Fast Detection and Localization of Open-Circuit Switch Faults in Nested Neutral Point Clamped (NNPC) Inverter

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***Abstract*— In this paper, a method is presented for the detection of open-circuit fault (OCF) in the power switches of nested neutral point clamped (NNPC) inverter for the first time. Using this method, the occurrence and location of OCF are determined in less than one fundamental period. In the proposed method, not only the output voltage and current but also the voltages of capacitors are used for the identification of the OCFs in NNPC. Besides, the effect of each switch OCF on the output voltage and current and also capacitors voltage is analyzed and based on this analysis, an OCF diagnosis scheme is presented. The expected values of capacitors voltages and output voltage and current are compared in each switching state with the measured ones, and the deviation of the measured and the expected values are used for OCF localization. Moreover, for verifying the performance and feasibility of the introduced method, the level-shifted pulse width modulation (LS-PWM) is applied to NNPC, and the OCF detection results are presented in the MATLAB/SIMULINK environment.**

Keywords*— *fault detection, open-circuit fault, nested neutral point (NNPC) inverter, multilevel inverter

I. Introduction

Recently, multilevel voltage source converters (ML-VSCs) are becoming significant parts of industrial applications and academic researches owing to their applicability and controllability. These converters provide high-quality output waveform with a wide variety of power and voltage ratings utilizing low-voltage fast power switches. The wide application of multilevel inverters (MLIs) such as renewable energy conversion, flexible alternating current transmission system (FACTS), uninterruptible power supplies (UPS), variable-speed motor drives, and hybrid and electrical vehicles (HEVs) take good reputation in industrials for them [1-3]. Cascaded H-bridge (CHB) is one of the well-known MLIs. Also, the neutral point clamped (NPC) MLI, flying capacitor (FC) MLI, and modular multilevel converter (MMCs) are the other popular MLIs that are widely utilized due to their acceptable performance. However, MLIs face some disadvantages, such as a high number of power components and balancing the voltage of the capacitors [1, 4, 5].

As the number of power components increases, the possibility of failure in the converter increases as well. Designing more reliable MLIs or applying some methods to improve the reliability of the existing MLIs are becoming important issues due to the vast penetration of MLIs in the power system. The first step of this procedure is detecting the type and location of the fault(s). An MLI includes different parts such as capacitors, power sources, power switches, control, processing unit, and the sensors. The probability of fault occurrence in capacitors and switches is more than in other parts of the system [6-8]. Isolated gate bipolar transistor (IGBT) and metal-oxide field-effect transistor (MOSFET) are the two semiconductor power switches that are widely used in MLIs. Two types of faults happen in power switches; open-circuit fault (OCF) and short-circuit fault (SCF). Forasmuch as SCF may cause a serious problem in a short time, some methods are developed to detect the SCF with hardware circuits that are integrated with the gate drivers to shut down the faulty part of the system immediately in the case of SCF occurrence. Unlike SCF, the OCF does not lead to the inverter interrupt; however, if it remains for a long time, it causes secondary problems, such as abnormal stress on the power switches and further damages to the healthy parts of the inverter [6, 9-12].

In [13], a fast and online detection algorithm for OCF is presented for T-type MLI. Monitoring the neutral point current and comparing it with existing data in each switching state is the principle of this method. The reduction of diagnostic accuracy in load disturbances is the main disadvantage of this method. In [14], a new method for OCF detection in the asymmetric configuration of CHB MLI is introduced. A new OCF detection method is suggested in [15] for three-level NPC MLI. The radiated electromagnetic signature is measured in the dc-bus of the inverter and utilized to diagnose the faulty switch. Adding the EMI filter or external antenna is costly, which is the main drawback of this method. In [16], an OCF detection method for grid-connected 3-level NPC inverter is introduced in which the grid current distortion is analyzed as a detection factor. However, to correct the operation of this method, reactive current injection to the grid is necessary. A detection method based on the comparison of the dimension of Concordia current with the normal value is presented in [17] for NPC inverter.

