Open-Circuit Fault Diagnosis for Cascaded H-Bridge Multilevel Inverter Based on LS-PWM Technique

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Abstract—Multilevel inverters have been widely used in high voltage and high-power applications on account of their remarkable performance in recent years. The multilevel inverters have an increased chance of switch fault due to a considerably large number of semiconductor switches associated with the power conversion. Therefore it is crucial to detect and locate faults quickly. In this context, an open-circuit fault diagnosis method for cascaded H-bridge multilevel inverter (CHBMI) based on the level-shifted pulse width modulation (LS-PWM) technique is proposed. Unlike the fault diagnosis based on the algorithm, the proposed method only needs a certain logical judgment to diagnose the fault based on subtle fault characteristics. The output voltage of the H-bridge and load current are used for fault diagnosis.

Index Terms—Cascaded H-bridge multilevel inverter, fault diagnosis, level shifted pulse width modulation, open-circuit fault.

I. INTRODUCTION

CASCADED H-bridge multilevel inverter (CHBMI) constructed by series-connected H-bridges, is a popular multilevel topology. Compared with the diode-clamped [1]–[3] and flying capacitor multilevel topologies [4]–[6], the topology of CHBMI is more suitable for the systems supplied by multiple independent DC sources. The CHBMI is composed of several cascaded monomers without using many diodes or capacitors, which reduces the cost of the system. It is highly modular and easy to implement and install when extending to higher voltage levels. The control of each cascade monomer can be independent of each other. The capacitor voltage imbalance is avoided, and the output waveform distortion rate is low. The power factor and efficiency of the system are very high, and the pollution to the grid is small. Therefore, the cascaded H-bridge inverter is widely used.

Transistors in CHBMI, mainly insulated gate bipolar transistors (IGBTs), could suffer from short-circuit (SC) and open-circuit (OC) faults [7]–[9]. Because the SC fault occurs quickly and is difficult to detect, the diagnosis and system protection of SC fault are mainly solved by hardware circuit design. The SC

fault can also be converted into an OC fault for processing by connecting the fast fuse to the circuit [10]. When the OC fault occurs, the system will operate continuously, which leads to some problems of non-fault power semiconductor devices such as flowing through more current, torque reduction, heating, and insulation damage. More severely, the whole system could be paralyzed [11]. At present, the research on fault diagnosis of multilevel inverters mainly focuses on OC faults. Therefore, it is significant to develop fast and accurate transistor OC fault diagnosis methods.

Transistor OC fault diagnosis methods can be generally categorized as current signal-based, voltage signal-based, and model-based methods. Current vectors [12], average currents [13], current reference errors [14], near-zero currents [15] and so on, can be utilized for transistor OC fault diagnosis. The fault diagnosis methods based on AC harmonic analysis are presented in [16], and the method based on current processed with an adaptive neuro-fuzzy inference system is proposed in [17]. The problems of these methods include slow diagnosis speed and low accuracy. The method based on the DC component of specific sampling current introduced in [18] can detect the faulty transistors, but this method can only be applied to the rectifying mode (RM), and the diagnosis time is also long.

Voltage signals, such as bridge arm pole voltages [19], bridge arm pole-to-pole (PTP) voltages [20], and gate voltages [21], can be used for transistor OC fault diagnosis. These methods can detect and identify the faulty transistor fast, but extra fault diagnosis circuits are needed, which increases cost, PCB size, and design complexity.

For the model, several model-based methods have been proposed for transistor OC fault diagnosis. An adaptive system is developed to observe the phase voltage distortions for diagnosis [22]. A dynamic model with mixed logic is built to estimate the deviations between the expected and the measured motor currents for fault identification [23]. In [24], a voltage observer is built to obtain the errors between the reference and the estimated output voltage. In [25], the current Luenberger observer model is implemented for diagnosis in back-to-back converters of permanent magnet synchronous generator (PMSG) drives. These methods have achieved significant advancements, but the detection speed still needs improvement, and the sampling frequency needs to be higher than the switching frequency, which would be an obstacle for application in high-frequency

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TABLE I
THE DIFFERENCE BETWEEN SCHEMES I AND II

	The required signal	Detection time (ms)	Number of sensors	Number of levels	Increase of switching frequency
Scheme I	driving signals, voltage or current	0.11(error 3%)	3	5	yes
Scheme II	voltage and current	around 0.4	2	3	no

inverters.

