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An On-line Diagnostic Method for Open-circuit Switch Faults in NPC Multilevel Converters

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Abstract
On-line condition monitoring is of paramount importance for multilevel converters used in safety-critical applications. A novel on-line diagnostic method for detecting open-circuit switch faults in neutral-point-clamped (NPC) multilevel converters is introduced in this paper. The principle of this method is based on monitoring the abnormal variation of the dc-bus neutral-point current in combination with the existing information on instantaneous switching states and phase currents. Advantages of this method include simpler implementation and faster detection speed compared to other existing diagnostic methods in the literature. In this method, only one additional current sensor is required for measuring the dc-bus neutral-point current, therefore the implementation cost is low. Simulation and experimental results based on a lab-scale 50 kVA adjustable speed drive (ASD) with a three-level NPC inverter validate the efficacy of this novel diagnostic method.

SECTION I. Introduction

Safety and reliability have been two critical factors in evaluating power electronic systems. With the increase of power capacity demand and the decrease of semiconductor device cost, multilevel power converters are being intensively applied in industries, especially for high-power (above 0.75 MVA) or medium-voltage (2.3-13.8 kV) applications [1]. One concern raised by the utilization of multilevel converters is the degraded system reliability due to the large number of switching devices and the associated gate driver circuits involved. Thus, there is a necessity to more frequently detect and diagnose common device faults, such as short-circuit and open-circuit faults that could occur in semiconductor power devices of multilevel converter. Solutions to detect short-circuit faults in the switching devices in power electronic systems have received much attention in the past decades [2]. One technically mature method is the so-called “desaturation detection” method, the circuit of which has been integrated into most of commercial gate drivers [3]. However, detection of open-circuit faults in switching devices has not received adequate attention. As a matter of fact, open-circuit faults in power converters can occur more often in certain applications where the related electric drives are operated for prolonged periods at low output frequency and heavy load, such as in elevators, wind turbine power systems, electric vehicles (EVs) or hybrid electric vehicles (HEVs), and the like. In such low-speed and heavy-load operating modes, there would be high fluctuations of junction temperatures in power devices of the multilevel inverters, due to the mismatch of Coefficient of Thermal Expansion (CTE) among different component materials and the resulting large thermal-mechanical stress on the bond wires and soldering joints inside these devices. Such phenomena will cause open-circuit faults due to subsequent bond wire lift-off or solder cracking in the switching devices, as renorted in [4].

Given such reliability concerns, a few diagnostic methods for open-circuit faults in multilevel power converters have been presented in the literature [5]–[6][7][8]. In [5], an open-switch fault diagnostic method was developed based on detecting the dimensions and orientation angle of the so-called “Concordia current patterns”. Such current pattern is determined by plotting the instantaneous ac current components in the two-axis orthogonal reference frame, i_α versus i_β. Under any healthy condition, the Concordia current pattern should be a circle ideally, which is distorted into a semicircle or other geometrical patterns once there is an open-circuit switch fault in the inverter. In this method, it was assumed that the distortion of the current pattern for each IGBT open-circuit fault is unique, and therefore can be detected by pattern recognition techniques. This method could be effective under most of the normal conditions. However, the drawback with this method is that, such “Concordia current patterns” may be dependent from the load balance condition, which may cause misdiagnosis of such open-circuit switch faults. Similarly, one more diagnostic method, the so-called “the average current park's vector approach”, was introduced in [6], for detecting open-circuit switch faults in a three-level NPC inverter. The fault detection in this method relies on the analysis of the Park's vectors [7] of the mean value of each inverter output ac current over one fundamental period. The advantages of this method are the noninvasive characteristics and no requirements on additional hardware or sensors. However, as clarified in [6], this method can only identify pairs of switch faults and is incapable to detect each unique switch fault. Recently, an open-switch fault detection method for a back-to-back NPC converter used in wind turbine systems was introduced in [8]. In this method, variations of the phase current directions and the time duration during which the phase current remains in the zero range are used as the indicators for open-circuit faults in back-to-back NPC converters. This method only requires the information on input and output phase currents, which are generally available in the associated microcontroller. Therefore, no external components or devices are demanded for the implementation of this method. However, as pointed out in [8], for any open-circuit switch faults in an NPC inverter, this diagnostic method can only distinguish the faults between the upper branch and lower branch in one phase leg, and is unable to identify a specific faulty switch. Obviously, such ambiguous diagnostic effect will pose challenges in the postfault maintenance or fault-tolerant operations. Another potential drawback is that, the required ac current information on the input of the NPC rectifier typically contains rich harmonics/ripples due to the high-frequency switching of the rectifier. Such harmonics/ripples may mask the fault signatures for diagnosing any open-switch faults in the NPC rectifier. Another diagnostic method based on the analysis of inverter pole voltages was proposed in [9] [10]. This method is based on the well-known fact that the pole voltages of the NPC inverter are distorted or disappear whenever there is an open-circuit switch fault, in comparison to these under normal conditions. One obvious drawback with this method is the dependence on utilizing voltage sensors for measuring the inverter pole voltages, which will significantly increase the system cost and hardware complexity.

As a summary, it can be seen that these existing diagnostic methods proposed in the literature either depend on the presence of numerous additional voltage sensors, or cannot identify the switch faults specifically. Therefore, developing a low-cost accurate diagnostic method for detecting open-circuit switch faults in multilevel converters is of high necessity and significance.

