac{V_{dc}}{\omega_d L_{HB}} e^{-\alpha t_1} \tag{10}$$

In the R-L-C resonant mode, the capacitor keep on charging the inductor until the capacitor voltage decreases to zero, hence the energy of the capacitor and inductor can be roughly expressed by:

$$\frac{1}{2}C_{HB}V_{dc}^2 = \frac{1}{2}L_{HB}I_{dc\max}^2 \tag{11}$$

The maximum value of short-circuit current can then be modified as:

$$I_{dc\max} = \sqrt{\frac{C_{HB}}{L_{HB}}}V_{dc} = \frac{V_{dc}}{\omega_0 L_{HB}} \tag{12}$$

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The fault characteristic analysis above is based on the bolted fault, and the one will be different by introducing the equivalent resistor R_k in capacitor voltage and short-circuit current. In the overdamped system, the equivalent resistor R_k can be given by:

$$R_k \geq 2\sqrt{\frac{L_{HB}}{C_{HB}}} \tag{13}$$

As a result, the capacitor voltage with overdamped response can be given by:

$$V_{dc}(t) = \frac{V_{dc}}{s_2 - s_1}(s_2 e^{s_1 t} - s_1 e^{s_2 t}) + \frac{V_{dc}}{C_{HB}(s_2 - s_1)}(e^{s_1 t} - e^{s_2 t}) \tag{14}$$

The short-circuit current can then be described as:

$$I_{dc}(t) = \frac{C_{HB} V_{dc} s_2 s_1}{s_2 - s_1}(e^{s_2 t} - e^{s_1 t}) + \frac{I_{dc}}{s_2 - s_1}(s_2 e^{s_2 t} - s_1 e^{s_1 t}) \tag{15}$$

3.2. Inductor Free-wheeling Mode

In the inductor free-wheeling mode, the capacitor voltage decrease to zero, and the inductor current goes though equivalent resistor R_k and anti-parallel diodes of IGBTs, with DC-link capacitor bypassed.

As the decay of short-circuit current is related to the inductor L_{HB}, conducting resistor of anti-parallel diode R_{DC}, and equivalent resistor R_k, the discharge constant can be given by:

$$\tau = \frac{L_{HB}}{R_{DC} + R_k} \tag{16}$$

Due to the characteristic of L-C circuit that the inductor current usually decrease to zero within 4 or 5 periods, the inductor free-wheeling time interval can then by given by:

$$t_2 = 5\tau \tag{17}$$

Combine equation (10) and equation (16), the short-circuit current can be given by:

$$I_{dc}(t) = I_{dc\max} e^{-\frac{R_{DC}+R_k}{L_{HB}} t} \tag{18}$$

The capacitor voltage equals to the on-state voltage drop of the anti-parallel diodes, which can be described as:

$$V_{dc}(t) = -R_{DC} I_{dc\max} e^{-\frac{R_{DC}+R_k}{L_{HB}} t} \tag{19}$$

Combine equation (8) and equation (18), the short-circuit current can then be given by:

$$I_{dc}(t) = \begin{cases} \dfrac{V_{dc}}{\omega_d L_{HB}} e^{-\alpha t} \sin(\omega_d t), t \leq t_1 \\ I_{dc\max} e^{-\frac{R_{DC}+R_k}{L_{HB}}(t-t_1)}, t_1 < t \leq (t_1 + t_2) \end{cases} \tag{20}$$

The characteristic of the DC pole-to-pole fault for short-circuit current can be derived from equation (20), which indicates that the resonant frequency and discharge time constant determine the time of R-L-C resonant mode and inductor free-wheeling mode, respectively.

Combine equation (7) and equation (19), the capacitor voltage can be given by:

$$V_{dc}(t)=\begin{cases} V_{dc}\dfrac{\omega_0}{\omega_d}e^{-\alpha t}\cos(\omega_d t-\theta), t\le t_1 \\ -R_{DC}I_{dc\max}e^{-\frac{R_{DC}+R_k}{L_{HB}}(t-t_1)}, t_1<t\le(t_1+t_2) \end{cases} \tag{21}$$

The characteristic of capacitor voltage can be derived from equation (20), which indicates that the capacitor voltage in R-L-C resonant mode will decrease to zero, and then become negative in the inductor free-wheeling mode due to the conducting of anti-parallel diodes.

4. Influence Factors with DC Pole-to-Pole Short-Circuit Fault

The assumptions listed above will be ignored to get a more common conclusion about fault characteristic in the analysis about the influence factors of DC pole-to-pole short-circuit fault.

