Efficient Fault Detection for Open Circuit Faults in HANPC Inverters Using Artificial Neural Network for Motor Drive Applications

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***Abstract*-- Open circuit faults are regarded as common faults that affect switching devices of the power converters. The early detection of these faults is a vital task in order to protect the other switching devices and the associated appliances such as motor drive systems. However, the conventional methods require different hardware devices to detect the variation in the current and voltage waveforms. Therefore, in this paper a creative method that use artificial intelligence by performing artificial neural network (ANN) to detect and identify the faulty devices effectively and precisely without the need to adapt additional hardware or modifying the original configuration of the inverter topology. The proposed ANN is trained using offline data and then tested and verified by applying it to hybrid active neutral point clamped (HANPC) topology. This topology is used to drive interior permanent magnet synchronous motor (IPMSM). The proposed method is verified by simulation results.**

***Index Terms*—Fault detection, HNPC, Open circuit, PMSM.**

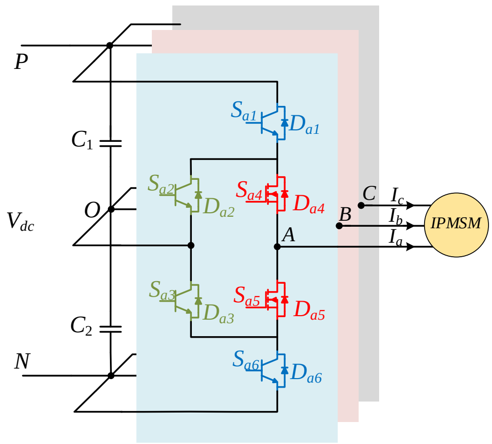

Fig. 1. Basic Single phase-leg circuit configuration of HANPC.

I. Introduction

Fault detection is an important aspect of power converters applications, which are widely used in various industries for motor drive appliances [1]. Open faults in power converters may lead to significant damage, leading to reduced productivity of the different industries. Inadequate detection of faults within power converters can potentially result in substantial damages, leading to a decline in productivity within diverse sectors. Hence, the presence of an efficient fault detection system becomes imperative to promptly identify any faults and initiate corrective measures before any severe harm is incurred [2], [3]. Motor drive applications find widespread use in diverse industries, including manufacturing, transportation, and energy sectors. These applications encompass a wide range of motors, from small ones employed in household appliances to large-scale ones utilized in heavy machinery, all of which are regulated by a power converter system [4]. Consequently, the effectiveness of fault detection in power converters assumes paramount significance to ensure the smooth operation and longevity of motor drive applications across numerous industrial fields. Open circuit faults in power converters can result from a wide range of factors, encompassing electrical, mechanical, and aging-related causes. Electrical faults often arise from conditions such as over-voltage, under-voltage, or over-current, which can overload the components and disrupt the normal operation of the converter [5]-[8]. Mechanical faults, on the other hand, can stem from issues like bearing wear or functional damage, which can impede the proper functioning of the converter system.

To detect and diagnose these faults, various methods can be employed, leveraging sensor technology and signal processing techniques. Sensors can be utilized to measure critical parameters such as converter output voltage and current, temperature, and switching behavior. These sensors provide real-time data that can be analyzed to identify any abnormalities or deviations from expected values, serving as indicators of potential faults.

Signal processing techniques play a crucial role in fault detection by analyzing sensor's data to extract meaningful information. These techniques involve filtering, feature extraction, pattern recognition, and statistical analysis [9]-[12]. By applying these methods to the collected data, it becomes possible to detect fault signatures and patterns that signify the presence of faults within the power