In this paper, a novel diagnostic method will be introduced for detecting IGBT open-circuit faults in NPC inverters. This method is achieved based on monitoring the variations of dc-bus neutral point current in combination with the information on switching patterns and phase current that are generally available in electric drives. The remainder content of this paper is described as follows. In Section II, open-circuit IGBT faults in an NPC inverter and their corresponding negative impacts on the inverter performance are discussed. In Section III, the principle of the new diagnostic method for detecting IGBT open-circuit faults in NPC inverters is presented. In Section IV, simulation results that can verify the efficacy of the proposed diagnostic method are given and explained. Experimental results based on a 50-kVA three-level NPC inverter ASD are demonstrated in Section V. Finally, conclusions are given in Section VI.

SECTION II. Negative Impact of IGBT Open-Circuit Faults in NPC Inverters

The circuit topology of an NPC inverter is given in Fig. 1. The operating principle of the NPC is detailed in [11], and therefore will not be repeated in this paper. The output voltage of each phase leg of the NPC inverter is designated as “P”, O”, and “N, ” to represent positive dc-bus voltage $(+V_{dc}/2)$, zero, and negative dc-bus voltage $(-V_{dc}/2)$. For instance, the switching state, (P, O, N), implies that the output pole voltages of Phase-A, Phase-B, and Phase-C are $(+V_{dc}/2)$,0, and $-V_{dc}/2)$, respectively. It is well known that there are 27 switching states for a three-level NPC inverter, as illustrated in the voltage space vector diagram given in Fig. 2. Such designations for each switching state of the NPC inverter will be used in the following analysis of IGBT open-circuit faults for the sake of simplicity.

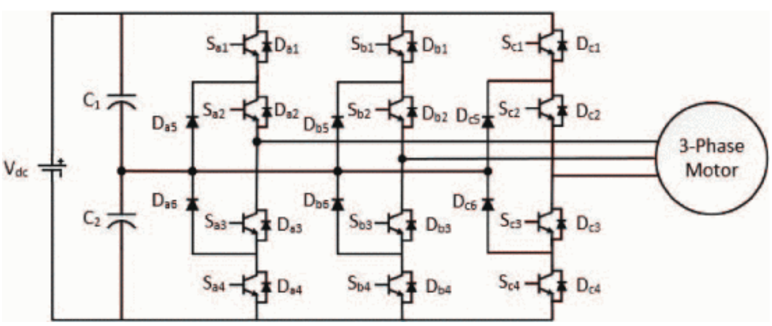


Fig. 1. Circuit topology of a three-level NPC inverter.

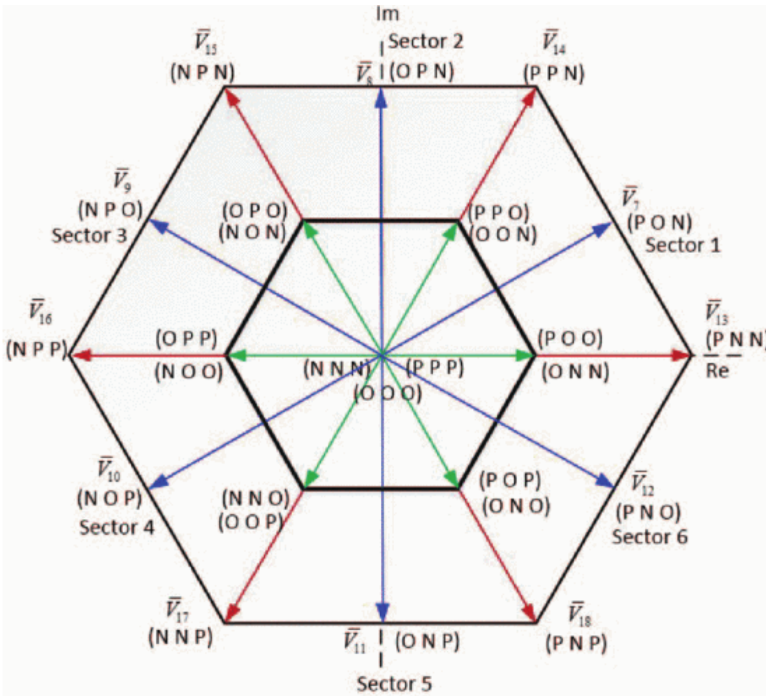


Fig. 2. Voltage space vector diagram for a three-level NPC inverter.

Considering the symmetrical topology of the NPC inverter, only the open-circuit faults in IGBTs $\mathrm{S_{a1}}$ and $\mathrm{S_{a2}}$ in Phase-A (shown in Fig. 1) are analyzed here. When IGBT $\mathrm{S_{a1}}$ encounters an open-circuit fault, the output terminal would not be connected to the positive dc-bus during the “P” state, at positive load current (Phase-A current flowing from the dc source to the load), as shown in the green current path in Fig. 3(a). Instead, the output terminal of Phase-A leg will be connected to the dc-bus neutral point through the clamping diode $\mathrm{D_{a2}}$ and the inner IGBT $\mathrm{S_{a2}}$, as shown in the red current path. As a result, the Phase-A current, i_a, loses large part of the positive current, as shown in Fig. 4(a). Additionally, the upper dc-link capacitor will be more charged than the lower capacitor due to the open-circuit fault in IGBT $\mathrm{S_{a1}}$, which will result in a much larger voltage in the upper capacitor $\mathrm{C_1}$ than that in the lower capacitor $\mathrm{C_2}$, as shown in Fig. 4(b). The voltages of the positive and negative dc-bus capacitors are given as follows:

$$\begin{aligned} v_{c1} &= \frac{1}{c}\int i_1 dt + \frac{V_{dc}}{2} \\ v_{c2} &= -\frac{1}{c}\int i_2 dt + \frac{V_{dc}}{2} \end{aligned} \qquad (1)(2)$$

where, v_{c1} and v_{c2} refers to the upper capacitor voltage and lower capacitor voltage, respectively. The capacitance value of $\mathrm{C_1}$ and $\mathrm{C_2}$ are assumed to be $C_1 = C_2 = C$. Here, V_{dc} is the dc-bus voltage, and i_1 and i_2 represent the upper capacitor current and lower capacitor current.

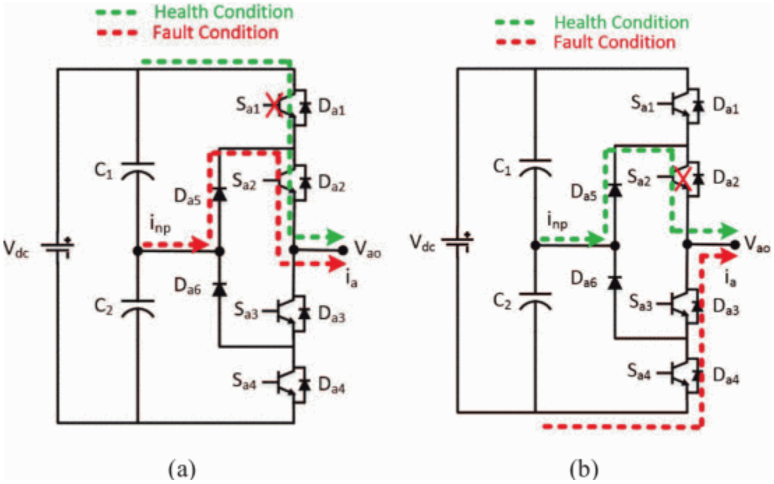


Fig. 3. Current flow direction under various open-circuit switch faults (a) open-circuit fault in IGBT S_{a1} (b) open-circuit fault in IGBT S_{a2},

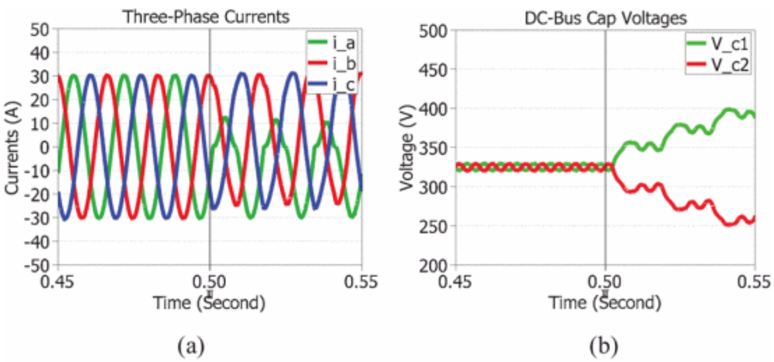


Fig. 4. Phase current and dc-bus capacitor voltage waveforms under healthy and open-circuit faulty condition of IGBT S_{a1} (the open-circuit fault is triggered at $t = 0.5$ second) (a) phase current waveforms (b) dc-bus capacitor voltage waveforms.

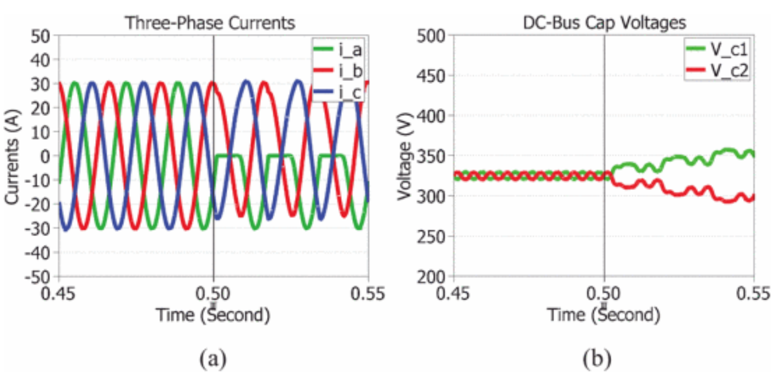


Fig. 5. Phase current and dc-bus capacitor voltage waveforms under healthy and open-circuit faulty condition of IGBT S_{a2} when $i_a > 0$ (the open-circuit fault is triggered at $t = 0.5$ second) (a) phase current waveform (b) dc-bus capacitor voltage waveforms.

Likewise, when the IGBT S_{a2} in Phase-A leg has an open-circuit fault, the output terminal could not be connected to the dc-link neutral point during the “O” state if the phase-A current is positive, as depicted in the green path shown in Fig. 3(b). Instead, the output terminal might be connected to the negative dc bus through the freewheeling diodes D_{a3} and D_{a4}, as shown in the red current path in Fig. 3(b), which depends on the fact that these diodes are reverse biased or positive biased. Since the open-circuit fault in S_{a2} interrupts the conduction path connecting the output terminal to the positive dc-bus voltage, the Phase-A current only contains negative half cycles, as shown in Fig. 5(a). Moreover, the lower dc-bus capacitor C_2 might be less charged than the upper capacitor C_1, which leads to a lower capacitor voltage in C_2 than that in C_1, as shown in Fig. 5(b). If no remedial actions are taken to balance the dc-bus voltages, the capacitor C_1 may fail over time due to the overvoltage stress across it. In summary, IGBT open-circuit faults in NPC inverters can severely degrade the performance of the related drive systems and may cause cascaded system failures if no diagnostic method is available. Therefore, developing an efficient online diagnostic method is of great necessity to improve the reliability of NPC-inverter-based power conversion systems.