NPC inverter is one of the most accepted MLIs in commercial applications in the last decades [18]. Nested neutral point clamped (NNPC) inverter is a new topology of the NPC family, which is introduced in recent years [19]. The NNPC is created by a combination of the NPC and FC, which exploits six power switches, two diodes, and two flying capacitors. Taking advantage of redundant switching states, the voltages of the flying capacitors are controlled and kept balanced. In the Four-level NNPC, the number of diodes has been reduced in comparison to NPC (from 6 to 2), and also, the number of capacitors is decreased compared to FC (from 3 to 2) [20]. Also, the NNPC inverter has some interesting features, i.e., wide operating range without requiring additional series switches, high-quality output voltage waveform, and the same voltage stress in the power switches [19-21] which makes it a suitable choice for medium voltage applications. Due to its wide applications, detection and localization of OCF in the power switches of NNPC is a significant challenge that has not already been investigated. In this paper, the post-fault operation of NNPC is investigated, and an OCF detection strategy is proposed for NNPC inverter.

The rest of this paper is organized as follows: In section II, the NNPC circuit configuration is described, and its normal (pre-fault) operation and the method for balancing the voltages of the capacitors are discussed. In section III, the effect of each switch OCF on the output voltage, the output current, and also the voltage of capacitors is analyzed, and based on this analysis, an OCF diagnosis scheme is presented. Finally, in section IV, comprehensive simulation results are provided to substantiate the claims in the previous sections, and the correct operation of the proposed OCF detection method.

II. The Normal Operation of NNPC (Pre-Fault Condition)

The single-phase NNPC circuit configuration is demonstrated in Fig. 1. As depicted in this figure, the NNPC structure consists of six switches, two flying capacitors, and two clamping diodes. By regulating the capacitor voltages at 1/3 of input dc voltage (V_{dc}), four voltage levels are generated in the output. This also helps to ensure that the voltage stress on the switches is the same [19-21].

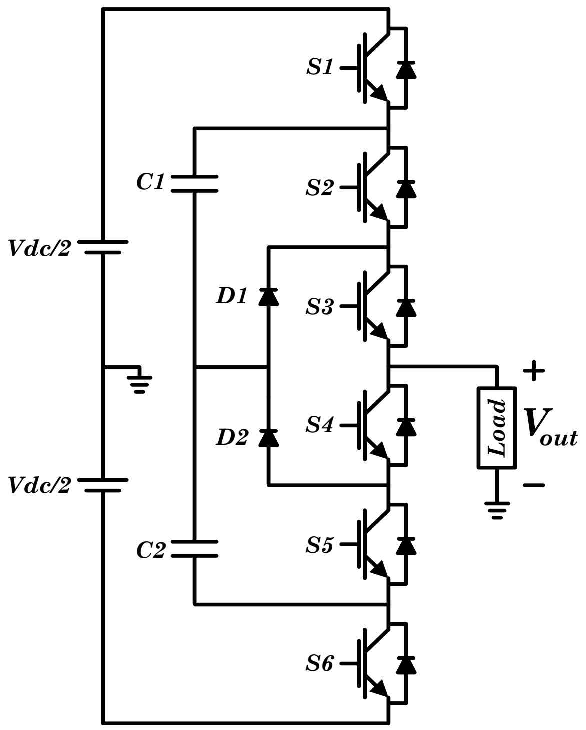

Fig 1. The circuit configuration of four-level NNPC MLI

The switching states and their redundancies are shown in Table I. The redundant switching states, i.e., (2A, 2B) and (3A, 3B) are utilized to regulate the flying capacitors voltage. In the other words, in the states of 2 and 3, the proper switching commands are selected based on the measured voltages of capacitors (V_{c1} and V_{c2}) and output current (I_{out}) in such a way that the voltages of capacitors are kept balanced and regulated in the rated value. [20, 21].

