Short Circuit and Open Circuit Fault Identification Strategy for 3-Level Neutral Point Clamped Inverter

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***Abstract*—Industrial drives have various applications to control speed, torque, frequency in industrial motors. The core of such a driving system is the power electronics converter. The three-level neutral point clamped (NPC) converter has a variety of applications in medium voltage inverter drive systems due to advantages such as better power quality, reduced cost, and increased efficiency. In general, the power converters are more vulnerable to power quality events. To enhance the NPC's reliability, various strategies are adapted, especially on critical applications. The focus of this research is to identify faulty switches to improve the reliability of a three-level NPC converter. An open circuit and short circuit fault detection technique for three-level three-phase NPC converters is established in this article. The proposed fault detection strategy for the NPC inverter is simulated in Matlab/Simulink, and the test results are presented in-depth. The novelty of the project lies within the experimental study of the system, which can diagnose both short-circuit and open-circuit faults occurring in the inverter.**

***Keywords*—fault identification, open circuit, short circuit, NPC inverter, industrial drives.**

I. INTRODUCTION

Fault analysis, detection, and protection are important in critical applications such as industrial, military, data centres, electric automobiles, and so on [1]. Sudden termination of these devices might result in significant financial loss as well as a safety danger. Power quality events such as voltage fluctuations and harmonics are the major sources of these failures. The consequences of its failures may be seen in the form of losses in a manufacturing plant or form of life hazards as well. Switching devices such as metal-oxide field-effect transistors (MOSFETs), insulated-gate bipolar transistors (IGBTs), and diodes are frequently used in converters and are susceptible to abnormal circumstances and failures [2]. This fact calls into question the system's capacity to operate reliably. As a result, adding redundancy to contemporary power applications is critical for increasing operating system dependability [3]. Short circuit (SC) faults, open circuit (OC) faults, degradation faults, and intermittent gate misfiring faults are the most common power converter issues [4]. The short circuit fault is the most severe of these faults for the system. Open circuit and degradation faults are not as harmful as compared to that of short circuit faults, but in turn, open circuit faults can cause performance degradation [5]. It accelerates damage of the equipment and probable failure of other equipment. Various fault identification methodologies have been deployed to detect and diagnose the faults in the converter system. Few of the prominent methods are based on several models, reference-based diagnostics and diagnostics based on either current or voltage signals [6,7]. There are two sorts of signal-based methods: voltage-based techniques and current-based techniques. Current-based techniques for fault diagnosis is more popular since it does not require extra sensors. Therefore making it a more cost-effective option than voltage-based diagnosis. In [9], the authors have integrated the average current Park vector method with fuzzy logic in a three-phase cascaded multilevel inverter (CMI) for a PMSM (Permanent Magnet Synchronous Motor) fed drive. In [10], the authors proposed a method that computes the current's mean value. It does that by gathering the current magnitude over a specific time duration as the Park's vector components. The selection of the threshold value is crucial in the method, as it is directly related to the precision of the outcomes. In [11], authors have proposed a technique of fault detection utilizing the derivative of absolute Park's vector phase. The proposed model was able to detect faults in multiple switches in a phase. As the current in inverters varies to the variation in speed and load, these techniques can lead to false tripping when the speed varies. Considering the following problem, normalized DC values can be used as a parameter of interest. The method is used to diagnose faulty switches, where the fundamental component of the current value is utilized as a normalized value [12]. This method is load-independent but, when used in a closed-loop, it has some drawbacks. To overcome these, in [13] a modified normalized current method was used. The method proposed is used for wind power systems, which applies a two-level structure. Taking these drawbacks into consideration, a fault detection and localization method for open-circuit fault and short circuit fault of NPC converter is put forward in the following paper.