SECTION III. The Proposed on-Line Diagnostic Method

The diagnostic method to be introduced in this paper is based on monitoring the dc-bus neutral-point current, i_{np}, of the NPC inverter, which can be expressed as follows, as function of the phase currents and the switching states of the inverter:

$$i_{np} = (1 - |S_a|)i_a + (1 - |S_b|)i_b + (1 - |S_c|)i_c \qquad (3)$$

where, S_a, S_b, and S_c are the switching functions of the three-level inverter, taking the value of 1, 0, or-1, and i_a, i_b, and i_c are the instantaneous three phase currents. Since an open-circuit IGBT fault can affect the actual switching state, the neutral point current, i_{np}, will be changed by the related fault. In other words, such current information in combination with the switching states and phase currents can indicate all the IGBTs' health condition during operation. More specifically, a faulty IGBT device in an NPC inverter can be identified by comparing the actual value of the neutral-point current under faulty condition to the expected value at otherwise healthy condition. For instance, when the IGBT S_{a1} in Phase-A has an open-circuit fault, such a fault can be identified at the given switching state of (P, O, O) by comparing the average value of i_{np} with zero. More specifically, if the average value of i_{np} during the state (P, O, O) is zero, an open-circuit fault in S_{a1} can be determined. This is because of the fact that the open-circuit fault in S_{a1} will make the switching state (P, O, O) operate as state (O, O, O). According to Equation (3), such change of the switching state enables the neutral point current, i_{np}, to change from Equation (2) to Equation (3) which are given as follows:

$$\begin{aligned} i_{np} &= i_b + i_c \\ i_{np} &= i_a + i_b + i_c \end{aligned} \qquad (4)(5)$$

Thus, i_{np} will be zero under the aforementioned fault condition, assuming that the neutral point of the load is isolated (in practice a small hysteresis band around zero should be considered in the judgment to avoid misdiagnosis). As shown in Fig. 6, at switching state (P, O, O) of the NPC inverter, the value of i_{np} under healthy condition is $(i_b + i_c)$, which is-20A in this case. However, when an open-circuit fault in S_{a1} is triggered at $t = 0.02$ second, the value of i_{np} becomes zero. All these variations of the value of i_{np} are marked in the red dashed ellipses in Fig. 6.

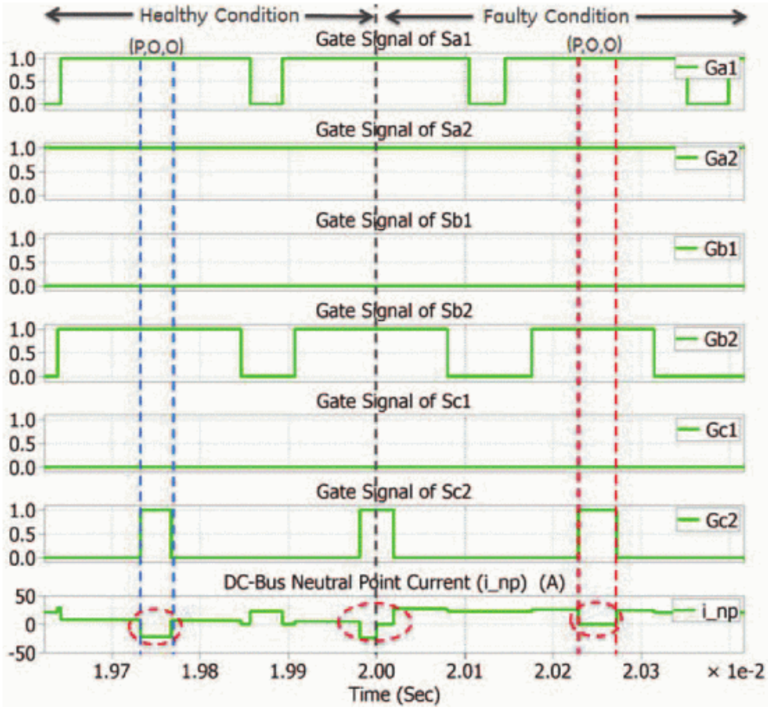


Fig. 6. Variations of the dc-bus neutral-point current (i_{np}) at the switching state (P, O, O) under healthy and S_{a1} open-circuit faulty conditions (an open-circuit fault in S_{a1} is triggered at $t = 0.02$ second).