III. OCF Diagnosis for Power Switches

As the first step of fault-tolerant operation, it is necessary to have a fast and accurate method for detecting an OCF in the power switches. By examining the output voltage and current, the OCF can be detected. However, to fast and accurate localization of the faulty switch, the deviation of capacitors voltages is also should be considered. The variation of the measured voltage of capacitors from its rated value is obtained as follow,

$$\Delta V_{ci} = V_{ci} - \tfrac{1}{3} V_{dc} \quad (i = 1, 2) \qquad (1)$$

Note that after OCF fault in an IGBT, the faulty IGBT remains permanently off regardless of its switching command. However, the current still flows through the anti-parallel diode of the faulty IGBT [12]. Table II demonstrates whether the current flows through the IGBT or the anti-parallel diode. To better analyze the post-fault condition, the power switches are divided into two groups: upper switches (S1, S2, and S3) and lower switches (S4, S5, and S6). The star sign in Table II indicates the devices through which the current flows. As depicted in Table II, the OCF in the upper switches can be detected only in the positive current, and in the same way, for detecting the OCF in the lower switches, the detection can be performed when the output current is negative.

A. Detection parameters for the upper switches

It should be noted that the following analysis in the upper switches is performed when the converter output current is positive (I_{out}>0). If I_{out} < 0, the current flows through anti-parallel diodes of the upper switches and the output voltage is not affected by OCF in the upper switches.

1) OCF occurrence in S1: If an OCF occurs in S1, states 1, 2A, and 3A are missed. Due to TABLE I, for I_{out} >0, the states 2A and 3A are responsible for charging C1. Since both of the states 2A and 3A are missed, the voltage of C1 decreases.

2) OCF occurrence in S2: In the case of an OCF in S2, the state 1 cannot be generated. Moreover, the state 2B is missed. As demonstrated in TABLE I, by losing the state 2B, one degree of freedom to balance the voltage of the capacitors is missed; however, the redundant switching states of 3A and 3B are still available. Hence, the voltage of the capacitor still remains balanced. However, the ripple of capacitors voltages is increased.

3) OCF occurrence in S3: As depicted in TABLE I, when an OCF happens in S3, states 1, 2A, 2B, and 3B cannot be generated. Therefore, the voltage of C1 becomes uncontrollable, and the voltage ripple of C2 is increased.

B. Detection parameters for the lower switches

The following investigation for the lower switches under OCF condition is done when I_{out}<0 because the current flows

TABLE I. SWITCHING STATES AND EFFECT OF AC-SIDE CURRENT ON THE VOLTAGES OF CAPACITORS

state		***Switching state***						***Flying Capacitors Voltages***		***V_{out}***
		S1	***S2***	***S3***	***S4***	***S5***	***S6***	***Vc1***	***Vc2***	
1		1	1	1	0	0	0	No impact	No impact	***$V_{dc}/2$***
2	***A***	1	0	1	1	0	0	Charging (I_{out}>0) Discharging (I_{out}<0)	No impact	***$V_{dc}/6$***
	B	0	1	1	0	0	1	Discharging (I_{out}>0) Charging (I_{out}<0)	Discharging (I_{out}>0) Charging (I_{out}<0)	
3	***A***	1	0	0	1	1	0	Charging (I_{out}>0) Discharging (I_{out}<0)	Charging (I_{out}>0) Discharging (I_{out}<0)	***$-V_{dc}/6$***
	B	0	0	1	1	0	1	No impact	Discharging (I_{out}>0) Charging (I_{out}<0)	
4		0	0	0	1	1	1	No impact	No impact	***$-V_{dc}/2$***

TABLE II. THE SEMICONDUCTOR DEVICES IN THE CURRENT PATH IN EACH SWITCHING STATE

state		S1		S2		S3		S4		S5		S6	
		T	D	T	D	T	D	T	D	T	D	T	D
1	$I_{out} > 0$	*		*		*							
	$I_{out} < 0$		*		*		*						
2A	$I_{out} > 0$	*				*							
	$I_{out} < 0$		*					*					
2B	$I_{out} > 0$			*		*							*
	$I_{out} < 0$				*		*					*	
3A	$I_{out} > 0$	*							*		*		
	$I_{out} < 0$		*					*		*			
3B	$I_{out} > 0$					*							*
	$I_{out} < 0$							*				*	
4	$I_{out} > 0$								*		*		*
	$I_{out} < 0$							*		*		*	

through the lower IGBTs when I_{out}<0. Otherwise, the current path is closed from the ante-parallel diodes of the lower switches and OCF will not affect the output voltage.