Detection and protection of faulty switches must take place dynamically, this leads to a short duration between fault occurrence and fault diagnosis. Detection techniques based on mathematical transformations are capable to recognize the faulty switch, but they aren't capable enough to cause some protective action. In [14], the authors used the increase in collector voltage as a parameter to detect short circuit fault. To provide dynamic protection, 'di/dt' feedback method is used. When the fault is detected, the current change rate is controlled. In [15], the authors used gate voltage as a parameter to detect short circuit faults. During faults, there is a notable increase in gate voltage. However, this method needs complicated protection circuitry. In [16], authors have used voltage space patterns to detect short circuit faults. This method is based on the concept of analyzing the Pulse Width Modulation switching signals. In [17], the authors have suggested the use of the neural network to detect the exact location of the faulty switch. The proposed method is said to be more efficient than the wavelet packet decomposition method. In [18], authors have proposed four gate voltage limiting topologies that are used to protect the switches against short circuit faults. However, it gives rise to the high change in current over a given time duration (di/dt) and thus leading to high Electromagnetic interference. In [19], the authors have used the average current park vector technique to diagnose the short circuit fault. The parameter of interest to determine the faulty switch is the phase angle of the park vector.

There is existing research on open circuit fault identification methodologies using normalized current values. In this paper, identification through normalized current values has been successfully implemented for short circuit fault identification as well. The proposed system integrates open circuit and short circuit fault localization in an integrated system. The structure of the paper is divided into 5 different sections. Section II provides a brief description of the behaviour of open circuit and short circuit faults in an NPC converter. Section III shows the proposed solution to tackle the problem and also how it was implemented along with the problems we faced. Section IV shows the results of the identification system in a graphical form and is concluded in section V.

II. OC and SC Fault on 3-Level NPC Inverter

Neutral point clamped inverters include twelve power switches and six clamping diodes. The input DC-link voltage is equally distributed by two capacitors, shown in Fig. 1. It also includes a gate drive controller which sends gate signals to the NPC inverter switches. The diodes have the function to clamp the voltage of the switches equal to that of the capacitor voltage. In the open circuit and short circuit, fault identification is carried out using the current signal as our base parameter. Phase current behaves differently in the case of normal and abnormal operating conditions.

During healthy conditions, the magnitudes of positive and negative half cycle current waveforms are equal as shown in Fig. 2(a). Hence, the average value of phase current for a sample time is zero. During a fault condition, the current waveform goes through a significant distortion. As a result, the mean of phase current per cycle is different compared to that of normal conditions. The open circuit and short circuit switch faults are designed to analyse and identify appropriate fault diagnostic techniques.

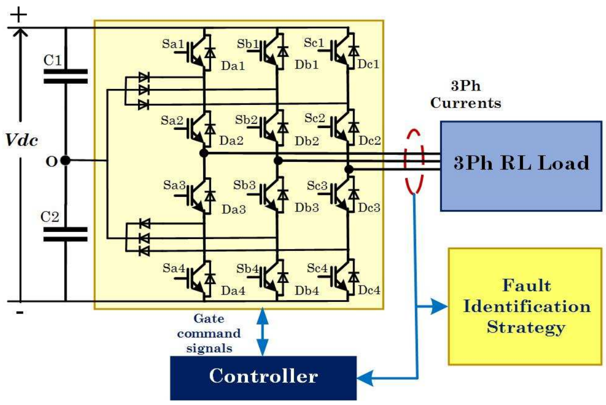

Fig. 1. NPC inverter circuit including gate drive controller

A. Open Circuit Fault

At a certain instant, an open circuit fault was induced in switches Sa1 and Sa2 with the two conditions (i) single switch fault, and (ii) double switch fault. It is observed that the magnitude of current in phase A reduces, but doesn't get clipped off completely. Further, if OC fault is induced in switch Sa2, the corresponding phase current waveform is affected more compared to that of switch Sa1. Fig. 2(b) shows the behaviour of the NPC inverter during OC faults. Double switch fault, switch S_{a1} is induced with OC fault at time 't = 0.05 secs' and switch Sa2 is induced with OC fault at 't = 0.1 secs'. In an event of an open circuit fault in any of phase A switches, the current waveform in phase B and phase C increases to compensate the reduction of current in phase A. In case of open circuit fault in Sa3 and Sa4, the system waveform shows similar results, but in the negative half cycle of phase A current.

