Analysis on IGBT and Diode Failures in Distribution Electronic Power Transformers

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Abstract. Fault characteristics of power electronic components are of great importance for a power electronic device, and are of extraordinary importance for those applied in power system. The topology structures and control method of Distribution Electronic Power Transformer (D-EPT) are introduced, and an exploration on fault types and fault characteristics for the IGBT and diode failures is presented. The analysis and simulation of different fault types for the fault characteristics lead to the D-EPT fault location scheme.

1. Introduction

Largely improved the intelligent level of power grid, the electronic power transformer (EPT), also as known as smart transformer (ST), normally consists of power electronic converters. Comparing to the traditional transformer, the EPT can control its input and output voltage in magnitude, frequency and phase angle to realize flexible voltage and current regulation, which realizes the assumption made in [1] by providing a customized power supply [2].

The reliability of power electronic components affects the one of converters, hence affects the reliability of power system that are connected with them. A failed power switching component always appears as short circuit or open circuit [3]. The short circuit fault always deteriorate in a very short time [4,5], hence normally protected by hardware protection, and the open circuit situations are also discussed in [6].

The reasons of open circuit include rupture caused by short circuit [7], IGBT driver invalid [6,7] and loose connection [8].

The study on switching component failure focus on the converters in motor drive system [9], and EPT structures are discussed in [10], applications in power grid [11]. In [12,13], 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.

In this paper, the topology structures and control schemes of D-EPT are introduced in Section 2. The failure analysis on IGBT and diode of D-EPT is presented in Section 3. The fault location method based on summaries derived from saber simulation is shown in Section 4, and conclusion is given in Section 5.

2. D-EPT Structures and Control Schemes

2.1. D-EPT Structures

The D-EPT structure which consists of rectifier section power cell (RSPC), DC-DC converter section power cell (DCPC) and inverter section power cell (ICPC) is shown in Figure 1.

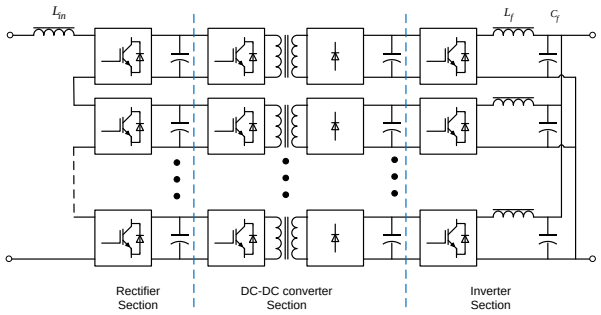

Figure 1. Structures of D-EPT

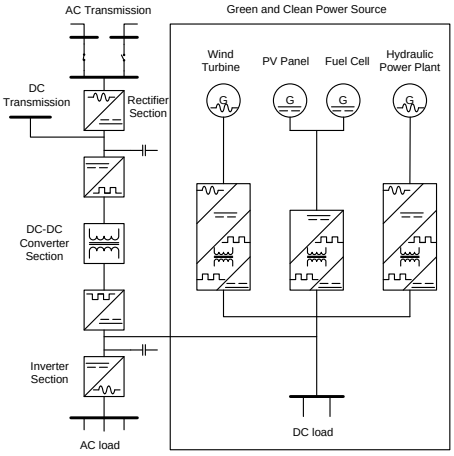

Figure 2. EPT based substation

Adopted by full-bridge rectifiers, the RSPC of D-EPT transfers the grid AC voltage to DC voltage for DCPC. The DCPC connects the RSPC and the ISPC with a converter, a High Frequency Transformer (HFT) and a diode bridge. The converter will invert RSPC DC-link voltage into AC voltage, which will be transmitted through HFT. The full-bridge inverters that form the ISPC are in parallel with each other, and convert the ISPC DC-link voltage to AC voltage.

Figure 2 shows a substation that applies EPT to connect AC transmission system, DC transmission system, and clean energy including hydraulic power, solar power, and wind power.

2.2. Control Scheme for D-EPT

The RSPC in Figure 3 includes a current loop to keep the input AC current sinusoidal in phase with the grid voltage for customized power factor, as well as a voltage loop to control the DC-link voltage.

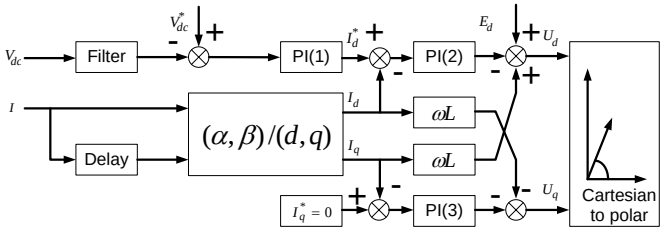

Figure 3. The control strategy of RSPC.