The literature review shows that previous fault diagnosis methods may have some limitations, such as adding extra circuits, incapability of fault identification, high sampling frequency, and long diagnosis time. In order to handle these problems, this paper presents a fault diagnosis method based on the LS-PWM technique.

Table I shows the difference between the proposed method (Scheme I) and the prior state-of-the art scheme [26] (Scheme II).

The major contributions of this paper can be summarized as follows:

- 1) A new fault characteristic is discovered for the cascaded five-level inverter. After fault occurs, the output voltage of the bridge arm will completely vanish during specific half periods under other modulation methods, but only part of the output voltage of the bridge arm based on LS-PWM will vanish, which can be utilized for diagnosing. Driving signals are introduced as diagnostic variables at the same time.
- 2) The diagnosis logic is put forward according to the new fault characteristics.
- 3) The detection time is improved based on the LS-PWM technique.
- 4) The number of levels is increased.
- 5) The switching frequency is increased.

The rest of the paper is organized as follows: The principle of CHBMI and the analysis of fault characteristics based on the LS-PWM technique are given in Section II. The proposed fault diagnosis method are given in Section III. The results of the experiment are demonstrated in Section IV. Lastly, Section V summarizes the paper.

II. THE PRINCIPLE OF CHBMI AND THE ANALYSIS OF FAULT CHARACTERISTICS

A. Operating Principle of CHBMI

The topological structure of a single-phase cascaded five-level inverter is shown in Fig. 1. The CHBMI includes two H-bridges, eight switches (S_1 – S_8) with healthy anti-parallel diode (D_1 – D_8), filter capacitor C , DC voltage source U_{dc} , LC filter, and inductive load. G_1 – G_8 are driving signals, respectively. In this paper, the CHBMI is controlled with a dual loop, where the output voltage of the H-bridge (v_{o1} , v_{o2}) and load current (i_l) are sampled for control. The relationship between the output voltage v_o and the switching state based on the LS-

Fig. 1. The topological structure of single-phase cascaded five-level inverter.

TABLE II
RELATIONSHIP BETWEEN V_o AND S_x

v_o	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8
$2U_{dc}$	1	0	0	1	1	0	0	1
U_{dc}	1	0	0	1	0	1	0	1
0	0	1	0	1	0	1	0	1
$-U_{dc}$	0	1	1	0	0	1	0	1
$-2U_{dc}$	0	1	1	0	0	1	1	0

PWM technique is shown in Table II, where 1 represents on, and 0 represents off.

For CHBMI, the number of output levels (m) is always odd. The number of output voltage levels from CHBMI is given in (1), and the number of the switch (X) can be derived in (2), where N is the number of series-connected H-bridge power cells and n is the number of carrier.

$$m = 2N + 1 = n + 1 \quad (1)$$

$$X = 2(m - 1) \quad (2)$$

LS-PWM and phase-shifted PWM (PS-PWM) are usually used for carrier-based PWM methods. LS-PWM has lower input current and output voltage distortion comparing with PS-PWM. There are three types in the LS-PWM method because of space and phase differences: PD PWM, phase opposite disposition (POD) PWM, and alternate phase opposite disposition (APOD) PWM. These control strategies generate slightly different output waveforms, which are reflected in the change of the harmonic spectrum. The PD PWM has better harmonic performance than the other two methods [27]–[28]. Therefore, PD PWM is selected as the control strategy in the paper.

B. Analysis of Fault Characteristics

The following terminologies are defined: the OC fault occurred in the switch S_x is represented as S_{xoc} ; the load current is represented as i_l , and it is negative to the left and positive to the right; the output voltage of the H-bridge 1 and 2 is represented as v_{o1} and v_{o2} ; the CHBMI output voltage and current is represented as $v_{o|oc}$ which can be derived in (3) and $i_{l|oc}$ during

Fig. 2. Fault characteristics of S_{1oc} and S_{4oc} . (a) Load current path under S_{1oc} . (b) Load current path under S_{4oc} . (c) The relationship between the four driving signals, the switch voltage in S_1 and S_2 , the output voltage (v_{o1loc}) and load current under S_{1oc} . (d) The relationship between the four driving signals, the switch voltage in S_3 and S_4 , the output voltage (v_{o1loc}) and load current under S_{4oc} .