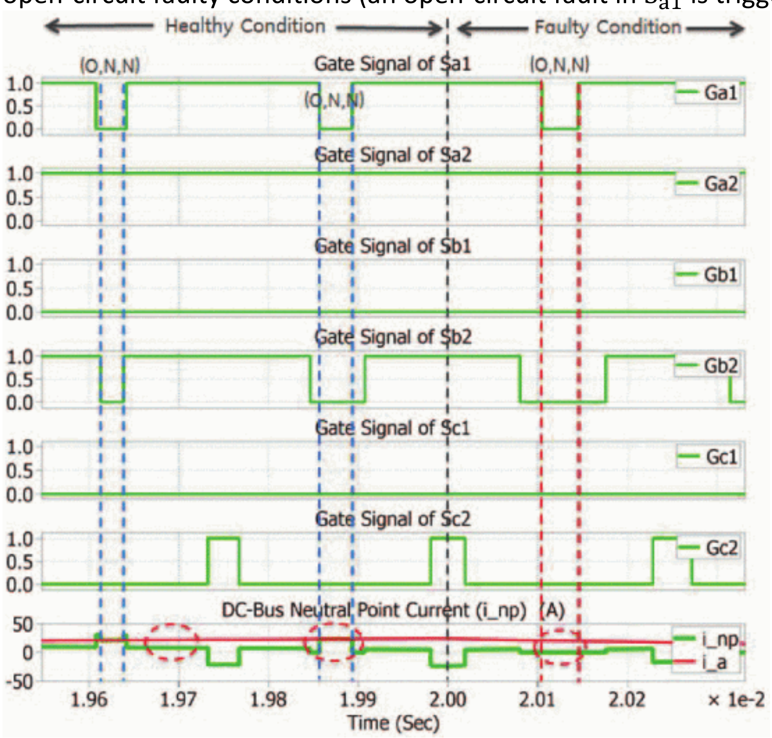


Fig. 7. Variations of the dc-bus neutral-point current (i_{np}) at the switching state (0, N, N) under healthy and S_{a2} open-circuit faulty conditions (an open-circuit fault inS_{a2} is triggered at $t = 0.02$ second).

Similarly, the variation of the neutral-point current, i_{np}, versus the open-circuit fault in the IGBT S_{a2} is illustrated in Fig. 7. Under heathy condition, the value of i_{np} at the switching state (0, N, N) is the same as the value of i_a, which changes into zero when an open-circuit fault in S_{a2} is triggered, as shown in the red dashed ellipses in Fig. 7. Faults in other IGBTs of the NPC inverter can also be detected and identified by using the same methodology. The diagnostic strategies for diagnosing all the IGBT open-circuit faults in an NPC inverter are listed in Table I. A working flow chart of this proposed diagnostic method is given in Fig. 8, in which it can be seen that the information on the neutral-point current, i_{np}, instantaneous switching states, as well as the three phase currents (i_a, i_b, i_c) are the inputs of the diagnostic algorithm, and the output will be the identified faulty switch.

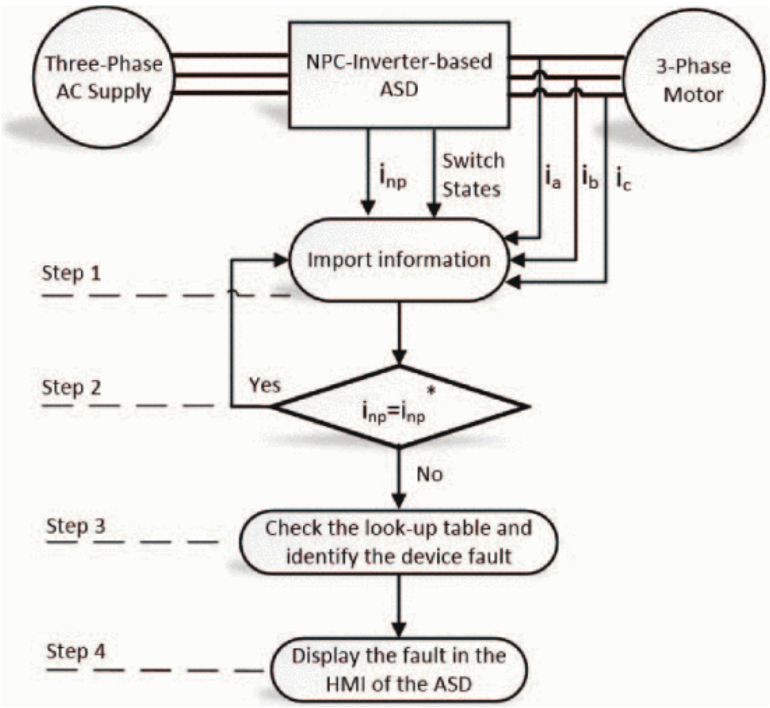


Fig. 8. Flow chart of the proposed diagnostic method.

Table I: Diagnostic look-up table for IGBT open-circuit faults in the three-level npc inverters