B. Short Circuit Fault

In a short circuit fault induced in phase A, it is observed that the magnitude of current is distorted minimally. This distortion of current magnitude is significantly observed for short circuit faults in Sa2 and Sa3. As the terminals of the switches are shorted, it results in an open pass for the current to flow. Unlike a short circuit fault across the load which creates a zero impedance path for the current and hence the current increases exponentially. This behaviour is shown graphically in Fig.2(c).

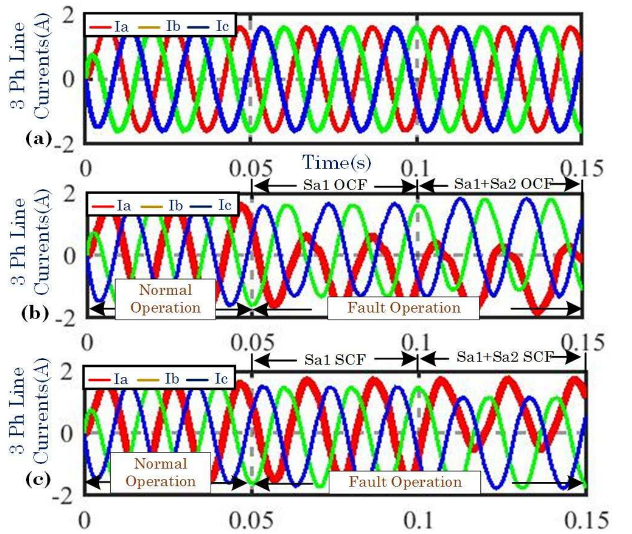

Fig. 2. Inverter output current waveforms under normal and fault conditions (a) Normal operation, (b) Single and double switch open circuit fault, (c) Single and double switch short circuit fault.

III. Fault Identification

The proposed system of fault identification is shown in Fig. 3. The solution comprises of three major components; computation of diagnostic variables, faulty phase identification and comparison of diagnostic variables with the pre-defined thresholds. The input and output variable of each

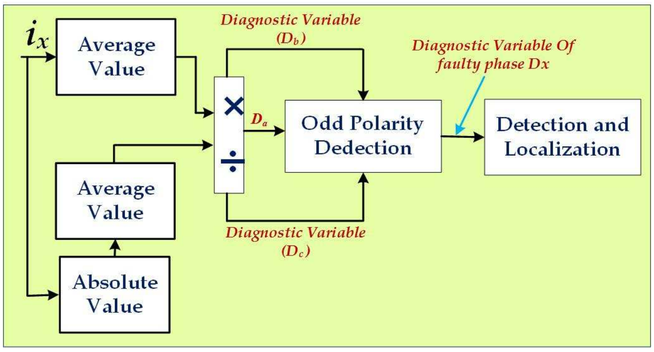

Fig. 3. Fault Identification Strategy.

components is represented. As discussed in Section II, the variation of current values during the OC and SC faults also affects mean values of phase currents. Considering this concept, normalised values of the phase current are chosen as parameters of interest for the project. The parameter can also be defined as the ratio of average current values to the average absolute current values. The formula for mean current and absolute current is calculated from equations (1)-(3). The ratio of these equations is referred to as the diagnostic variable (L_x) {x = a, b, c} of the corresponding phase.

$$Lx = \frac{\mathrm{i_{avg}}}{|\mathrm{i_{avg}}|} = \frac{\text{Mean value of x phase current}}{\text{Mean value of absolute phase current}} \tag{1}$$