Fig. 3. Fault characteristics of S_{5oc} and S_{8oc} . (a) The relationship between the four driving signals, the switch voltage in S_5 and S_6 , the output voltage (v_{o2loc}) and load current under S_{5oc} . (b) The relationship between the four driving signals, the switch voltage in S_7 and S_8 , the output voltage (v_{o2loc}) and load current under S_{8oc} .

the fault respectively. The influence of OC fault on the output

voltage can be reflected on the output voltage of the H-bridge where the fault switch is located. At this time, it is assumed that two H-bridges start to work simultaneously, so a load ($Load_1$) is assumed on H-bridge 1 to analyze the current direction conveniently. The fault characteristics of the H-bridge will be analyzed in the following sections.

$$v_{o1oc} = v_{o1loc} + v_{o2loc} \quad (3)$$

Where v_{o1loc} and v_{o2loc} are the output voltage of the H-bridge 1 and 2 during the fault.

For the CHBML, S_1 and S_4 are taken as examples, and the analyses of other switches are similar. Fig. 2 shows the fault characteristics of S_{1oc} and S_{4oc} . The red arrows in Fig. 2 are load current paths, and they can not be omitted. The following is a detailed analysis of the fault characteristics of S_1 and S_4 .

The switching waveforms under S_{1oc} can be discussed for two cases as follows:

- 1) $S_1 = S_4 = 1, S_2 = S_3 = 0$, the switch voltages across $U_{S1} \approx U_{dc}, U_{S2} \approx 0, v_{o1loc} \approx 0, i_{lloc} > 0$.
- 2) $S_2 = S_4 = 1, S_1 = S_3 = 0$, the switch voltages across $U_{S1} \approx U_{dc}, U_{S2} \approx 0, v_{o1loc} \approx 0, i_{lloc} > 0$.

The load current path is same in either case. Also, the switching waveforms under S_{4oc} can be divided into two cases and analyzed as follows:

- 3) $S_1 = S_4 = 1, S_2 = S_3 = 0$, the switch voltages across $U_{S3} \approx 0, U_{S4} \approx U_{dc}, v_{o1loc} \approx 0, i_{lloc} > 0$.
- 4) $S_2 = S_4 = 1, S_1 = S_3 = 0$, the switch voltages across $U_{S3} \approx 0, U_{S4} \approx U_{dc}, v_{o1loc} \approx -U_{dc}, i_{lloc} > 0$.

The above squiggly equals sign is generated by taking into account the on-state voltage drop of the diode.

Fig. 4. The PD LS-PWM signals.

TABLE III
WORKING MODES

Working modes	Mode 1	Mode 2	Mode 3	Mode 4
v_m	positive	negative	positive	negative
i_l	positive	negative	negative	positive

Fig. 2 (a) and (b) shows the load current path under S_{1oc} and S_{4oc} . The variation of the output voltage in the H-bridge 1 under S_{1oc} and S_{4oc} can be seen in Fig. 2 (c) and (d), respectively. The variation of the output voltage in the H-bridge 2 under S_{5oc} and S_{8oc} can be seen in Fig. 3 (a) and (b), respectively.

The five-level inverter output voltage is generated by four level-shifted carriers in a phase-disposition (PD) pattern. The generation of PD LS-PWM signals is shown in Fig. 4, where the driving signals are the result of a comparison between the modulating sinusoidal signal $v_m(t)$ and four amplitude shifted high-frequency triangular carrier signals $c_1(t)$ – $c_4(t)$. The healthy operation of CHBML with inductive load can be divided into four working modes according to the voltage and current characteristics as shown in Table III, where v_m is the modulating sinusoidal signal and i_l is the load current. The CHBML is only running in these four modes with inductive load under normal circumstances. The output voltage of the faulty H-bridge, load current, and the corresponding working mode under S_{1oc} – S_{8oc} are shown in Fig. 5.

