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Published in:
2021 IEEE 12th Energy Conversion Congress & Exposition - Asia (ECCE-Asia)

DOI (link to publication from Publisher):
10.1109/ECCE-Asia49820.2021.9479285

Publication date:
2021

Document Version
Early version, also known as pre-print

Link to publication from Aalborg University

Citation for published version (APA):
Open-Circuit Fault Analysis and Fault-Tolerant Control for 2/3-Level DAB Converters

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Abstract—Open-circuit faults (OCFs) on power switches are crucial issues for the two-three (2/3)-level dual-active-bridge (DAB) DC-DC converters, resulting in various performance degradation such as DC bias, overcurrent and capacitor voltage imbalance. There are two necessary steps for overcoming these problems, i.e., fault diagnosis and fault-tolerant control. In order to identify the faulty switch, the characteristics of the transient waveforms when the OCF occurs on each switch are analyzed in this paper. Based on the analysis, the midpoint voltage of each bridge arm is employed as the diagnosis signals. According to the mean values and duty cycles of the midpoint voltages, the faulty switch can be located accurately. Subsequently, a fault-tolerant control method called “complementary-switch-blocking” (CSB) is proposed through modulation reconfiguration. In the proposed CSB method, when one switch breaks down, the gate-driving signal of its complementary switch is blocked and the OCF effects can be offset. Finally, simulation results demonstrate that the OCF effects can be reduced significantly with the proposed fault-tolerant method, and the power transmission capacity can be improved compared with the traditional fault-tolerant method.

Keywords—DAB converter, open-circuit fault, fault diagnosis, fault-tolerant control.

I. INTRODUCTION

Solar energy is one of the fastest growing renewable energy driven by the strong demand for renewable energy, reduction in cost of photovoltaic (PV) modules, and the development of the PV technologies [1], [2]. Recently, medium-voltage DC (MVDC) structure is considered a promising solution for large-scale PV plants to increase the power capacity and improve the performances with higher efficiency and flexibility, and lower control complexity [3]. In the MVDC PV system, the interfacing DC-DC converter between the low-voltage DC (LVDC) bus and MVDC bus plays a key role, which should withstand high rated voltage and achieve high step-up ratio. Dual-active-bridge (DAB) DC-DC converters have a wide range of applications in the LVDC systems, due to the advantages such as high power density, current isolation and soft-switching capability. However, limited by the performance and reliability of MV power semiconductors, it is challenging to interface the MVDC network with a traditional two-level DAB converter. Compared with two-level DAB converters, the two-three (2/3)-level DAB converters, as shown in Fig. 1, have a higher voltage blocking capability, and provide more control degrees of freedom (DoFs) to further improve the performance with the neutral point-clamped (NPC) bridge in the MV side. Therefore, 2/3-level DAB converters have a high potential to be applied in medium-voltage DC systems [4].

Due to an increased number of power devices for the MV power electronics systems, ensuring their reliability is very crucial. According to previous studies, one of the most vulnerable component in power electronics applications is the power semiconductors [5]. Beside, the gate drivers are also a factor which is prone to failure. As a result, open-circuit faults (OCFs) for the converters account for a large proportion of reliability research. When the OCFs occurs on the DAB converters, the terminal voltage waveforms of the transformer will be asymmetrical, resulting in the DC bias, overcurrent, capacitor voltage imbalance and other issues. These effects will increase the voltage and current stresses on the power devices, and threaten the safety and reliability of the DAB converters with long term operation [6]. In order to overcome these issues, two steps should be taken, i.e., fault diagnosis and fault-tolerant control.

For fault diagnosis, the methods require simple, fast, and accurate detection. Some fault diagnosis methods have been proposed based on the residual analysis, circuit analysis, and DC components of phase currents for the two-level DAB converters, matrix converters, and three-phase DAB converters, respectively [7]–[9]. However, they can merely determine the faulty bridge arm rather than the accurate switch. In [10]–[12], fault diagnosis methods are applied based on the midpoint voltage of each bridge arm. However, these methods are proposed for the two-level DAB converters. When the midpoint voltages are employed as the diagnosis signals for the 2/3-level DAB converters, the diagnosis process should be redesigned, because the midpoint voltage waveform in the NPC bridge is different from that in the two-level full bridge.