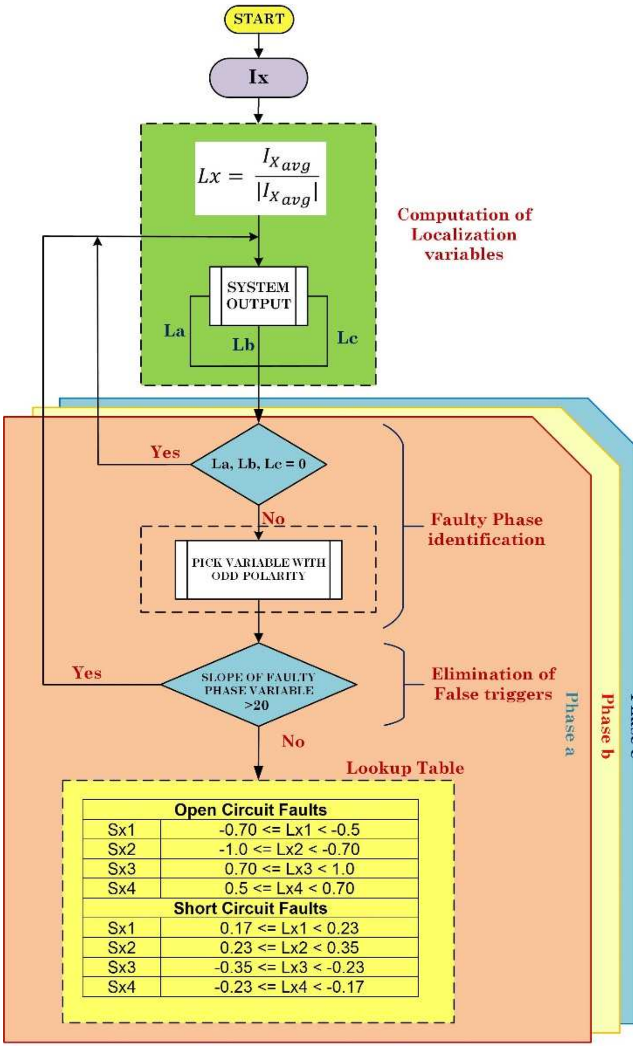

Fig. 4. Fault Identification algorithm with lookup table.

The mean value of the absolute current of the corresponding phase current is computed as follows:

$$i_{|avg|} = \frac{1}{N}\sum_{n=k-N+1}^{k} |i(n)| \tag{2}$$

The mean value of phase current is computed as follows:

$$i_{avg} = \frac{1}{N}\sum_{n=k-N+1}^{k} i(n) \tag{3}$$

It is crucial to note the steps in which fault identification is carried out for the proposed system. The first step in the proposed diagnostic system is to calculate the diagnostic variable. Utilizing these variables as a parameter of interest, localization of the faulty phase is carried out in the NPC converter. The next step is to eliminate the potential false triggers through slope computation mechanism. The final step is to compare the diagnostic variable of the faulty phase with pre-defined threshold ranges, which are set through intensive experimental analysis. The threshold ranges have been shown in the lookup table. Deployment of this chronological order avoids false alarms in the system. The working of the identification system has been comprehensively represented in Fig. 4. Similarly, Fig. 5 describes the simulation design used to test the proposed fault detection model.

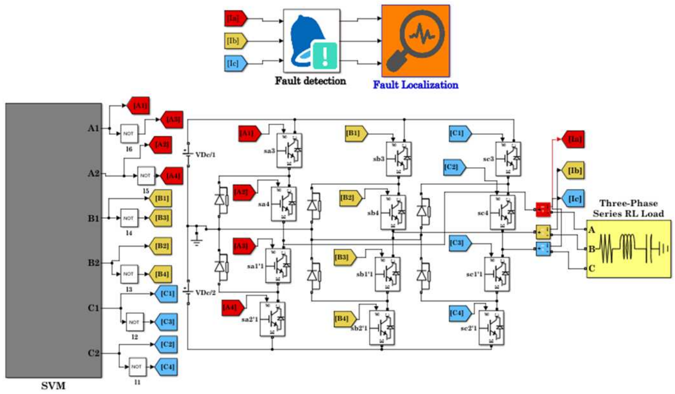

Fig. 5. Fault detection and localization simulink diagram.

A. Faulty leg identification logic

The diagnostic variables are fundamental for the proposed methodology as the deductions are carried out using these values. Identification of faulty phase is done by identifying the diagnostic variable which is an odd polarity. The phase corresponding to that variable is the faulty phase. Once, the faulty phase is identified, the fault variable corresponding to that phase updates its value to '1'. This action acts as a trigger for the rest of the diagnostic operation. The relation between fault variable and diagnostic variable has been depicted in Table I. As it can be observed through the following table, the diagnostic variables having an odd polarity triggers the corresponding fault variable.

