Open-Switch Fault Detection in Five-Level Hybrid Active Neutral-Point-Clamped Inverters

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ABSTRACT

This paper presents a creative and efficient approach for detecting open-switch faults in five-level hybrid active neutral-point-clamped (HANPC) inverter systems. The proposed open-switch faults detection technique offers significant advantages over existing methods, as it does not require any external hardware components or complex calculations, which helps reduce system costs and complexity. Alternatively, it uses a distorted reference voltage angle to classify the fault of each switch, making it an easier-to-implement and more effective solution for identifying open-switch faults. The approach is also safe to use during load and no-load trials, ensuring the protection and reliability of the system. Simulation results indicate the effectiveness of the proposed method for detecting and identifying open-switch faults in five-level HANPC inverters, which could potentially improve the overall performance and safety of these systems.

1. INTRODUCTION

Among multilevel inverters, five-level hybrid active neutral-point-clamped (HANPC) inverters have attracted much attention of industries and academia for various advantages over other traditional multilevel topologies [1]. These merits include but not limited to hybrid structure with few flying capacitors, capability to operate at high frequency domain, low d*v*/d*t*, and low stress on switching devices. In addition, this topology can be controlled by various pulse-width-modulation (PWM) schemes. The most interesting approach is phase-shift PWM due to its ease of implementation and natural balancing of voltage across dc-link and flying capacitors [2].

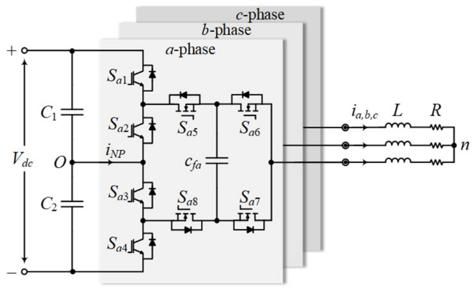

Fig.1 Circuit topology of a five-level HANPC inverter

Table 1 Switching status of five-level HANPC

Switching status	S_{a1}	S_{a2}	S_{a5}	S_{a6}	V_{an}
V_1	ON	OFF	ON	ON	$V_{dc}/2$
V_2	ON	OFF	ON	OFF	$V_{dc}/4$
V_3	ON	OFF	OFF	ON	$V_{dc}/4$
V_4	ON	OFF	OFF	OFF	0
V_5	OFF	ON	ON	ON	0
V_6	OFF	ON	ON	OFF	$-V_{dc}/4$
V_7	OFF	ON	OFF	ON	$-V_{dc}/4$
V_8	OFF	ON	OFF	OFF	$-V_{dc}/2$

However, to enhance the reliability of this inverter, a modification on the modulation scheme is necessary. This is a challenging task as the number of active switching devices in this topology is relatively high. The most cause of the system failure is from its active switching devices. Fast and effective fault detection is essential to reduce the maintenance cost. There have been few studies to detect the open-switch faults in three- [3] and five-level HANPC inverters [4]. However, these studies are complex and depending on information of phase current and its angle to identify the particular faulty switch.

To mitigate the drawbacks of the abovementioned approaches, a creative and efficient approach for detecting open-switch faults in five-level HANPC inverter is proposed. This technique does not require any external hardware components or complex calculations. Alternatively, it uses a

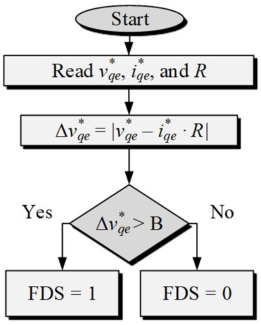

Fig.2 Proposed fault detection algorithm

Table 2 Proposed faults rules for different switching devices

Fault at	ΔV^*_{qe}	θ_{dqs}
S_{a1}	50 V > && < 90 V	[0° to 90°]
S_{a2}	7 V > && < 50 V	[90° to 120°]
S_{a5}	90 V > && < 320 V	[15° to 115°]
S_{a6}	320 V >	[30° to 150°]

distorted reference voltage angle to classify the fault of each switch, making it an easier-to-implement and more effective solution for identifying open-switch faults. The approach is also safe to use during load and no-load trials, ensuring the protection and reliability of the system.

2. FIVE-LEVEL HANPC INVERTER

2.1 Structure

Fig. 1 shows the circuit topology of a five-level HANPC inverter. It can be shown that this topology consists of three phases (*a*, *b*, and *c*). Each phase include eight active switching devices. Taking phase (a) as an example, the switching devices (S_{a1}–S_{a4}) are using Si-IGBT semiconductor switching devices. While (S_{a5}–S_{a8}) consists of SiC-MOSFET devices. It is also important to mention that a single flying capacitor (C_{fa}) is required for producing the five-level output voltage. Finally, dual dc-link capacitors (C1 and C2) are connected in series and separated by neutral-point (*O*). This hybrid topology has two types of switching devices to maintain an effective cost to performance as it is capable to operate in high frequency range to reduce the distortion of the output voltages and therefore reduce the output filter.