After fault diagnosis has been carried out, the fault-tolerant control method should be applied to eliminate the OCF effects and ensure safe operation of the DAB converters. In [9], a fault-tolerant control method was proposed for the three-phase DAB converters. When the faulty bridge arm is located, it will be disabled and the converters will operate in single-phase state. This method is simple but not suitable for the single-phase DAB converters due to its limited redundancy. A fault-tolerant method called “primary side lower power - secondary side bypass arm” (PLP-SBA) has been proposed and applied to the two-level DAB converters [11], [12]. In this method, when the OCF occurs on the switch in the primary side, the transferred power is reduced to ensure that the maximum inductor current is within the rated value. On the other hand, if the OCF occurs on the switch in the
II. OPEN-CIRCUIT FAULT ANALYSIS AND FAULT DIAGNOSIS

A. OCF effects and fault modes analysis

As shown in Fig. 1, \( V_1 \) and \( V_2 \) are the two DC-link voltages. \( v_{ab} \) and \( v_{cd} \) are the AC terminal voltages of the isolated transformer with the turns ratio \( n \). \( L_c \) is the series inductor, and \( i_L \) denotes the inductor current of \( L_c \). \( o \) is the midpoint of the two capacitors \( C_2 \) and \( C_3 \), and \( g \) is the negative output point of the NPC bridge. Phase-shift control is the most popular control scheme for the DAB converters, as shown in Fig. 2, in which \( T_{sw} \) is a half switching cycle. The magnitude of the transferred power is adjusted by the phase-shift ratio \( D \) between the two bridges, whose range is \( 0 < D \leq 0.5 \).

From Fig. 2, it can be seen that in the normal state, the waveforms of the voltages and inductor current are symmetric over one switching cycle. Therefore, there is no DC bias in \( i_L \). However, when the OCF occurs on the switch in the NPC leg, the symmetry will no longer be maintained, and the waveforms of \( v_{cd} \) and \( i_L \) will be affected. Note that the OCF analysis for the full bridge in the LV side can be achieved in the same way as it has been done for the two-level DAB converters. Therefore, we focus on the OCFs in the MV side in this paper.

To analyze the distortion of the waveforms caused by OCFs clearly, the detailed switching characteristics when the OCF occurs on \( S_21 \) are discussed, as shown in Fig. 3. In Fig. 3, \( v_{cd} \) and \( v_{dg} \) are the midpoint voltages of the two bridge arms in the MV side, and \( t_0 \) is the first zero-crossing point of \( i_L \) during one switching cycle. It can be seen that compared with the normal state, the waveform of \( v_{cd} \) is distorted during the interval \([A, B]\), whose value reduces from \( V_2 \) to \( 0.5V_2 \). This is because during the interval \([A, B]\), \( i_L \) becomes negative. During the normal operation, where \( S_21 \) can function properly, the current will flow through \( S_21 \), \( S_22 \), \( S_27 \) and \( S_28 \), as shown in Fig. 4 (a). However, when the OCF occurs on \( S_21 \), the current draws from the midpoint \( o \), will flow through \( D_1 \) instead of \( S_21 \), as shown in Fig. 4 (b). In this condition, the value of \( v_{cd} \) decreases to \( 0.5V_2 \). Furthermore, in the normal state, the waveforms of the midpoint voltages \( v_{cd} \) and \( v_{dg} \) are square waves with 50% duty cycle. However, during the faulty interval \([A, B]\), from Fig. 4 (b), it can be seen that the value of \( v_{cd} \) also decreases from \( V_2 \) to \( 0.5V_2 \).

According to the fault analysis, the waveform of \( v_{cd} \) is not symmetric in one switching cycle. The slope and value of the inductor current \( i_L \) is determined by the two voltages \( v_{ab} \) and \( v_{cd} \), which can be seen from the expression of \( i_L \).
voltages different from each other for the eight switches. In this paper, be located accurately, because the midpoint voltages are

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... the faulty-state waveforms when the OCF occurs on the first bridge arm, the waveform of

... switches has OCF. Fortunately, if the midpoint voltages

... the faulty switch is located in one certain arm. Because the faulty conditions when the OCF occurs on the first arm and the

... second arm are similar, only the condition for the fault in the first arm is analyzed in detail in the following two steps.

Step 2: When the mean value of $v_{dg}$ is less than $0.5V_2 - \alpha$, the faulty switch can be located on S21 or S22. Otherwise, when it is larger than $0.5V_2 + \alpha$, the faulty switch can be located on S23 or S24. Note that $\alpha$ is the threshold voltage to regulate the sensitivity of the diagnosis method and avoid false operation.