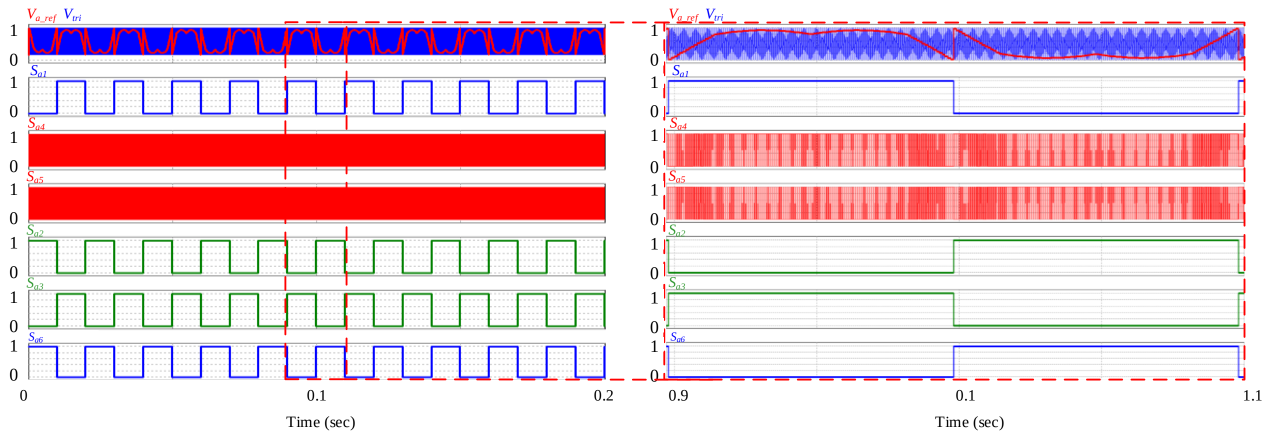

Fig. 2. PWM switching signals of HANPC detailed (left side) and zoomed (Right side).

TABLE I
CONVENTIONAL SWITCHING SEQUENCES WITH VOLTAGE OUTPUT AND STATUS

State	S_{a1}	S_{a2}	S_{a4}	S_{a6}	S_{a3}	S_{a5}	Output voltage
P	1	0	1	0	1	0	$V_{dc}/2$
O+	1	0	1	0	0	1	Off
O–	0	1	0	1	1	0	Off
N	0	1	0	1	0	1	$V_{dc}/2$

converter system.

Many methods were proposed using different approaches by employing the dwelling time [6], distortion in current and voltage waveforms [5], and artificial intelligence (*AI*) techniques [7]. However, these conventional methods can often be complex to configure and may require a significant amount of time to detect faults. Furthermore, they may be limited to specific converter topologies, making them less versatile. In this paper, a creative approach is proposed, utilizing an artificial neural network (ANN), to effectively and accurately detect and identify faulty devices without the need for additional hardware or modifications to the original inverter configuration. The proposed ANN is trained using offline data and then tested and verified by applying it to a hybrid active neutral point clamped (HANPC) topology. The data used for training includes; the average and normalized current for the three-phase system, the voltage difference of the DC-link capacitors, and the normalized angle. The proposed method is verified and demonstrated by simulation results.

II. Proposed Fault Detection method

In this section, the proposed fault detection method is explained. However, it is necessary to highlight the conventional operation of the converter and motor drive system.

A. Conventional Operation

Under conventional operation, the HANPC shown in Fig. 1 performs in a complementary performance of the switching devices. This involves the operation at two different switching frequencies; fundamental frequency (f_{fund}) of 50 Hz and hybrid frequency (f_{hyb}) of 30 kHz as clarified in Fig. 2. In this figure, *A* phase is considered to explain the operation of the converter. Four IGBT's labeled by (S_{a1}, S_{a2}, S_{a3}, S_{a4}, and S_{a6}) and two MOSFETs labeled by (S_{a4} and S_{a5}) are implemented in each phase leg. The operation of IGBTs are carried out based on the f_{fund} while the MOSFETs are operated at f_{hyb}, as the MOSFETs devices are able to operate at higher switching frequencies with lower switching losses, in addition to being able to handle higher junction temperature [8]. Therefore, the HANPC topology does not require even distribution of the switching losses between the switching devices.

Each kind of switching device (i.e., MOSFETs and IGBTs) are operated in a special switching sequence as presented in Table I in order to achieve all voltage statues (*P*, *O+*, *O–*, and, *N*). Under normal operation the system is able to achieve all voltage statuses and balanced the output waveforms (voltage and currents) and the input DC-link voltages (top and bottom) as shown in Fig. 3. Simulation parameters are shown in TABLE II. The system is able to achieve the maximum voltage at V_{dc} while each switch needs to block only half of the DC link voltage ($V_{dc}/2$) thus no additional requirements are needed to install devices with higher voltage blocking capabilities. In contrast,