4) OCF occurrence in S4: The switching states of 2A, 3A, 3B, and 4 remain available. As demonstrated in TABLE II, in the case of an OCF in S4, the voltage of C2 becomes uncontrollable, and the voltage ripple of C1 is increased.

5) OCF occurrence in S5: If S5 is open-circuited, the states 3A and 4 are missed. State 3A is one of the states which is responsible for voltage balancing. So, in this condition, the balancing procedure faces some problem that leads to an increase in the capacitors' voltage ripple. Since 2A and 2B are still available, the voltages of capacitors remain balanced.

6) OCF occurrence in S6: According to TABLE I, after OCF occurrence in S6, the states 2B, 3B, and 4 cannot be produced. Since states 2B and 3B are essential in balancing the voltage of C2, missing these states makes the voltage of C2 uncontrollable. Hence, the voltage of C2 starts to decrease.

According to the above analysis on the post-fault operation of NNPC, the OCF fault diagnosis scheme is illustrated in Fig. 2. In the comparing unit, the real-time value of converter output voltage (V_{out}) and the voltage of the capacitors (V_{c1} and V_{c2}) are compared with the expected values, and the error signals are generated in each switching state. The error signals values, current switching state, and the ac side current (I_{out}) are the inputs of the fault detection unit. In this unit, the faulty switch is diagnosed based on the explanations given in sections A and B.

IV. SIMULATION RESULTS

To verify the performance and feasibility of the proposed OCF detection method, it is simulated on a single-phase 4-level NNPC in MATLAB/SIMULINK. In all simulation cases, the OCF has occurred in t=0.5 (s). The simulation parameters of the case study are given in TABLE III. To generate the ac side voltage, multi-carrier level-shifted pulse width modulation (LS-PWM) is applied to the converter.

In Figures 3, 4, and 5, the OCF effects on the upper switches are investigated, and the faulty switch is diagnosed based on the proposed method. In Fig. 3, OCF has occurred in t=0.5 in S1. The ac side voltage waveform is shown in Fig. 3(a), which is distorted after failure occurrence. The capacitors voltages are demonstrated in Fig. 3(b). It can be seen that the voltage of C1 is decreased after OCF in S1 while the voltage of C2 remains regulated at the reference value. The fault detection signal is shown in Fig. 3(c). This signal is the output of the detection unit in Fig. 2 and is changed from 0 to 1 when the OCF is detected in S1. It is evident that the OCF is localized in less than one fundamental cycle (20 ms).

TABLE III. THE PARAMETERS OF THE SIMULATION CASE STUDY

Parameter	**Value**
DC supply voltages (V_{dc})	900 V
PWM carrier frequency	3 KHz
Output voltage frequency	50 Hz
Load resistance	10 Ω
Load inductance	16 mH