TABLE I. FAULTY LEG IDENTIFICATION LOGIC

Diagnostic variables			Bit to integer	Faulty phase	Fault Variables		
D_a	D_b	D_c			F_1	F_2	F_3
+ / 1	- / 0	- / 0	4	A	1	0	0
- / 0	+ / 1	+ / 1	3	A	1	0	0
- / 0	+ / 1	- / 0	2	B	0	1	0
+ / 1	- / 0	+ / 1	5	B	0	1	0
- / 0	- / 0	+ / 1	1	C	0	0	1
+ / 1	+ / 1	- / 0	6	C	0	0	1

Once the diagnostic variables are computed, they are forwarded to 'sign' blocks, which outputs the polarity of the variable. If the variable is negative, the sign variable gives output as '0'. Whereas, if the variable is positive, the output is '1'. The output of the signature block for each phase is sent to the 'Bit to Integer' block, where it is concatenated into a vector. The vector is then converted into an integer value based on binary to decimal conversion. The bit to integer values of each fault case is also depicted in Table I. These integer values represent the exact location of the faults in the converter. Combinations of diagnostic variables and respective integer values are shown in Table I. After the comparison, the output of this subsystem is the fault variables F_1, F_2 and F_3. Whichever leg has the fault, the corresponding variables becomes '1' and no-fault phase variables becomes '0'.

B. Faulty switch identification logic

As mentioned in section II, during faulty conditions corresponding diagnostic variables behave in a certain way. This variation in the variables is dependent on the resistance and inductance values of the load. The threshold ranges have been set through intensive simulation tests on the system. During OC faults considering power switches Sa1 and Sa2, the positive half cycle of the current gets affected. As a result, the average value of the current becomes negative. And thus, the diagnostic variable also becomes negative. This suggests that an open circuit fault has occurred in one of the top two switches of the NPC converter. To accurately localize the faulty switch, the corresponding diagnostic variables are compared with the diagnostic threshold ranges. Similarly, for an open circuit fault occurring in power switches Sa3 or Sa4, the negative half cycle gets distorted. Hence, the diagnostic variable becomes positive. In short circuit faults concerning Sa1 and Sa2, the waveform is positively clamped. As a result, the average value of the current becomes positive. And thus, the diagnostic variable also becomes positive. This suggests that an open circuit fault has occurred in one of the top two switches of the NPC converter. Similarly for a short circuit fault in power switches Sa3 or Sa4, the current waveform is negatively clamped. Hence, the diagnostic variable becomes negative. As NPC inverters have 4 switches in one leg, the behaviour of the top two switches and bottom two switches is similar. The only difference between the behaviour of these variables is that the polarity is the opposite. Intensive Simulink tests of the proposed diagnostic system reveals that the variation of the diagnostic variable for a particular switch, during a particular faulty condition is limited to a range. Table II, shows the threshold ranges of each switch for open circuit and short circuit fault.

TABLE II. THRESHOLD DATA LOCALIZATION VARIABLE ASSIGNMENTS

Open Circuit Faults		Localization Variable
Sx1	-0.70 <= Lx1 < -0.5	1
Sx2	-1.0 <= Lx2 < -0.70	2
Sx3	0.70 <= Lx3 < 1.0	3
Sx4	0.5 <= Lx4 < 0.70	4
Short Circuit Faults		
Sx1	0.17 <= Lx1 < 0.23	5
Sx2	0.23 <= Lx2 < 0.35	6
Sx3	-0.35 <= Lx3 < -0.23	7
Sx4	-0.23 <= Lx4 < -0.17	8
		X = A, B and C Phases

The above threshold ranges were used in Matlab functions to implement the identification system. An integrated system for OC and SC fault identification has been implemented to accurately distinguish between the types of faults. The implementation of the following system is not straightforward as explained. In some cases, the diagnosis system shows false alarms as the diagnostic variable passes through the fault threshold range of another switch. Hence, until the diagnostic variable reaches a steady-state, precise identification of faulty switches is not possible. To overcome this problem a new variable has been created that will bypass the overlapping thresholds during the movement of diagnostic variable values.