IGBT	Switching States	Diagnostic Indices
S_{a1}	(P, O, O)	If $i_{np} = 0$ and $i_a > 0$, S_{a1} "Open"
	(P, N, N)	If $i_{np} = i_a$ and $i_a > 0$, S_{a1} "Open"
S_{a2}	(O,P,N), (O, N, P) (O, N, N), (O, P, P)	If $i_{np} = 0$ and $i_a > 0$, S_{a2} "Open"
S_{a3}	(O,P,N), (O, N, P) (O, N, N), (O, P, P)	If $i_{np} = 0$ and $i_a < 0$, S_{a3} "Open"
S_{a4}	(N, O, O)	If $i_{np} = 0$ and $i_a < 0$, S_{a4} "Open"
	(N, P, P)	If $i_{np} = i_a$ and $i_a < 0$, S_{a4} "Open"
S_{b1}	(O, P, O)	If $i_{np} = 0$ and $i_b > 0$, S_{b1} "Open"
	(N, P, N)	If $i_{np} = i_b$ and $i_b > 0$, S_{b1} "Open"
S_{b2}	(P, O, N), (N, O, P) (N, O, N), (P, O, P)	If $i_{np} = 0$ and $i_b > 0$, S_{b2} "Open"
S_{b3}	(P, O, N), (N, O, P) (N, O, N), (P, O, P)	If $i_{np} = 0$ and $i_b < 0$, S_{b3} "Open"
S_{b4}	(O, N, O)	If $i_{np} = 0$ and $i_b < 0$, S_{b4} "Open"
	(P, N, P)	If $i_{np} = i_b$ and $i_b < 0$, S_{b4} "Open"
S_{c1}	(O, O, P)	If $i_{np} = 0$ and $i_c > 0$, S_{c1} "Open"

	(N, N, P)	If $i_{np} = i_c$ and $i_c > 0$, S_{c1} "Open"
S_{c2}	(P, N, O), (N, P, O) (N, N, O), (P, P, O)	If $i_{np} = 0$ and $i_c > 0$, S_{c2} "Open"
S_{c3}	(P, N, O), (N, P, O) (N, N, O), (P, P, O)	If $i_{np} = 0$ and $i_c < 0$, S_{c3} "Open"
S_{c4}	(O, O, N)	If $i_{np} = 0$ and $i_c < 0$, S_{c4} "Open"
	(P, P, N)	If $i_{np} = i_c$ and $i_c < 0$, S_{c4} "Open"

Here, it should be mentioned that this proposed diagnostic method only requires one additional current sensor to measure the dc-bus neutral-point current, i_{np}. Thus, this implies slight cost increase is necessary, if one is to implement this method in commercial multilevel ASDs or power electronic systems. In this diagnostic method, the required information on the switching states and load currents of such an NPC inverter is generally available in the system microcontrollers of these inverters. Therefore, no other hardware components are required.

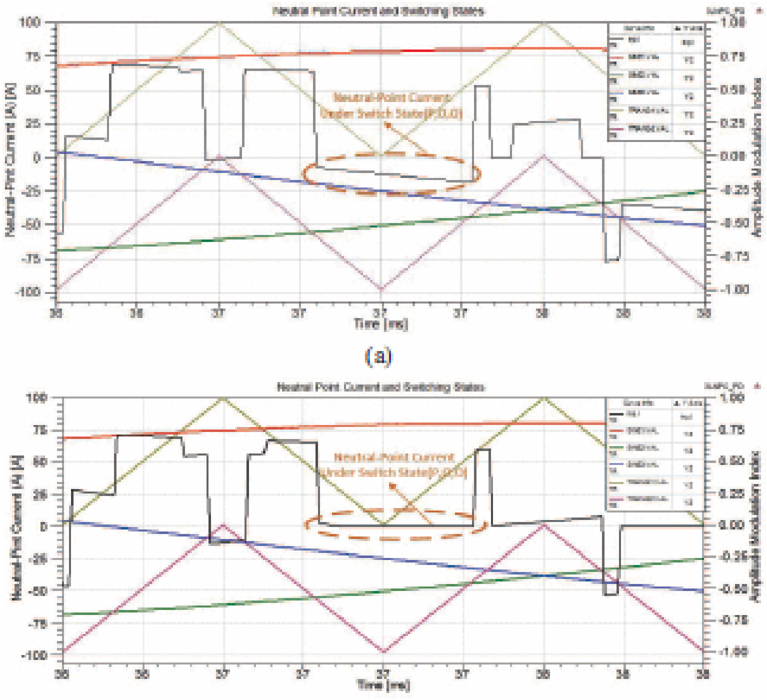
SECTION IV. Simulation Results

To verify the efficacy of the proposed diagnostic method, simulations of an ASD based on a three-level NPC inverter have been carried out in ANSYS Simplorer software environment. The parameters of the ASD used in the simulation are provided in Table II. As introduced in Section III above, the fault signatures under investigation here are the variations in the dc-bus neutral-point current under certain switching states of the NPC inverter. To graphically illustrate the fault signatures under various switching states, a carrier-based Phase Disposition PWM (PD-PWM) method with the injection of zero-sequence component was adopted to modulate the three-level NPC inverter.

First, an open-circuit fault in IGBT, S_{a1}, was simulated and investigated. As is shown in Fig. 9(a)-(b), during the switching state (P, O, O), the dc-bus neutral-point current, i_{np}, represented by the black trace, increases in magnitude from —7*A* to —20 *A* under healthy condition as shown in Fig. 9(a), which drops to a constant zero value under the same given switching state (P, O, O) when the IGBT, S_{a1}, has an open-circuit fault, as shown in Fig. 9(b). As analyzed in Section III, such an abnormal variation in i_{np} results from the fact that the switching state (P, O, O) is forced to become (O, O, O) under the open-circuit faulty condition of IGBT S_{a1} at positive load current, and the value of i_{np} at the switching state of (O, O, O) is according to Equation (3) given in Section III of this paper. Through monitoring the value of i_{np}, the open-circuit fault in the IGBT S_{a1} can be diagnosed. One more switch state, (P, N, N), can also be used for detecting S_{a1} fault, as given in Table-I.