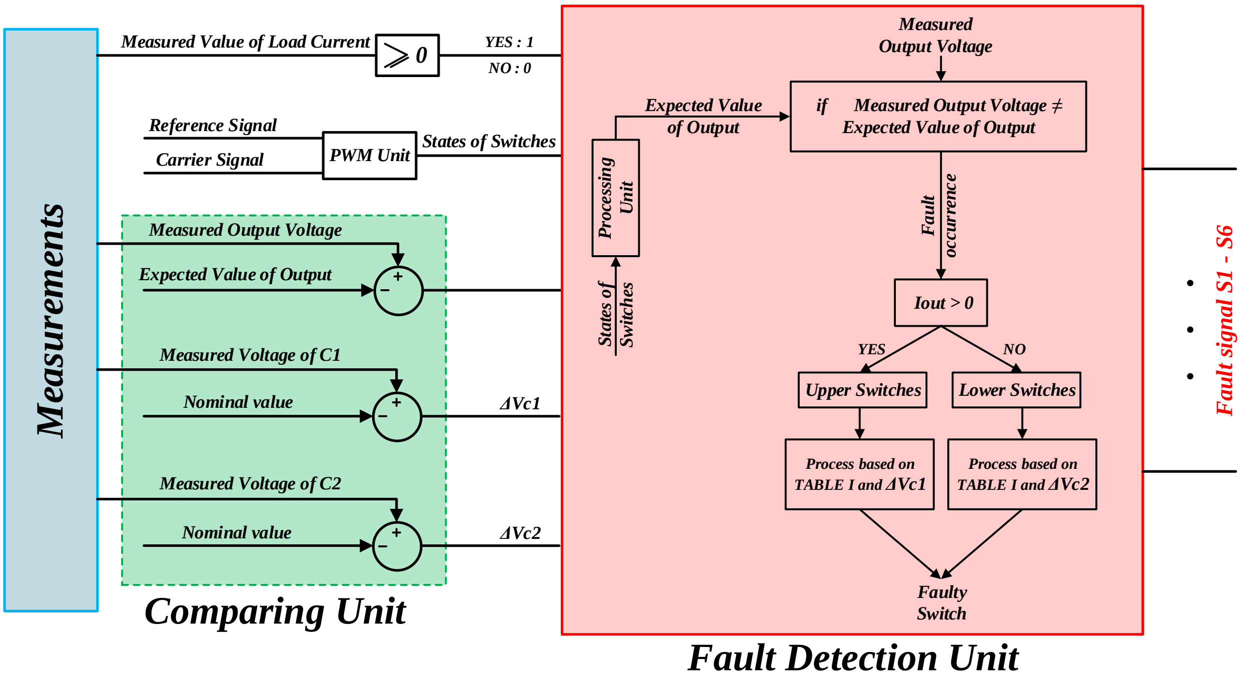

Fig. 2. The block diagram of the proposed fault diagnosis method

The occurrence of OCF in S2 is verified in Fig. 4. The output voltage of the converter is shown in Fig. 4(a). As shown in Fig. 4(b), the voltage of C1 and C2 are still balanced after a failure occurs since the switching states for adjusting the voltage of capacitors are still available. However, the ripple of the voltage of the capacitor is increased. As shown in Fig. 4(c), the OCF detection is performed in less than one fundamental cycle.

The simulation results for OCF in S3 are presented in Fig. 5. After a failure occurs, the output voltage is distorted, as shown in Fig. 5(a). Moreover, the voltage of C1 has become uncontrollable, which is expected due to TABLE I and the analyses given in section III. The fault detection signal is given in Fig. 5(c), which confirms the proper operation of the presented method in detection of OCF in S3.

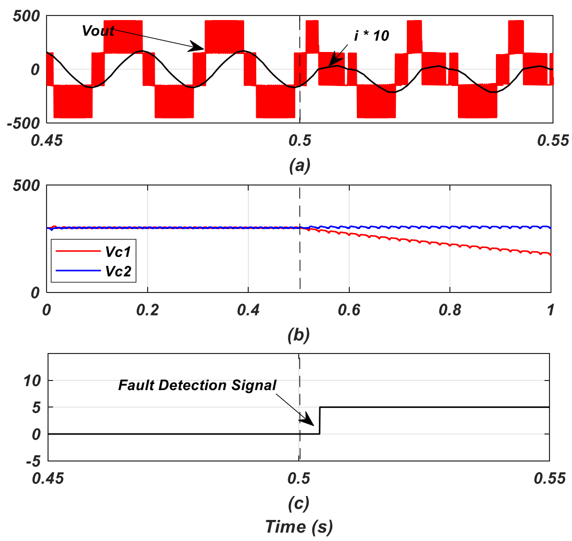

Fig. 3. OCF in S1, (a) converter output voltage waveform, (b) flying capacitors voltage, (c) S1 OCF detection signal