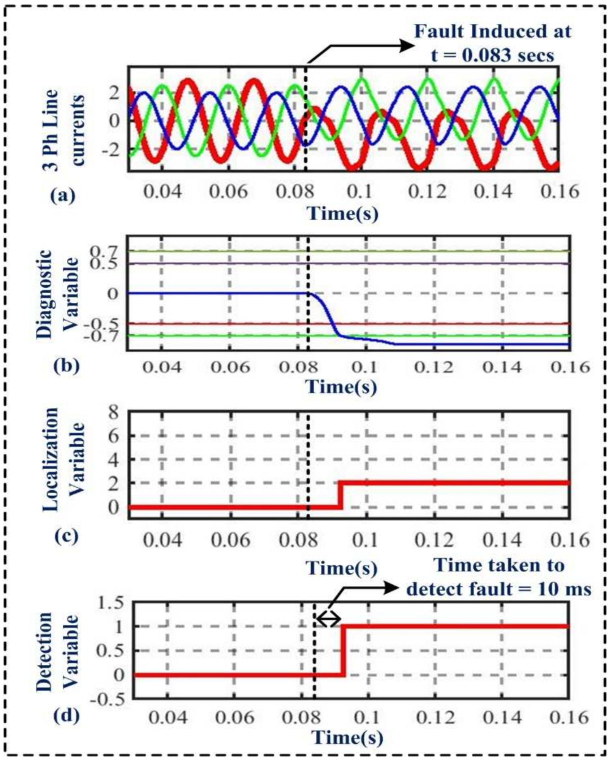

Fig. 6. Open circuit fault on positive switch (Sa2);
(a) Phase currents, (b) Diagnostic variable,
(c) Localization variable, (d) Detection variable

The variable introduced is the slope of the diagnostic variable. At the point where the fault is induced, the diagnostic variable undergoes steep movement in its values resulting in a significant amount of slope. After some time, the diagnostic variable reaches a steady state value and the value of the slope is minimal. After stabilization of the diagnostic variable, this particular variable is compared with the defined threshold ranges shown in Table II. The project is executed using Simulink as the simulation tool. For a visual representation of the fault type in the respective faulty leg, the proposed system also has a lamp indicator. Each switch has a lamp indicator that has been programmed in such a way that it lit up with a specific colour for the type of fault. The truth table for the lamp indicator is shown below in Table III.

TABLE III. COLOUR CODE FOR LAMP INDICATOR

Lamp Colour	Faulty Leg Identification
Red	Short circuit fault
Blue	Open circuit fault
Green	No-fault

IV. Result and Discussion

It is crucial to note that, the proposed system works on real time comparison of the diagnostic variable with the threshold ranges. A localization variable has been introduced to objectively represent which switch has a fault. It is represented by α, ß, and Γ for phase A, phase B and phase C respectively. Table II represents the identification mechanism using localization variable to accurately identify faulty switch In the case of Fig. 6, which is the case of power switch Sa2, after the occurrence of open circuit fault, diagnostic variable is decreasing and crosses the diagnostic threshold ranges of short circuit fault at Sa3 and Sa4, along with threshold range of open circuit fault in switch Sa1. However due to the steep movement of diagnostic variable, and deployment of the slope mechanism which has is explained in previous section, the system is able to avoid the false alarm. As depicted in Table II, the localization variable gives an output of '2' for OC fault in switch Sa2. Hence, the identification system is able to accurately diagnose the fault, detection variable (δ) this case is 10 milliseconds.

Unlike OC fault in switch Sa2, OC fault in switch Sa4 has distinct characteristics. In the case of Fig. 7 which is the case of power switch Sa4, after the occurrence of open circuit fault, diagnostic variable does not cross the diagnostic threshold ranges of any other switch, hence not triggering the slope mechanism. As the current waveform reaches negative half cycle the inverter realizes the open circuit fault. As depicted in Table II, the localization variable gives an output of '4', indicating an OC fault in switch Sa4. As the fault is diagnosed, the detection variable (δ) updates its value to '1'. In the graph, time taken to detect the fault after fault occurrence is also represented. The time utiilized to detect the open circuit fault in Sa4 is 7 milliseconds, and the detection