2.2 Operational Principle

Among PWM techniques, phase-shift PWM strategy is an effective in balancing the dc-link capacitors voltages and flying capacitor voltages, but it requires two inverted PWM carriers to

Table 3 System parameters

Item	Value	Unit
Dc−link voltage	600	V
Dc−link capacitor	4700	μF
Flying capacitor	30	μF
Load resistance	10	Ω
Load inductance	2	mH
Fundamental frequency	60	Hz
Switching frequency	30	kHz
Sampling time	100	μs

construct the five-level output pole voltage (V_{an}). Table 1 illustrates the eight possible switching statues of the five-level HANPC inverter, which can be achieved by the switching mechanism of the phase-shift PWM method. The switching devices S_{a1}–S_{a4} need to operate at fundamental frequency of 50 or 60 Hz, while S_{a5}–S_{a8} are turning ON or OFF depending on the PWM carrier frequency which can be as high as 30 kHz.

3. PROPOSED FAULT DETECTION METHOD

The proposed open-switch fault detection algorithm is given in Fig. 2. It can be seen from this figure that the proposed fault detection method is simple for identifying the faulty condition from the healthy. It depends on the reference q-axis voltage (V^*_{qe}) which should be within a small band (*B*) (i.e., 1%) of fixed value of the reference voltage magnitude, that can be obtained by considering i^*_{qe} and load resistance *R*. If the difference of V^*_{qe} (ΔV^*_{qe}) is greater than *B*, then the fault detection signal (FDS) is trigged and assigned as "1". Otherwise the healthy operation is identified as "0" when ΔV^*_{qe} is within *B*.

The second step is to classify the faults among switching devices of the five-level HANPC inverter (i.e., S_{a1}, S_{a2}, S_{a5}, or S_{a6}). It is worth mentioning that other switching devices in this system have similar behavior due to the symmetrical structure of this topology. Table 2 summarizes the proposed rules for identifying the location of open-switch fault. It is important to note that those rules depend on simple classification algorithm which takes into account ΔV^*_{qe} and angle between d- and q-axis stationary reference frame reference voltages (θ_{dqs}). Therefore, the proposed fault detection method can be very useful and safe to use during load and no-load tests. In addition, it does not require any additional components or sensors.

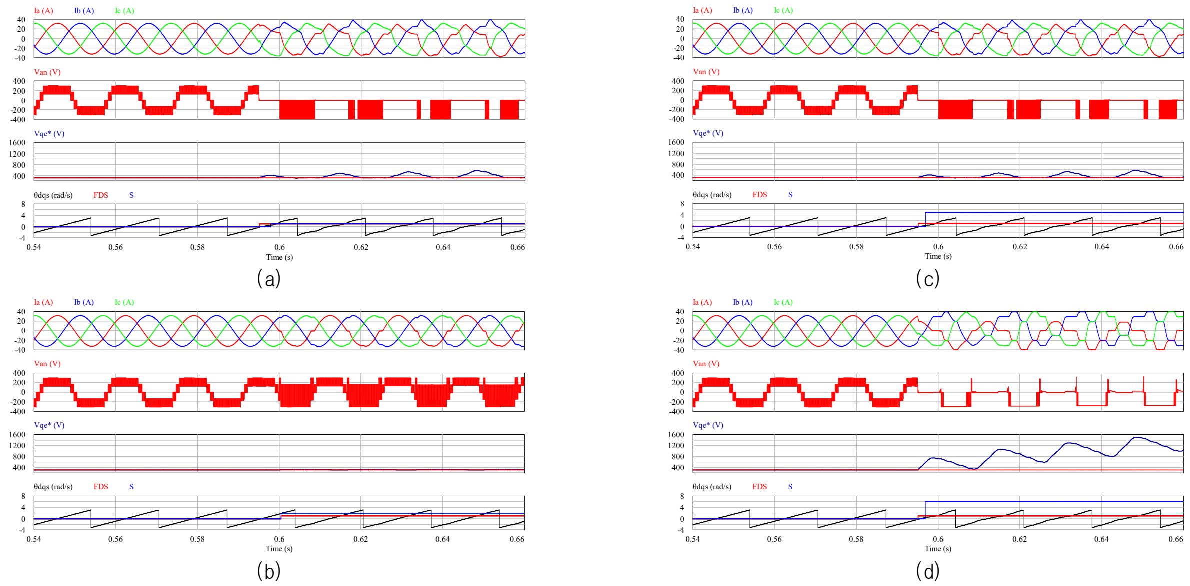

Fig.3 Performance analysis of five-level HANPC inverter under open-switch fault operation at (a) S_{a1}, S_{a2}, S_{a5}, and S_{a6}

4. SIMULATION RESULTS

This section provides a comprehensive simulation results which has been obtained from PSIM simulation tool. The full list of system parameters are present in Table 3. Fig. 3 shows the faulty operation of the five-level HANPC inverter during open-switch fault at S_{a1}, S_{a2}, S_{a5}, and S_{a6}. The open-switch fault has different level of distortion and impact on the system. For example, S_{a1} and S_{a5} have a moderate effect on the system as it can be seen from a dramatic increment in V_{qe}^{*}. While there is a slight change in V_{qe}^{*} during open-switch fault at S_{a2}. Nevertheless, the most critical case is when open-switch fault occurs at S_{a6}. Therefore, the proposed detection algorithm is effective in differentiating between healthy and faulty cases.

5. CONCLUSION

This paper proposes a cost-effective and efficient method for detecting open-switch faults in five-level HANPC inverter systems. The approach uses a distorted reference voltage angle to classify switch faults, making it simpler and more effective than existing methods. The proposed technique has been successfully tested in all possible cases and can improve the overall performance and safety of five-level HANPC inverters.

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