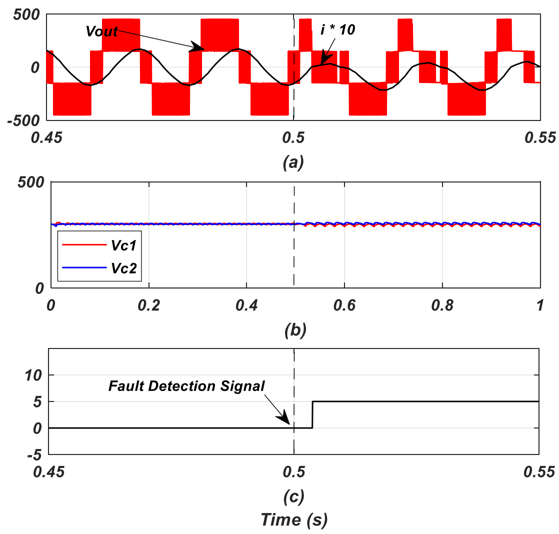

Fig. 4. OCF in S2, (a) converter output voltage waveform, (b) flying capacitors voltage, (c) S2 OCF detection signal

In the same way, Figs 6, 7, and 8 demonstrate the simulation results for the detection of OCF in the lower switches.

The simulation results for OCF detection in S4 is presented in Fig. 6. As shown in Fig. 6(a), by failure occurrence in t=0.5s, the output voltage is distorted. According to Table I, the redundant switching states for controlling the voltage of C2 is lost. Hence, the voltage of C2 decreases, as seen in Fig. 6(b). Regarding Fig. 6(c), the OCF in S4 is properly detected in less than 20 ms. The detection of OCF in S5 is verified, as illustrated in Fig. 7. The ac side voltage waveform of the converter is shown in Fig. 7(a). Also, regarding Fig. 7(b), by OCF in S5, both of the voltages of the capacitors are controllable employing the remaining redundant switching states. Utilizing the presented fault detection method in Fig. 2, the OCF in S5 is diagnosed as depicted in Fig. 7(c).

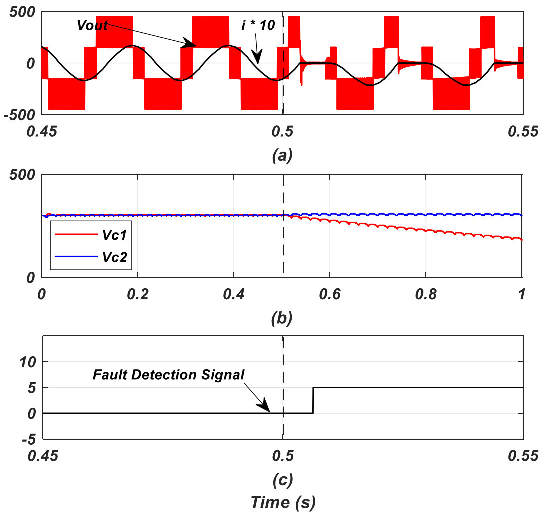

Fig. 5. OCF in S3, (a) converter output voltage waveform, (b) flying capacitors voltage, (c) S3 OCF detection signal

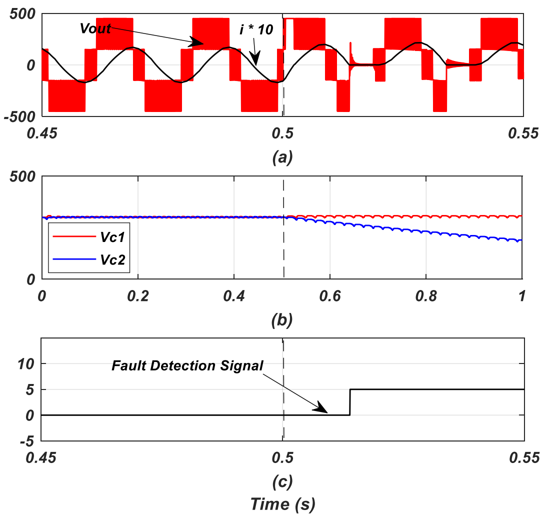

Fig. 6. OCF in S4, (a) converter output voltage waveform, (b) flying capacitors voltage, (c) S4 OCF detection signal