The control diagram of RSPC can be given by:

$$\begin{cases} L\dfrac{dI_d}{dt} = E_d - U_d + \omega L I_q \\ L\dfrac{dI_q}{dt} = -U_q + \omega L I_d \end{cases} \tag{1}$$

DCPC applies an open loop PWM control to generate a high frequency square wave to, and then has it rectified by a diode bridge. As DCPC acts like a proportional amplifier, ISPC DC-link voltage can be given by:

$$V_{ISPC} = k \times V_{RSPC} \tag{2}$$

By applying carrier phase shifting sinusoidal PWM (CPS-SPWM), the ISPC provides a constant AC voltage output. The RMS value of the output voltage is multiplied by the standard sinusoidal wave to keep the output voltage sinusoidal. The single phase control diagram for ISPC is shown in Figure 4, and its mathematic model can be given by:

$$\begin{cases} C_f \times \dfrac{dv_o}{dt} = i_L - i_o \\ L_f \times \dfrac{di_L}{dt} = v_i - v_o \end{cases} \tag{3}$$

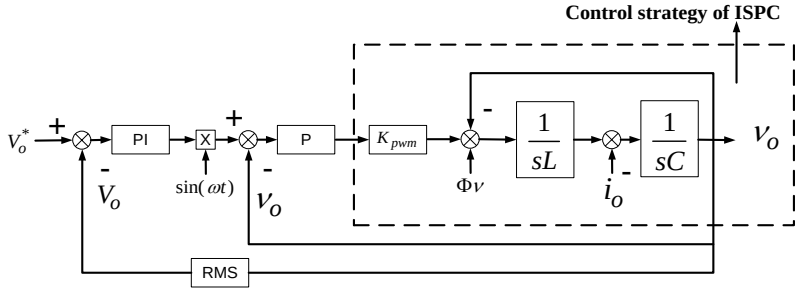

Figure 4. The control strategy of ISPC.

3. IGBT and Diode Fault Analysis in D-EPT

Figure 5 illustrates 14 different types of fault for IGBTs and diodes, which are numbered as RSPC Fault 1 (R1), RSPC Fault 2 (R2), RSPC Fault 3 (R3), RSPC Fault 4 (R4), DCPC Fault 1 (D1), DCPC Fault 2 (D2), DCPC Fault 3 (D3), DCPC Fault 4 (D4), DCPC Fault 5 (D5), DCPC Fault 6 (D6), ISPC Fault 1 (I1), ISPC Fault 2 (I2), ISPC Fault 3 (I3), and ISPC Fault 4 (I4). Only R1, D4, I1 and I4 faults are discussed, as the fault effects are similar for R3 and R4, D3 and D4, I1 and I2, I3 and I4 fault. The IGBTs and diodes that have the possibility to fail in D-EPT are marked in Figure 6.

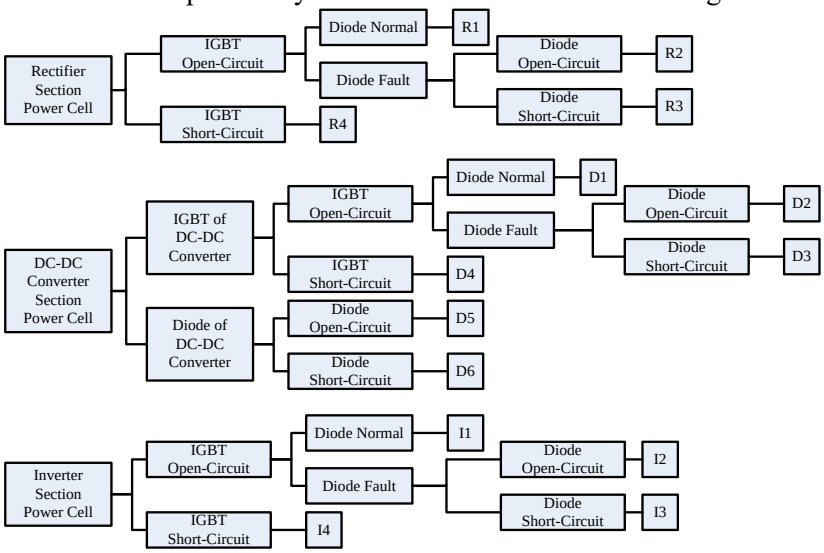

Figure 5. Types of IGBT and diode faults in D-EPT.