4.1. System Parameters

(1) The DC-link capacitor of H-bridge power module

When the D-EPT is working properly, the capacitor voltage is rated DC-link voltage. As shown in equation (12), the peak value of short-circuit current becomes larger when the capacitance is larger, hence extends the R-L-C resonant time according to equation (9).

(2) The inductor of H-bridge power module

The peak value of short-circuit current becomes smaller and the time of inductor free-wheeling mode is longer when the inductor is larger.

(3) The on-state resistor of anti-parallel diode

The short-circuit fault detection and protection system will detect the failure in a very short time, and then the IGBT driver will turn the corresponding IGBT off immediately. As a result, the anti-parallel diodes of IGBT will then conduct in the inductor free-wheeling mode, and its on-state resistor will reduce the time of inductor free-wheeling mode.

4.2. Load Current

If the fault happens with a load current, the condition in equation (4) needs to be modified as:

$$\begin{cases} K_1+K_2=V_{dc} \\ K_1 s_1+K_2 s_2=-\dfrac{I_{dc}}{C_{HB}} \end{cases} \tag{22}$$

where, I_{dc} represents the proper working load current.

The capacitor voltage in equation (7) will then be modified to:

$$V_{dc}(t)=V_{dc}\frac{\omega_0}{\omega_d}e^{-\alpha t}\cos(\omega_d t-\theta)-\frac{I_L}{\omega_d C_{HB}}e^{-\alpha t}\sin(\omega_d t) \tag{23}$$

And the inductor current in equation (8) can then be modified as:

$$I_L(t)=\frac{V_{dc}}{\omega_d L_{HB}}e^{-\alpha t}\sin(\omega_d t)+\frac{L_{HB}\omega_0}{\omega_d}e^{-\alpha t}\cos(\omega_d t+\theta) \tag{24}$$

As a result, the time for R-L-C resonant mode can be expressed as:

$$t_1=\begin{cases} \dfrac{1}{\omega_d}\arctan\theta_L, \theta_L\ge 0 \\ \dfrac{1}{\omega_d}\arctan\theta_L+\dfrac{\pi}{\omega_d}, \theta_L<0 \end{cases} \tag{25}$$

where, $\theta_L = \dfrac{\omega_d V_{dc} C_{HB}}{I_L - \alpha V_{dc} C_{HB}}$.

It can be derived from equation (25) that the R-L-C resonant mode time will be longer when the load current and capacitor discharging current are in the same direction, and the one will be shorter when the two currents are in the opposite direction, which indicates that the short-circuit current is the overlay of load current and capacitor discharging current, and the load current decreases in R-L-C resonant mode and is negligibly small comparing to capacitor current, so as to the influence to the short-circuit current.

4.3. Configuration of H-bridge power module

The D-EPT, STATCOM and FACTS usually apply modularized design of H-bridge power module to implement the converter with multilevel output voltage. Hence the ways of connection about the H-bridges power modules including in parallel and in series (cascaded) affect the DC pole-to pole short-circuit fault characteristic. figure 4 shows that the cascaded connection of H-bridge power modules can tolerant high voltage input, and figure 5 shows that the paralleled connection of H-bridge power modules can increase the output current and achieve higher power capability.