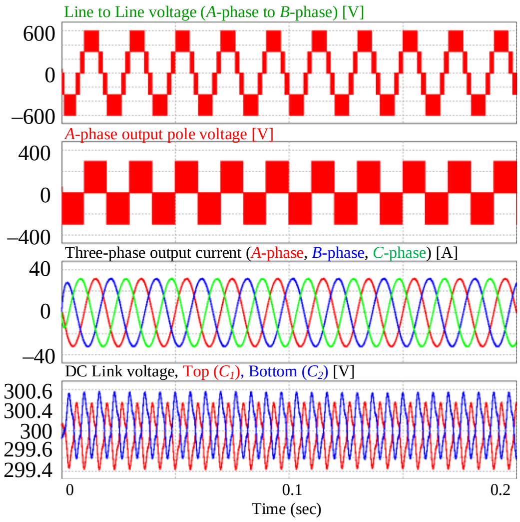

Fig. 3. Simulation result of the output waveforms under normal operation.

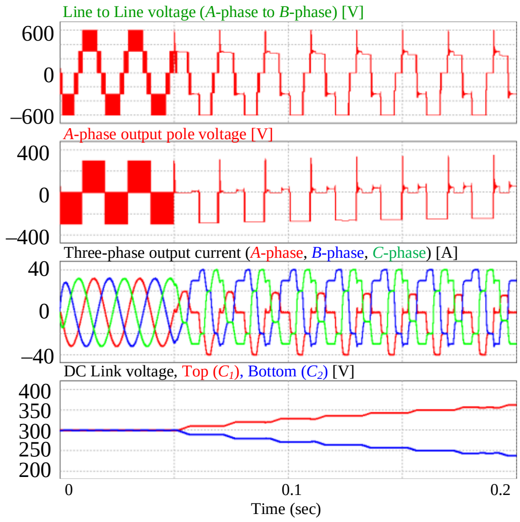

Fig. 4. Simulation result of the output waveforms under open circuit fault of S_{a1}.

under faulty conditions, the inverter could not achieve all of these voltage statutes due to losing some of the switching devices. This implies higher instability of the output waveforms which may result in unbalancing the voltage stress on the different switching devices and lead series of faults in the system as shown in Fig.4. In this figure an open circuit fault is occurring at the upper IGBT switching device which results in cutting the upper path of the current and losing the *P* voltage states. Due to this fault, the DC link voltage got unbalanced where the upper capacitor (C_1) keeps charging and the lower capacitor (C_2) keeps discharging. Meanwhile, open circuit faults are regarded as the most common faults in power conversion systems. In these regards, an accurate and effective fault detection method is needed for early detection and identifying the faulty devices.

B. *Proposed Fault Detection Method*

The effects of the fault appear clearly on the output voltage and current waveforms. However, some of these faults have similar effects, thus accurate fault detection is necessary. Meanwhile, due to the typical structure of the HANPC topology, faults at the upper part of the converter (i.e., S_{a1}, S_{a2}, and S_{a4} switching devices) are examined, where the proposed fault detection method is applicable for the lower part of the converter (i.e., S_{a3}, S_{a5}, and S_{a6} switching devices). The proposed method mainly depends on detecting the voltage and current waveforms as well as the current angle normalized those values and then applied the ANN to train the system to detect any faults.

The ANN is built using a multi-layer system using a single hidden layer only and trained using MATLAB software. Consequently, the weights and biases are applied to PSIM and Visual Studio software to perform the necessary simulation. Simulation parameters are highlighted in TABLE II.

Due to the similar effects on the voltage and current waveforms in addition to the effects of the noise on these waveforms, the phase currents need to be modified before being used. In this regard, the average value of each phase current is calculated as shown in (1),

$$I_{Nx\_ave} = \begin{cases} \int_0^{2\pi} \frac{I_a}{\sqrt{(I_{ds})^2 + (I_{qs})^2}}, \\ \int_0^{2\pi} \frac{I_a}{\sqrt{(I_{ds})^2 + (I_{qs})^2}}, \\ \int_0^{2\pi} \frac{I_c}{\sqrt{(I_{ds})^2 + (I_{qs})^2}}. \end{cases} \quad (1)$$

Where I_{ds}, I_{qs} are the reactive and active currents in a stationary reference frame, respectively. I_c, I_b, and I_c are the three-phase currents for *A*, *B*, and *C* phases, respectively. Where the voltage difference is calculated by using (2),

$$V_{Na} = \int_0^{2\pi} V_{top} - V_{bot}, \quad (2)$$

where V_{top} and V_{bot} are the voltage of the top and bottom capacitors C_1 and C_2, respectively. In addition, due to motor drive applications, the angle is necessary to be