Likewise, another type of representative fault in such an NPC inverter, namely, an open-circuit fault in the IGBT, S_{a2}, was simulated and examined. At the switching state of (0, N, N), the dc-bus neutral-point current, i_{np}, again represented by the black trace, is a positive current under healthy condition as shown in Fig. 10(a), which decreases to a constant zero value at the same given switching state (0, N, N) under the condition of an open-circuit fault in this IGBT, S_{a2}, as shown in Fig. 10(b). Such dramatic change in the dc-bus neutral-point current derives from the fact that the switching state (0, N, N) becomes (N, N, N) under such open-circuit faulty condition, which can be explained again by Equation (3). It should be noted that, the variations of the neutral-point current under three other switching states, namely, (0, P, P), (0, N, P), and (0, P, N), can also be used to identify the open-circuit fault in S_{a2}. The nature of these fault signatures is similar to the fault signature discussed above, and thus will not be repeated here.

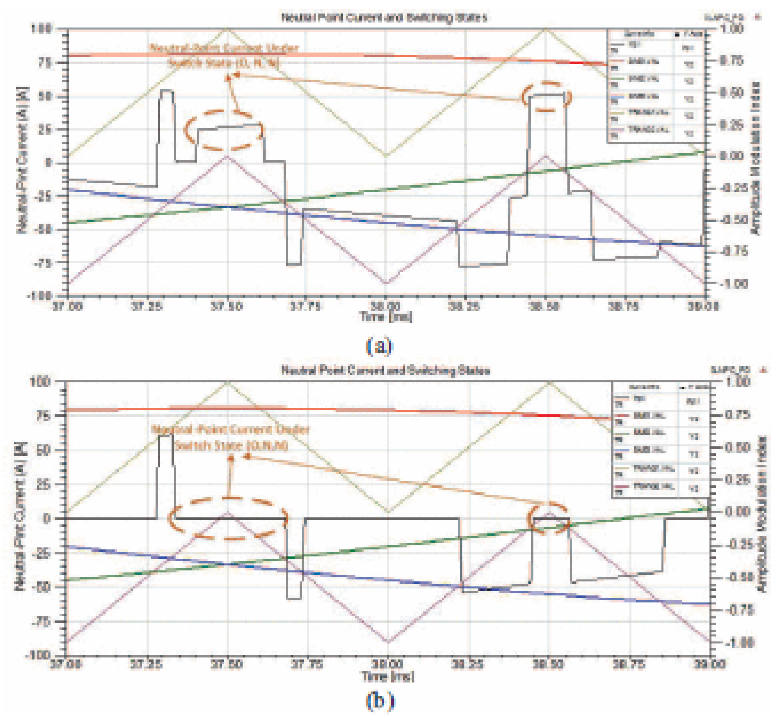
From all these simulation results, it can be concluded that the open-circuit switch faults in a three-level NPC inverter can be effectively diagnosed by monitoring the dc-bus neutralpoint current under certain switching states. The experimental results given in next section will further confirm the efficacy of this new diagnostic method.



(a)

(b)

Fig. 9. Fault signature (i.e., the abnormal variation of the inpat the switching state (p, O, O), circulated in yellow dashed line) under (a) healthy condition and (b) sal open-circuit faulty condition.



(a)

(b)

Fig. 10. Fault signature (i.e., the abnormal variation of inpat the switching state (0, N, N), circulated in yellow dashed line) under (a) healthy condition and (b) sa2 open-circuit faulty condition.

Table II: Main parameters of the NPC inverter used in simulation

Parameter	Value	Unit
Input line-to-line voltage	480	Volts

Input frequency	60	Hz
DC bus voltage	650	Volts
Inverter switching frequency	4	kHz
Load resistor	0.8	Ω
Load inductor	6	*mH*
Output frequency	60	Hz

SECTION V. Experimental Verifications

To experimentally verify this proposed diagnostic method, a 50-kVA ASD based on a three-phase three-level NPC inverter has been designed and implemented in the laboratory, as shown in Fig. 11. The open-circuit faults in the IGBTs of the NPC inverter were emulated by disabling the related PWM signals. The fault signatures, namely, the variations of the dc-bus neutral point current, i_{np}, at certain switching states, were monitored and captured by using a high-bandwidth oscilloscope, when an open-circuit switch fault was enabled in the NPC inverter. As can be seen in Fig. 12(a)-(b), when an open-circuit fault occurred in the IGBT, S_{a1}, of the NPC inverter, the value of i_{np} changes from an average value of-3A to almost zero at the switching state (P, O, O), as marked in the yellow dashed ellipses in Fig. 12(a)-(b). Likewise, when the IGBT S_{a2} has an open-circuit fault, the value of i_{np} will change from an average value of 7A to quasi-zero value at the switching state (O, N, N), as the test results shown in Fig. 13(a)-(b). With such experimental verifications on these two representative open-circuit switch faults in the three-level NPC inverter, we can conclude that any single IGBT open-circuit fault in the NPC inverter can be detected and identified by monitoring the abnormal variations of the dc-bus neutral point current i_{np} at certain switching states.