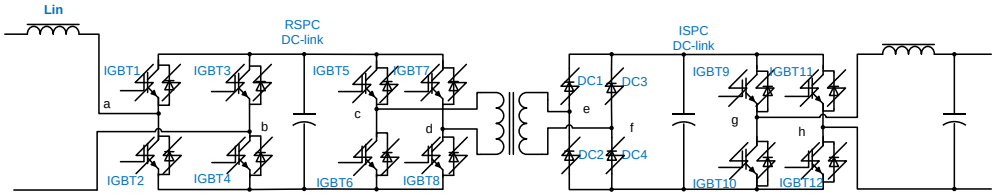

Figure 6. IGBT and diode failures in D-EPT.

3.1. Rectifier section power cell IGBT Open Circuit (R1)

Any failed IGBT in the full-bridge will lead to same result because of the CPS-SPWM schemes. Before the R1 fault, the current go through IGBT1 and IGBT3 when *Vs>0*. Assuming IGBT3 is open circuit, the current will then charge RSPC DC-link through the body diodes BD1 and BD4, which are shown in Figure 7(a). Therefore, the RSPC DC-link voltage will be different from other normal RSPC DC-link voltages.

3.2. Rectifier section power cell IGBT and body diode open circuit (R2)

In the normal operation, the voltage drop on IGBT2 equal to RSPC DC-link voltage, and can be described as:

$$V_{IGBT\,2} = V_{da} = V_s + L_{in}\frac{di}{dt} = V_{RSPC} \tag{4}$$

When R2 fault happens, the open circuit of IGBT1 equals to an open circuit resistor R in Figure 7(b), hence the voltage drop on IGBT2 equal to RSPC DC-link voltage adding open circuit resistor voltage, which is given by:

$$V_{IGBT\,2} = V_{da} = V_s + L_{in}\frac{di}{dt} = V_{RSPC} + V_R \tag{5}$$

The IGBT1 current will be reduced due to the open circuit resistor, hence the RSPC voltage will decrease and V_{IGBT2} will increase largely, which would cause over voltage on IGBT2.

3.3. Rectifier section power cell IGBT short circuit (R4)

As shown in Figure 7(c), the RSPC DC-link capacitors will be short circuit by conducting IGBT1 and IGBT2 simultaneously. As a result, the RSPC as well as ISPC DC-link voltage will be reduced and IGBT1 as well as IGBT2 will be over current.

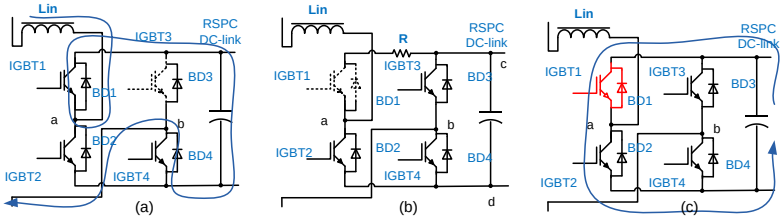

Figure 7. Current flow of RSPC for (a) Fault R1 (b) Fault R2 (c) Fault R4.

3.4. DC-DC converter section power cell IGBT open circuit (D1)

As shown in Figure 8(a), the DC-DC converter of DCPC acts like a two-switch forward converter when IGBT5 is open circuit, and the body diodes of BD5 and BD8 will prevent the magnetic flux of the HFT core build-up gradually.

3.5. DC-DC Converter section power cell IGBT and body diode open circuit (D2)

As shown in Figure 8(b), fault D2 makes the body diodes BD5 and BD8 impossible to prevent the saturation of transformer core, as the current to reset the magnetic flux is blocked.

3.6. DC-DC Converter section power cell IGBT short circuit (D4)

As shown in Figure 8(c), the RSPC DC-link capacitors will be short circuit by conducting IGBT5 and IGBT7 together. As a result, the RSPC as well as ISPC DC-link voltage will be reduced and IGBT5 as well as IGBT7 will be over current.

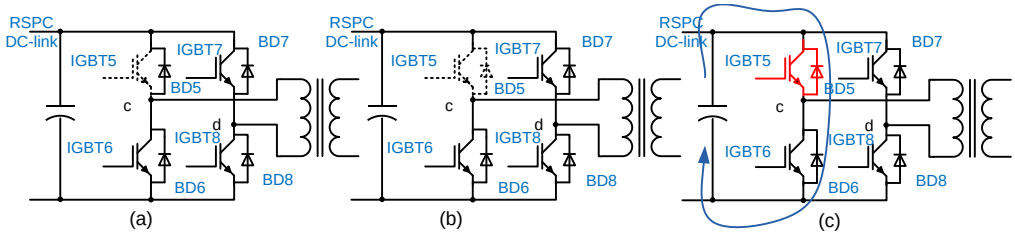

Figure 8. Current flow of DCPC for (a) Fault D1 (b) Fault D2 (c) Fault D4.