TABLE III
SIMULATION PARAMETERS

Parameter	Value [Unit]
V_{DC}	600 [V]
$C1 = C2$	4700 [μF]
R	10 [Ω]
L	2 [mH]
f_{fund}	50 [Hz]
f_{hyb}	30 [kHz]

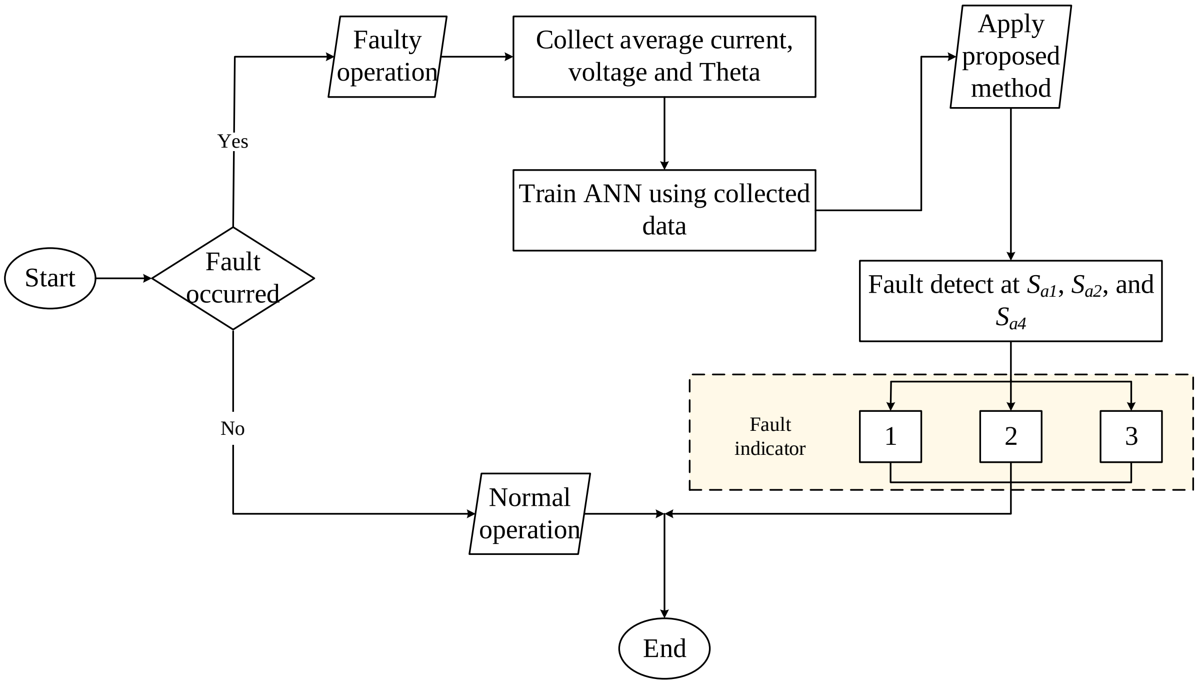

Fig. 5. Proposed method.

calculated in prior of detecting the faults, which is calculated as shown in (3),

$$\theta_{ave} = \int_{0}^{2\pi} tan^{-1}\left(\frac{I_{ds}}{I_{qs}}\right), \tag{3}$$

Where θ_{ave} is the average value of the current angle over one cycle. Fig. 5 summarized the proposed approach.

III. Results and Discussion

In this section, a comprehensive analysis and interpretation of the findings were attained through the proposed fault detection method using an artificial neural network (ANN) for power converters. This is obtained to provide a detailed examination of the performance, accuracy, and effectiveness of the developed approach in detecting and identifying faulty devices within the power converter system. The data is collected over one cycle of the system performance for four main cases. Case I, which includes the healthy operation. Case II – Case IV, includes the faulty cases after open circuit faults occurred at upper IGBT switch S_{a1}, Upper clamped IGBT switch S_{a2}, and Upper MOSFET switch S_{a4}.