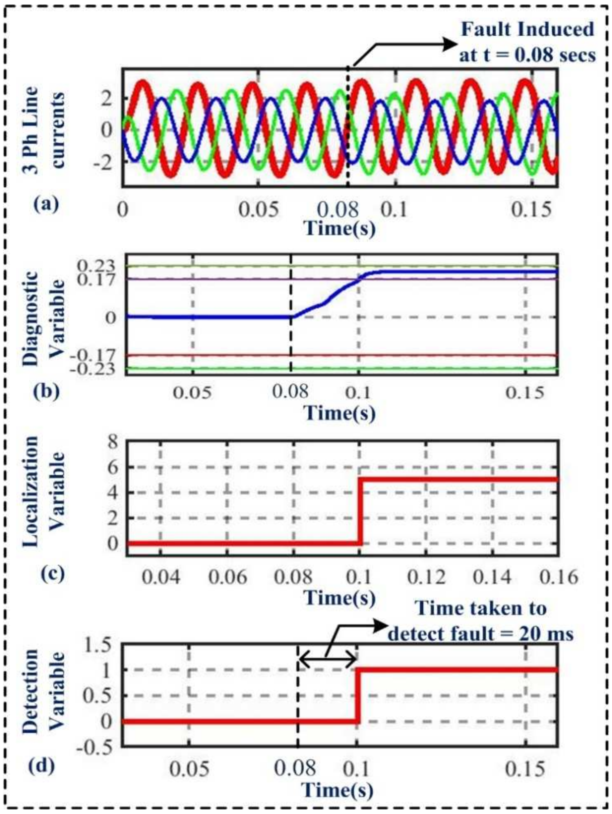

Fig. 8. Short circuit fault on positive switch (Sa1);
(a) Phase currents, (b) Diagnostic variable,
(c) Localization variable, (d) Detection variable

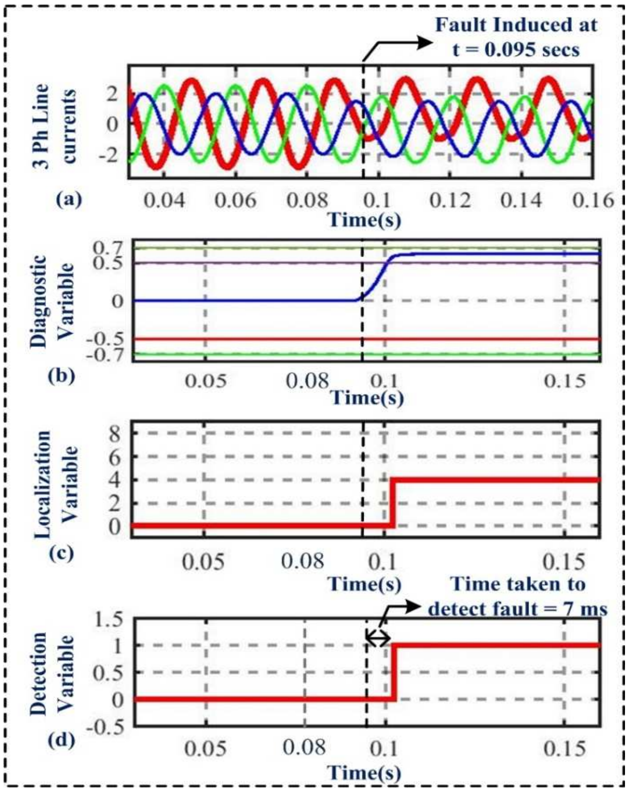

Fig. 7. Open circuit fault on negative switch (Sa4);
(a) Phase currents, (b) Diagnostic variable,
(c) Localization variable, (d) Detection variable