3.7. DC-DC Converter section power cell diode open circuit (D5)

As shown in Figure 9(a), the open circuit on RD1 will block the current flow from rectifier diodes RD1 and RD4. The energy of the current will be saved in the HFT and then releases by RD2 and RD3, which might cause over current on IGBTs of DC-DC converter, RD2 and RD3.

3.8. DC-DC Converter section power cell diode short circuit (D6)

As shown in Figure 9(b), the HFT will be shorted as RD1 and RD3 conducts together. As a result, RSPC as well as ISPC DC-link voltage will be reduced and RD1 as well as RD3 will be over current.

3.9. Inverter section power cell IGBT open circuit (I1)

As shown in Figure 9(c), the failure on IGBT9 forces inverter to work in the negative half cycle, making output current only flow in the negative half cycle.

3.10. Inverter section power cell IGBT short circuit (I4)

As shown in Figure 9(d), the faulty currents will connect the positive and negative poles of ISPC DC-link capacitors on one hand, and connect positive and negative poles of output filter on the other hand. As a result, the ISPC DC-link voltage and ISPC output voltage will be reduced, and IGBT9, IGBT10 and IGBT11 will be over current.

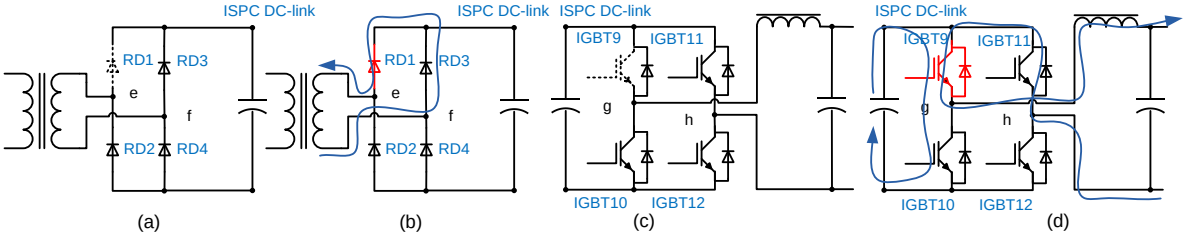

Figure 9. Current flow of DCPC for (a) Fault D5 (b) Fault D6, and Current flow of ISPC for (c) Fault I1 (d) Fault I4.

4. Simulation Results Switching Component Fault Analysis of D-EPT

The Saber simulation is performed based on the proposed D-EPT in Figure 1, which transforms the 10kV AC voltage (5774V in phase) to 400V AC voltage (230V in phase). The RSPC has 4 full bridge cascaded; hence there are 4 RSPC and ISPC DC-link voltages, 4 DCPC current as well as 4 ISPC output currents. The system parameters are designed as rectifier inductance 0.03 Henry, RSPC DC-link capacitance 0.003 Faraday, ISPC DC-link capacitance 0.23 Faraday and load impedance 1.9 ohm.

The failure IGBTs and diodes are in accordance with fault types illustrated in Figure 5, and the abbreviations “error1”, “error2”, “error3”, “error4” as well as “norm” in the summary based on saber simulation in Table 1 refer to errors including under voltage, over voltage, over current, currents unbalance as well as normal, respectively.

Table 1. Summary on IGBTs and diodes faults in D-EPT.