SECTION VI. Conclusions

In this paper, a novel fault diagnostic method has been introduced to diagnose IGBT faults in a three-level NPC inverter. The main principle of this method is to monitor the variation in the dc-bus neutral-point current, and compare it to the expected value of neutral-point current under normal operation. The advantages of this diagnostic method include the lower implementation cost (only one additional current sensor is required), simpler diagnostic process, and fast detection speed (within one fundamental period of the output frequency). This method is quite simple to be embedded into system microprocessors and no complex computation is involved. One concern with this diagnostic method might be the high frequency bandwidth required for sensing the dc-bus neutral-point current in high-frequency applications, which will be investigated in future work. Nevertheless, one should be aware that the switching frequency utilized in medium-voltage drives or high-power NPC converters is typically quite low (below 5kHz), which makes the implementation of this diagnostic method more feasible in high-power applications.

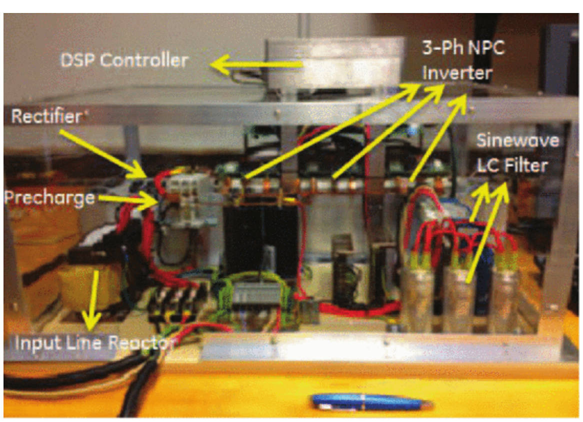


Fig. 11. The customized 50-kVA ASD prototype based on an NPC inverter.

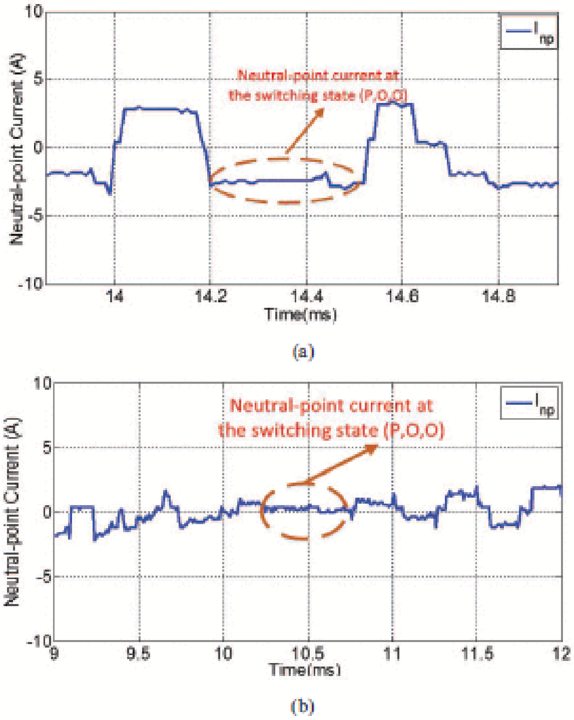


Fig. 12. Zoom-in view of the measured dc-bus neutral-point current i_{np} at the switching state of (P, O, O) under the condition of (a) healthy operation (b) an open-circuit fault occurred in the IGBT S_{a1} of the NPC inverter.

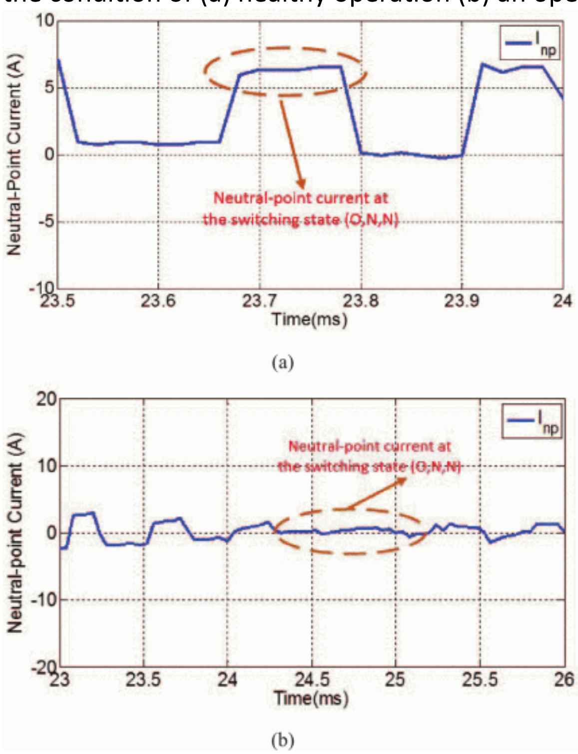


Fig. 13. Zoom-in view of the measured DC-bus neutral-point current i_{np} at the switching state of (O, N, N) under the condition of (a) healthy operation (b) an open-circuit occurred in the IGBT S_{a2} of the NPC inverter.

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Keywords

IEEE Keywords

Decision support systems

INSPEC: Controlled Indexing

condition monitoring , electric current measurement , electric sensing devices , fault diagnosis , power convertors

INSPEC: Non-Controlled Indexing

online diagnostic method , NPC multilevel converters , online condition monitoring , safety-critical applications , open-circuit switch fault detection , neutral-point-clamped multilevel converters , dc-bus neutral-point current abnormal variation monitoring , instantaneous switching states , phase currents , current sensor , dc-bus neutral-point current measurement , lab-scale adjustable speed drive , ASD , three-level NPC inverter , apparent power 50 kVA

Author Keywords

Open-circuit switch faults , fault diagnosis , neutral point clamped inverter , neutralpoint current