As shown in Fig. 5, the diagonal switches show fault characteristics in the same working mode for each H-bridge (the red rectangle) in fault. It only needs to detect the fault in the two modes (mode 1, 2), which significantly reduces the calculation of the system. In order to distinguish diagonal fault switches in the same working mode, the following fault characteristics are found through the above analysis: the value of $v_{o1loc} \approx 0$ if $G_1 = 0$ under S_{1oc} ; the value of $v_{o1loc} \approx 0$ if $G_1 = 1$ and $v_{o1loc} \approx -U_{dc}$ if $G_1 = 0$ under S_{4oc} ; the value of $v_{o1loc} \approx 0$ if $G_3 = 1$ and $v_{o1loc} \approx U_{dc}$ if $G_3 = 0$ under S_{2oc} ; the value of $v_{o1loc} \approx 0$ if $G_3 = 0$ under S_{3oc} ; the value of $v_{o2loc} \approx 0$ if $G_5 = 0$ under S_{5oc} ; the value of $v_{o2loc} \approx 0$ if $G_5 = 1$ and $v_{o2loc} \approx -U_{dc}$ if $G_5 = 0$ under S_{8oc} ; the value of $v_{o2loc} \approx 0$ if $G_7 = 1$ and $v_{o2loc} \approx U_{dc}$ if $G_7 = 0$ under S_{6oc} ; the value of $v_{o2loc} \approx 0$ if $G_7 = 0$ under S_{7oc} . However, for the H-bridge 2, when the fault occurs in the time range (TR) as shown in Fig. 3 (b), the above diagnosis characteristics based on the driving signals are no longer applicable considering the system error. The start time of TR is defined as T_{s1} and T_{s2} for S_6 , S_7 . It is the current fluctuation that causes the voltage change during TR. By amplifying the load current and the bridge arm voltage as shown in Fig. 5, we can find the following fault characteristics: the value of $v_{o2loc} \approx 0$

Fig. 5. Fault characteristics and working modes under S_{1oc} – S_{8oc} .

if $i_{loc} > 0$ and $v_{o2loc} \approx U_{dc}$ if $i_{loc} < 0$ under S_{6oc} ; the value of $v_{o2loc} \approx 0$ if $i_{loc} < 0$ and $v_{o2loc} \approx -U_{dc}$ if $i_{loc} > 0$ under S_{8oc} .

III. THE PROPOSED FAULT DIAGNOSIS METHOD

Based on the analysis of switch fault characteristics, the

Fig. 6. Proposed fault diagnosis method.

Fig. 7. The generation of $A-F$ and K .

proposed fault diagnosis method is shown in Fig. 6. The fault diagnosis method is developed for load current i_l , the output voltage of each H-bridge, corresponding error v_{e1} and v_{e2} , and respective driving signals considering inductive load, where v_{e1} and v_{e2} are the unit resultant of actual H-bridge output voltage to reference H-bridge output voltage. The generation of $A-F$ and K is shown in Fig. 7. With regard to v_{e1} and v_{e2} , they usually vary in a range; v_{e1} belongs to the range from v_{o1l} to v_{o1h} , and v_{e2} pertains to the range from v_{o2l} to v_{o2h} in the healthy operation. f_1 and f_2 are constantly associated with system parameters. In order to improve reliability, w_1 and w_2 are taken as 2.5% and 3% respectively in this paper, where w_1 and w_2 are considered as the margin of error variation.

Whether it's H-bridge 1 or 2, make an identification on the working modes firstly. All diagnoses are made under mode 1 or 2. When the detection condition is not satisfied, that is $K=1$, the H-bridge output voltage does not need to be detected, and

TABLE IV
SYSTEM PARAMETERS

Symbol	Parameters	Value
U_{dc}	DC voltage	40 V
$f_o(=1/T_o)$	Fundamental frequency	50 Hz
f_c	Carrier frequency	3 kHz
L_f	Filter inductance	9.5 mH, 0.35 Ω
C_f	Filter capacitor	10 μ F, 0.03 Ω
C	Voltage stabilizing capacitance	20 mF
M	Modulation index	0.9
Z_L	Load impedance	8 Ω , 9 mH

TABLE V
PARAMETERS OF THE CONTROL LOOP

Symbol	Parameters	Value
K_{vp}	Proportion index of voltage loop	0.1
K_{vi}	Integration index of voltage loop	4.5
K_{ip}	Proportion index of current loop	0.01
K_{ii}	Integration index of current loop	0.01

the corresponding counter need to work, so the computation of the control system is greatly reduced. When the detection condition ($K=0$ or 2) is satisfied, the output voltage of the H-bridge needs to be detected to judge whether it is beyond the error range to obtain the corresponding driving signals. However, for the H-bridge 2, when the output voltage meets the

Fig. 8. H-bridge output voltage, load current, driving signals and fault detection signal under S_{2oc} , S_{3oc} , and S_{5oc} , S_{8oc} ($f_c = 3$ kHz).

detection conditions, judge the detected time range through the clock and counter first to determine whether the load current needs to be detected. Finally, the fault diagnosis is carried out according to the detected voltage, load current, and corresponding driving signals. After the fault switch is diagnosed, faulty switch isolation and fault-tolerant operation is put into effect to ensure the safe and stable operation of the system.