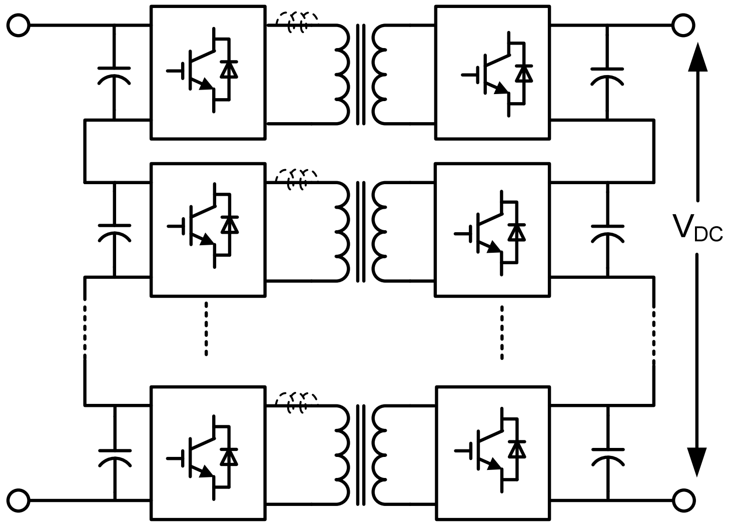

Figure 4. Configuration of parallelled connection for H-bridge power module

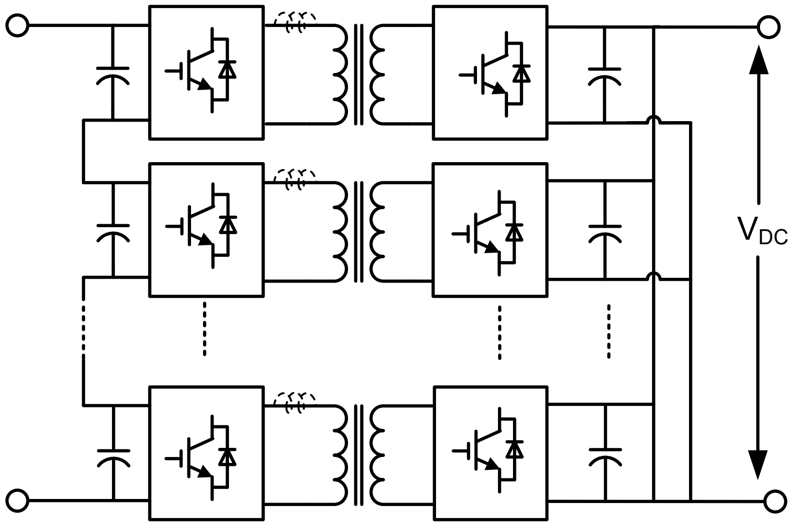

Figure 5. Configuration of cascaded connection for H-bridge power module

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Table 1. Effects of different configuration on equivalent parameters.

Parameters	Cascaded	Parallelled
Rated voltage	NV_{dc}	V_{dc}
Rated current	I_{dc}	NI_{dc}
Equivalent capacitor	C_{HB}/N	NC_{HB}
On-state resistor of anti-parallel diode	NR_{DC}	R_{DC}/N
Inductor	L_{HB}	L_{HB}

The effect of the configuration to the equivalent parameters of H-bridge power module is shown in Table 1, and the short-circuit current characteristics of it can then be compared on different configurations, and summaries can be listed below:

(1) The effect of load current to the peak value of short-circuit current is negligibly small, and the peak value of short-circuit current to the parallelled connection is higher than cascaded one.

(2) The peak value of short-circuit current for bolted fault is determined by the number of modules. For instance, the peak value of short-circuit current for N H-bridge power modules is $\sqrt{N}$ of single one H-bridge power module.

(3) The R-L-C resonant mode and inductor free-wheeling mode of parallelled connection power modules are both longer than cascaded connection one.

(4) The larger number of cascaded H-bridge power modules is applied, the higher peak value of short-circuit current will be, and the shorter two fault modes last, hence the capacitor will discharge much quickly, which can easily cause damage to the capacitor. The larger number of parallelled H-bridge power modules is applied, the higher peak value of short-circuit current will be, and the longer two fault modes last, hence the anti-parallel diodes might get over heat in inductor free-wheeling mode.

To prevent the damage to the components of the H-bridge power module caused by short-circuit current, certain measures are listed below:

(1) If the H-bridges are connected in parallel, the peak value of short-circuit current can then be reduced by cutting the number of H-bridges. However, the H-bridge numbers should be sufficient to provide the rated power.

(2) If the H-bridges are connected in series, the H-bridge numbers should be sufficient to provide the rated power as well as the rated DC-link voltage. The N+1 redundancy design can be applied by reserving a backup H-bridge to replace the failure one. As a result, the peak value of short-circuit current will be reduced due to the redundant H-bridge according to equation (12).

(3) To reduce the peak value of short-circuit current, the DC-link capacitor should be reduced, however still meeting the requirement of the ripple voltage. The peak value of short-circuit current can also by reduced by applying large inductor, however the saturation of the inductor will then reduce its inductance, which will increase the short-circuit current.

5. Conclusions

Based on the structure of Distribution Electronic Power Transformer (D-EPT), the DC pole-to-pole fault characteristic is discussed with theoretical analysis on capacitor voltage and short-circuit current. By dividing the process of the fault into R-L-C resonant mode and inductor free-wheeling mode, the analysis indicates that the fault characteristic is determined by the configuration and relevant parameters of the failed H-bridge power module. The influence factors including DC-link capacitor, inductor, anti-parallel diode, load current, configuration and H-bridge number of H-bridge power modules are all analyzed in detail. The summaries and suggestions based on the analysis can provide abundant information for engineers to gain a better understanding of the fault response for different configurations and system parameters, hence improving the reliability of D-EPT.

Acknowledgments
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