Step 3: The faulty switch is located accurately by waveforms transition. The main aim of the waveforms transition is to convert the waveforms of $v_{cg}$ to square waveforms and differentiate them according to their duty cycles. The details of the waveforms transition can be seen in Fig. 7 (b). After the waveforms transition, the faulty switch can be differentiated between S21 and S22, as well as between S23 and S24 based on the duty cycle of the final signal $v_{oc}$. It should be noted that $\beta$ is also a threshold value for calculating the duty cycle of the final signal $v_{oc}$, which is mainly determined by the dead time.

III. PROPOSED FAULT-TOLERANT CONTROL METHOD

After identifying the faulty switch, the fault-tolerant control scheme should be employed to overcome the OCF issues. In previous research about the secondary-side-bypass-arm (SBA) method, the transferred power range was only considered when $k = 1$. Therefore, in this section, both the SBA method and the proposed CSB method will be analyzed, to make a comprehensive comparison.

A. Traditional SBA method

In the SBA method, when one of the four switches in a bridge arm is detected to be faulty, the gate-driving signals of the other three switches should be blocked to overcome the OCF effects. Fig. 8 gives the equivalent structures of the NPC bridge after employing the SBA method. For such equivalent structures, the steady-state waveforms of $v_{ab}$, $v_{cd}$ and $i_o$ during one switching cycle are shown in Fig. 9. Fig. 9 (a) and (b) are the waveforms in high power range and low power range, respectively, which are defined as Mode 1 and Mode 2. Due to the symmetry of $i_o$ in one switching cycle, and according to the expression of $i_o$ as shown in (1), the expressions of $i_0$ of Mode 1 and Mode 2 can be obtained as

$$i_0 = \begin{cases} k(1 + D)T_{0o}/(2k + 1) & \text{Mode 1} \\ DT_{0o}/(1 - k) & \text{Mode 2} \end{cases}$$

The unified expression of the power $P$ can be described as (3), and the normalized power $P_0$ can be calculated as (4), where $P_0 = V_1 V_2 T_{0o}/4nLr$ is the maximum power.

$$P = \frac{1}{T_{0o}} \int_{t_0}^{t_0 + T} v_{ab}(t) i_o(t) dt$$

$$P_0 = \frac{P}{P_N} = \begin{cases} 2(-t_0^2 - 2kt_0 - D^2 + 2D + k - 1), & \text{Mode 1} \\ 2(-t_0^2 + 2Dt_0 - D^2), & \text{Mode 2} \end{cases}$$

From Fig. 9, it can be seen that the range of $i_0$ in Mode 1 is $0 \leq i_0 \leq D$, and in Mode 2, $D \leq i_0 \leq 1$. Combining the ranges with (2) and (4), the power range by using the SBA method can be obtained as

$$\begin{cases} -2k^2 + 2k < P_0 \leq (4k^2 + 4k - 1)/(2k + 1)^2, & \text{Mode 1} \\ 0 \leq P_0 \leq -2k^2 + 2k, & \text{Mode 2} \end{cases}$$
in the second arm.

From Fig. 6, it can be seen that when the OCF occurs on S24 or S25, the impact is similar with the above description. Therefore, when S21 is identified as the faulty switch, blocking the gate-driving signal of S24 or S25 can reduce the impact on the waveforms distortion of \(v_{cd}\) and \(i_L\). When the OCF occurs on S21, from Fig. 4 (b), it can be seen that at the faulty interval \([t_0T_{th}, (1+D)T_{th}]\), the current \(i_0\) draws from the midpoint \(o\). Fig. 11 (a) and (b) show the current flow paths during the interval \([t_0T_{th}, DT_{th}]\) when blocking the gate-driving signal of S24 and S25 is blocked, respectively. From Fig. 11 (a), it can be seen that the current \(i_0\) will inject into midpoint \(o\). Therefore, when choosing S24 as the complementary switch to S21, the total charge injected into and drawn from the midpoint \(o\) will be equal to zero in one switching cycle, and the capacitor voltage balancing state can be guaranteed. However, from Fig. 11 (b), it can be seen that if S25 is chosen as the complementary switch to S21, the current \(i_0\) will also draw from \(o\), which will accelerate the capacitor voltage imbalance. Therefore, S21 and S24 are a pair of complementary switches for fault-tolerant control. When one of S21 and S24 is detected to be faulty, the gate-driving signal of another one should be blocked. Similarly, S22 and S23, S25 and S26, S27 and S28 are other three complementary-switch pairs. Noted that when the gate signals of S22 and S23, or S26 and S27 are blocked, there is no current flow path on the four switches in the bridge arm. Therefore, the switching characteristics are similar to those in the SBA method. Thus, for the proposed CSB method, only two complementary pairs S21 and S24, S25 and S28 need to be further discussed.