IV. EXPERIMENT ANALYSIS

Experiments have been carried out to prove the effectiveness of the proposed fault diagnosis method. The system parameters are detailed in Table IV. Parameters for the control system are given in Table V. System control and fault diagnosis are pro-

cessed with DSP TMS320F28335. By giving an external interrupt signal to DSP, the PWM signal that needs to turn off the switch is changed to a low level to realize the given OC fault. Meanwhile, set a certain delay in the logic detection module to consider the sensors' dynamic delay. S_{2oc} , S_{3oc} , and S_{5oc} , S_{8oc} are taken as examples for verification.

The waveforms of H-bridge output voltage, load current, driving signals, and fault detection signal under S_{2oc} , S_{3oc} , and S_{5oc} , S_{8oc} are presented in Fig. 8. For S_{2oc} , S_{3oc} , and S_{5oc} , S_{8oc} , fault occur at $t = t_1$ and t_4 , respectively. At $t = t_2$, t_3 , t_5 , t_6 , the fault is detected accordingly. Similarly, other switches have also achieved the same diagnostic results. All OC faults can be detected within one switching interval. Time of fault and time of fault detection under different switching frequencies (f_{sw}

TABLE VI
TIME OF FAULT AND TIME OF FAULT DETECTION UNDER DIFFERENT SWITCHING FREQUENCY

S _{2oc}				S _{3oc}			
Time of fault (ms)	Time of fault detection (ms)			Time of fault (ms)	Time of fault detection (ms)		
	$f_c = 3$ kHz	$f_c = 5$ kHz	$f_c = 7$ kHz		$f_c = 3$ kHz	$f_c = 5$ kHz	$f_c = 7$ kHz
16	0.1122	0.1125	0.1127	16	0.1119	0.1121	0.1126
16.5	0.1123	0.1123	0.1128	16.5	0.1117	0.1123	0.1126
17	0.1122	0.1126	0.1129	17	0.1119	0.1124	0.1128
17.5	0.1120	0.1124	0.1126	17.5	0.1120	0.1123	0.1127
18	0.1121	0.1125	0.1127	18	0.1118	0.1123	0.1126
Average	0.11216	0.11246	0.11274	Average	0.11186	0.11228	0.11266

S _{5oc}				S _{8oc}			
Time of fault (ms)	Time of fault detection (ms)			Time of fault (ms)	Time of fault detection (ms)		
	$f_c = 3$ kHz	$f_c = 5$ kHz	$f_c = 7$ kHz		$f_c = 3$ kHz	$f_c = 5$ kHz	$f_c = 7$ kHz
6	0.1119	0.1124	0.1127	6	0.1121	0.1126	0.1128
6.5	0.1118	0.1123	0.1127	6.5	0.1122	0.1126	0.1129
7	0.1119	0.1123	0.1126	7	0.1122	0.1124	0.1129
7.5	0.1119	0.1123	0.1128	7.5	0.1123	0.1126	0.1126
8	0.1121	0.1124	0.1126	8	0.1121	0.1125	0.1127
Average	0.11192	0.11234	0.11268	Average	0.11218	0.11254	0.11278

$= 2Nf_c$) are shown in Table VI. From Table VI, we can find that the diagnosis time of the lower switch of each H-bridge is slightly longer than that of the corresponding upper switch by setting different fault times. This is caused by the same logic value generated by the corresponding driving signal and output voltage when the fault occurs, so the fault can not be detected immediately, and it usually does not exceed a switching interval. Moreover, the detection time will be appropriately longer within the error tolerance when the switching frequency increases.

V. CONCLUSION

In this paper, a fault diagnosis method for CHBMI based on the LS-PWM technique is proposed. The OC fault results in the incomplete vanishment of the faulty H-bridge voltage, which can be detected by the proposed method. The fault can be detected within one switching period from the H-bridge output voltage change with a healthy output voltage state. Since the CHBMI output characteristics under diagonally opposite switch fault characteristics are challenging to identify, this paper presents a detection method to identify each faulty switch in the CHBMI uniquely. For IGBT-based inverters with a high switching frequency, the related experimental results have been given to demonstrate the effectiveness of the proposed method. However, for SiC or GaN-based inverters, further experiments are needed to verify it. The proposed diagnosis method may be used for

fault diagnosis of other multilevel inverters. Although the proposed method increases the number of sensors, it achieves the desired effect.

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