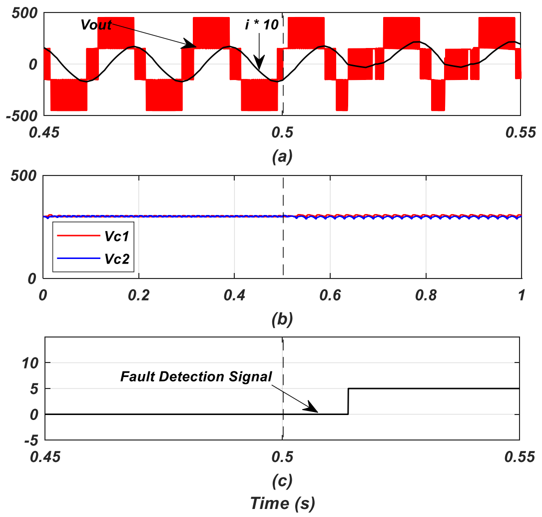

Fig. 7. OCF in S5, (a) converter output voltage waveform, (b) flying capacitors voltage, (c) S5 OCF detection signal

Finally, the operation of the proposed fault detection method is investigated in the case of OCF in S6. The converter output voltage waveform, the flying capacitors voltage, and the fault detection signal are shown in Fig. 8(a), 8(b) and 8(c), respectively. After OCF, the voltage of C2 becomes uncontrollable which leads to discharging of C2, however, the voltage of C1 is kept regulated at the desired value utilizing the available redundant states. Finally, the fault detection signal of S6 depicted in Fig. 8(c) validates the performance of the proposed fault detection method.

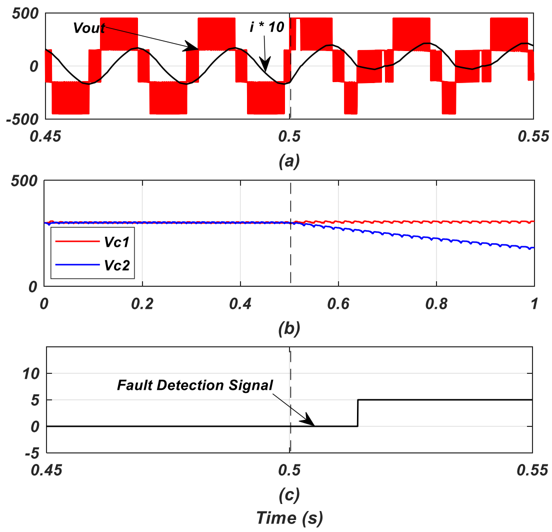

Fig. 8. OCF in S6, (a) converter output voltage waveform, (b) flying capacitors voltage, (c) S6 OCF detection signal

V. Conclusion

Nested neutral point clamp (NNPC) is a recently introduced multilevel topology which offers outstanding features and wide applications. Detection and diagnosis of switch faults in NNPC is an important challenge that has not been investigated yet. In this paper, the open-circuit fault (OCF) in the power switches and its consequences on the converter output voltage and capacitors voltages are analyzed. Based on this analysis, fault detection and localization method is presented. In the proposed method, the converter output voltage and current, and also voltages of flying capacitors are used to detect the faulty switch. The comparison between the measured value of these parameters with their expected value allows us to diagnose OCF in the power IGBTs. Furthermore, determining the exact location of the faulty switch in less than one fundamental period is the superiority of this method. The occurrence of OCF in each IGBT is simulated in MATLAB/SIMULINK and the faulty switch is properly diagnosed validating the effectiveness of the presented method.

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