When the OCF occurs on S21 or S24, and S25 or S28, the equivalent structures of the NPC bridge after employing the proposed CSB method are shown in Fig. 12. The steady-state waveforms during one switching cycle are shown in Fig. 13. Fig. 13 (a) and (b) are the waveforms in high power range and
low power range, respectively, which are defined as Mode 3 and Mode 4. The expressions of the zero-crossing point $t_0$, the transferred power, and the power range can be calculated as those in the SBA method, and the transferred power range can be obtained as

$$2^{n-2}k^2 + k + 1)/3 < P_k < (16k^2 + 24k + 5)/(4k + 3)^2, \quad \text{Mode 3}$$

$$0 < P_k < 2^{n-2}(k^2 + k + 1)/3, \quad \text{Mode 4}$$

The power-transfer capacity of the SBA and the proposed CSB method is shown in Fig. 14, where the upper boundaries of the power ranges for the two methods are illustrated. It can be seen that with variable values of $k$, the maximum power with the proposed CSB method is higher than that of the SBA method, which means the converters increase the power transmission capacity by employing the CSB method, especially when $k$ is much lower than unity.

**IV. SIMULATION RESULTS**

To verify the performances of the proposed fault-tolerant control method, simulation results are provided. The main parameters are: the input voltage is 200 V, the transformer turns ratio $n$ is 1, the auxiliary inductor is 100 μH, the capacitors $C_1$, $C_2$, and $C_3$ are 1 mF, and the switching frequency is 10 kHz.

Fig. 15 shows the waveforms when the OCF occurs on $S_{21}$, where the reference output voltage is 300 V ($k = 0.67$), and the transferred power is 4500 W. It can be seen that under the OCF state, the waveform of $v_{cd}$ becomes asymmetric, where the DC bias occurs and the current stress increases significantly. Fig. 16 shows the simulation waveforms of the two capacitor voltages $V_{C2}$ and $V_{C3}$. It can be seen that during the faulty state, the value of $V_{C2}$ increases, because the current $i_o$ draws from the midpoint $o$, and upper capacitor charges during the faulty interval, resulting in the capacitor voltage imbalance.

Fig. 17 shows the waveforms with the SBA method. It should be noted that the system is controlled by a closed-loop control scheme. From Fig. 17, it can be seen that when the SBA method is employed, the DC bias and the overshoot current can be eliminated. However, the output voltage
decreases significantly, which means the reference voltage and power cannot be achieved by using the SBA method, even with the largest phase-shift ratio \( D \) regulating by PI controller.

Fig. 18 shows the waveforms with the proposed CSB method. From Fig. 18, it can be seen that by using the CSB method, the DC bias and overshoot current are eliminated. Therefore, the CSB method can bring the 2/3-level DAB converter back to the safe operation. Furthermore, according to the waveform of the output voltage \( V_2 \), it can be seen that the reference output voltage can be achieved by the closed-loop control, which means the power range is wider than that with the SBA method.

In addition, to verify that \( S_{24} \) is the complementary switch of \( S_{21} \) rather than \( S_{25} \), the waveforms of \( V_{C2} \) and \( V_{C3} \) when blocking the gate-driving signal of \( S_{24} \) and \( S_{25} \) are shown in Fig. 19. From Fig. 19 (a), it can be seen that when OCF occurs on \( S_{21} \), and the gate-driving signal of \( S_{24} \) is blocked, the values of the capacitor voltages \( V_{C2} \) and \( V_{C3} \) remain equal during the fault-tolerant operation. However, when the gate-driving signal of \( S_{25} \) is blocked, from Fig. 19 (b), it can be seen that compared with Fig. 16, the capacitor voltage imbalance condition will be exacerbated, which verify the theoretical analysis about the complementary-switch pairs.

V. CONCLUSION

This paper proposed a fault diagnosis and fault-tolerant control method for the 2/3-level DAB converters to address the open-circuit faults. The detailed analysis of OCFs on each power switch was discussed. Based on the analysis, a fault diagnosis method by using the midpoint voltage of each bridge arm is derived to identify the faulty power switch accurately. Furthermore, a fault-tolerant control method is proposed to overcome the OCF effects such as DC bias, overshoot current and capacitor voltage imbalance. In this method, every two power switches form a complementary pair. When one of them is detected to be faulty, the gate signal of another one will also be blocked. Simulation results have verified that the DC bias and overshoot current can be reduced with the proposed CSB method, and the power transfer capability is increased compared with the traditional fault-tolerant method, improving the reliability performance of the 2/3-level DAB converters.

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