RSPC	**R1**	**R2**	**R3/R4**	**DCPC**	**D1**	**D2**	**D3/D4**	**D5**	**D6**	**ISPC**	**I1/I2**	**I3/I4**
PF	<0.99	<0.99	<0.99	PF	0.99	0.99	<0.99	0.99	<0.99	PF	0.99	<0.99
I_in	norm	norm	OC	I_in	norm	norm	error3	norm	error3	I_in	norm	error3
RSDC1	error1	error1	UV	RSDC1	norm	norm	error1	norm	error1	RSDC1	norm	error1
RSDC2	error1	error1	OV	RSDC2	norm	norm	error2	norm	error2	RSDC2	norm	error1
RSDC3	error1	error1	OV	RSDC3	norm	norm	error2	norm	error2	RSDC3	norm	error1
RSDC4	error1	error1	OV	RSDC4	norm	norm	error2	norm	error2	RSDC4	norm	error1
ISDC1	error1	error1	UV	ISDC1	norm	norm	error1	norm	error1	ISDC1	norm	error1
ISDC2	error1	error1	OV	ISDC2	norm	norm	error2	norm	error2	ISDC2	norm	error1
ISDC3	error1	error1	OV	ISDC3	norm	norm	error2	norm	error2	ISDC3	norm	error1
ISDC4	error1	error1	OV	ISDC4	norm	norm	error2	norm	error2	ISDC4	norm	error1
IGBT1	norm	error2	OC	IGBT5	norm	norm	error3	norm	error3	IGBT9	norm	error3
IGBT2	norm	error2	OC	IGBT6	norm	norm	error3	norm	norm	IGBT10	norm	error3
IGBT3	norm	norm	norm	IGBT7	error3	error3	norm	error3	error3	IGBT11	norm	error3
IGBT4	norm	norm	norm	IGBT8	error3	error3	norm	error3	norm	IGBT12	norm	error3
				It_1	norm	error3	norm	norm	error3	Io_1	error4	error4
				It_2	norm	norm	norm	norm	norm	Io_2	error4	error4
				It_3	norm	norm	norm	norm	norm	Io_3	error4	error4
				It_4	norm	norm	norm	norm	norm	Io_4	error4	error4

By monitoring the parameters mentioned in Table 1, almost all IGBT and diode fault can be identified and located by applying a fault location scheme in Figure 10. By monitoring input current, one can make a distinction between open circuit fault and short circuit fault, as the latter one always accompanies with over current and requires hardware protection circuit embedded in IGBT gate driver. The input power factor calculation program on input current can identify R4, D4, D6 and I4 fault. By monitoring DC-link voltages such as RSPC and ISPC DC-link voltages, one can check the voltage abnormality including over voltage, under voltage and voltage unbalance, which can tell I4 fault and R1 fault in Figure 10.

As faults like C1 and E1 will distort the HFT currents, the monitor on HFT currents on needed. Moreover, different algorithms are needed for the measurement on HFT currents, including RMS value for current unbalance, maximum value on amplitude for over current and average value for saturated core in HFT.

In order to identified G1 fault whose average value of output is not zero, both RMS value and average value calculation on ISPC output voltage and current are required.

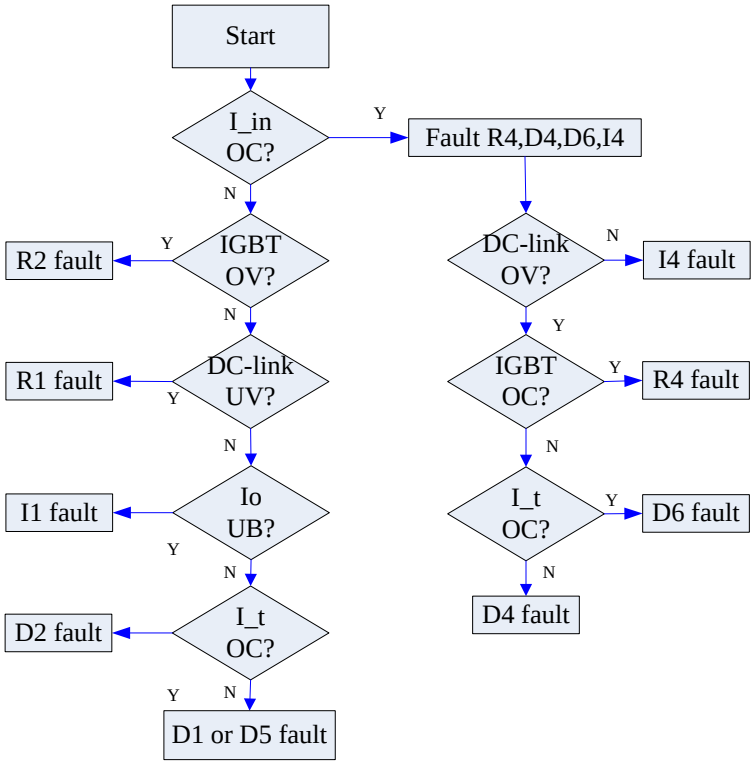

Figure 10. Flowchart of IGBT and diode fault location method.

5. Conclusions

Based on different types of IGBT and diode failures in Distribution Electronic Power Transformer (D-EPT), the theoretical analysis as well as the simulation results is presented. By monitoring abnormalities in parameters including input current, DC-link voltages, HFT currents, and ISPC voltages which are summarized in Table 1, the fault location scheme that is based on unique feature to each fault can be applied to identify the failure IGBT or diode.

Acknowledgments

This work was financially supported by the State Grid Hubei Electric Power Company Science and Technology Project (521538160010).

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