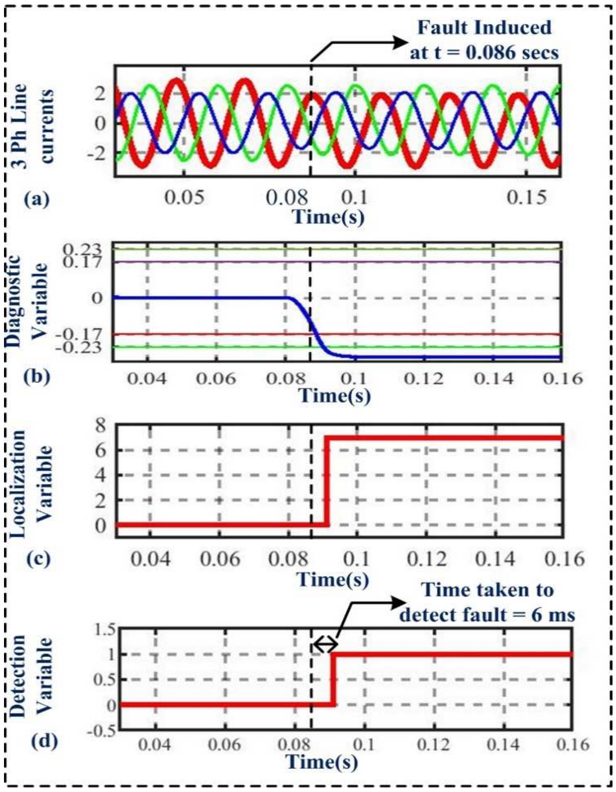

Fig. 9. Short circuit fault on negative switch (Sa3);
(a) Phase currents, (b) Diagnostic variable,
(c) Localization variable, (d) Detection variable

variable (δ) updates its value to ‘1’. In the graph, the time utilized to detect the fault after fault occurrence is also represented.

Fig. 8 and Fig. 9 represents short circuit case for switches Sa1 and Sa3 respectively. Contrary to open circuit, short circuit fault waveforms for NPC inverters do not show major distortions. Hence, the absolute values of diagnostic variable are smaller in value compared to open circuit fault cases. In the case of Fig.8, which is the case of SC fault in power switch Sa1, after the occurrence of fault, diagnostic variable does not cross the diagnostic threshold ranges any other switch, hence not triggering the slope mechanism. As the system realizes the fault, the localization variable gives an output of ‘5’, suggesting an SC fault in switch Sa1. As the fault is diagnosed, the detection variable (δ) updates its value to ‘1’. In the graph, time utilized to detect the fault after fault occurrence is also represented. The time taken to detect the short circuit fault in Sa1 is 20 milliseconds.

In the case of SC fault in switch Sa3, unlike the case of Fig. 9, the diagnostic variable crosses the diagnostic threshold range of other switches. As the diagnostic variable crosses the threshold ranges of other switches with a significant slope, the slope mechanism is able to prevent false alarms. The localization variable gives an output of ‘7’, suggestive of SC fault in power switch Sa3. Further, the detection variable also updates its value indicating a fault in the system. The time taken to detect the short circuit fault in Sa3 is 6 milliseconds. The fault detection time for different switches are mentioned in Table IV.

TABLE IV. TIME TAKEN FOR FAULT DETECTION

Switch induced with Artificial Fault	Time of Fault occurrence	Value of Localization variable	Time taken to detect fault (milliseconds)
Sa1	T = 0.080 secs	5	20 ms
Sa2	T = 0.083 secs	2	10 ms
Sa3	T = 0.086 secs	7	6 ms
Sa4	T = 0.095 secs	4	7 ms

V. CONCLUSION

The proposed method for fault identification has been successfully simulated through Matlab/Simulink. The time taken by the system is a crucial parameter, as longer durations of fault inheritance can damage the system. The proposed system is able to diagnose fault type in a range of 6 to 20 milliseconds. As the time taken to detect the fault is less, it is possible to avoid a follow-up fault by isolation of the phase from the fault. This enhances the reliability of the system. The proposed system has been successfully simulated for two different short circuit and open circuit fault test cases each. Further research should be done using research methods such as ‘Hardware-in-the-loop’. Additionally, research can be carried out to identify multiple short circuit or open circuit fault in converters. Similar techniques should be experimented with other types of inverters such as, five level NPC inverter, Cascaded H-bridge inverter, Cascaded multi-level inverters.

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