The collected data for open circuit fault at S_{a1} is shown in Fig. 6, the effects clearly appear at the current waveforms, while losing the *P* states results in missing the upper part of the current waveforms. This lead to unbalancing the DC link voltage where the V_{Na} shows how the top capacitor (C_1) keeps charging and the bottom capacitor (C_2) discharged at a high rate, thus early detection is needed to avoid the accumulative fault effects. Additionally, the effects on the current angle is clearly appearing only after using the average value presented in (3). It is worth mentioning that in the case of an open circuit fault at the upper clamped IGBT S_{a2} the system loses the *O*– voltage states. This results in losing the zero crossing points (i.e, of the current output waveforms) as shown in Fig. 6b. In this case, the system losses the unbalance at a slower rate compared to the open circuit fault at S_{a1} and S_{a4}. Subsequently, when an open circuit fault occurred at S_{a4} the system loses the *P* voltage states in a similar way to the fault at S_{a1}, however, the distinguish lies at the average current angle as clarified in Fig. 6c.

Applying the proposed method shown in Fig. 5 and expressed in (1)–(3) leads to effectively detecting all faulty cases within the phase leg of the inverter. Fig. 7 shows the results of applying the proposed method while in all cases the normal operation (i.e., without fault) are labeled by (0).

The results presented in Fig. 7a show that the proposed method successfully identifies the open circuit fault at S_{a1}. By analyzing the collected data and applying the trained ANN, the fault detection algorithm accurately recognizes the fault condition and assigns the corresponding label (1) to signify its presence. This demonstrates the capability of the ANN to learn and recognize fault patterns from the training data and effectively can be generalize to real-time fault detection.

The successful detection and identification of the open circuit fault at S_{a1} highlight the potential of the proposed method in enhancing the reliability and performance of power converter systems. By promptly detecting faults and providing precise fault identification, the proposed approach enables timely corrective actions to be taken, minimizing the impact of faults on the system's operation and preventing further damage or failures. It is important to note that the effectiveness of the proposed method in detecting and identifying faults can be further assessed by

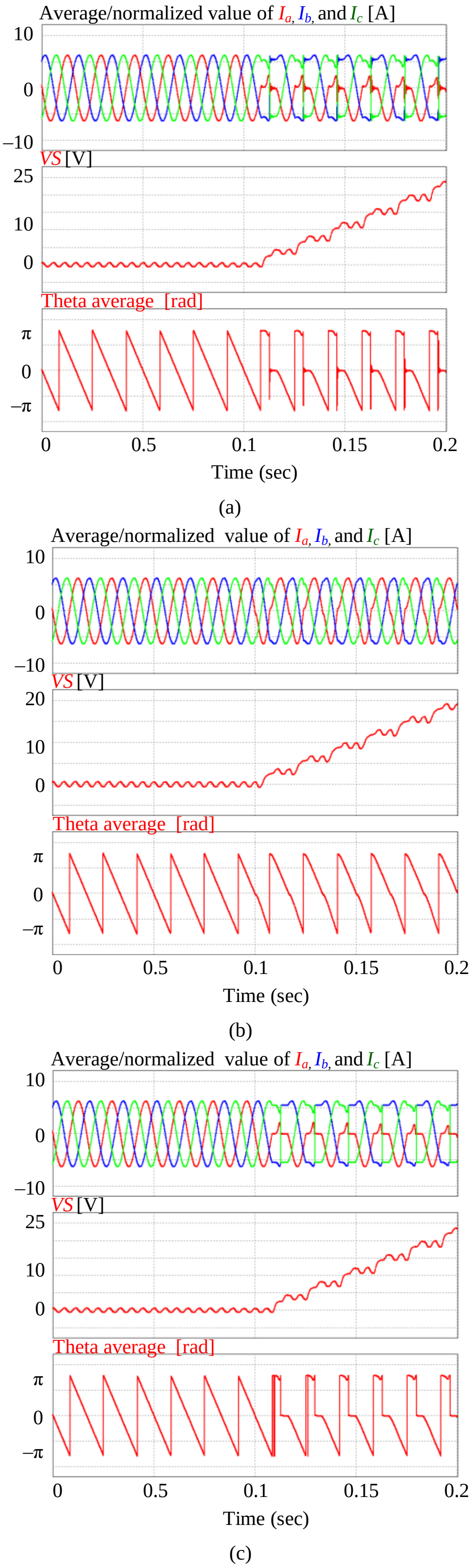

Fig. 6. Simulation result of an open circuit fault for the data used for training the ANN at fault in (a) S_{a1} (a) S_{a2}, and (a) S_{a4}

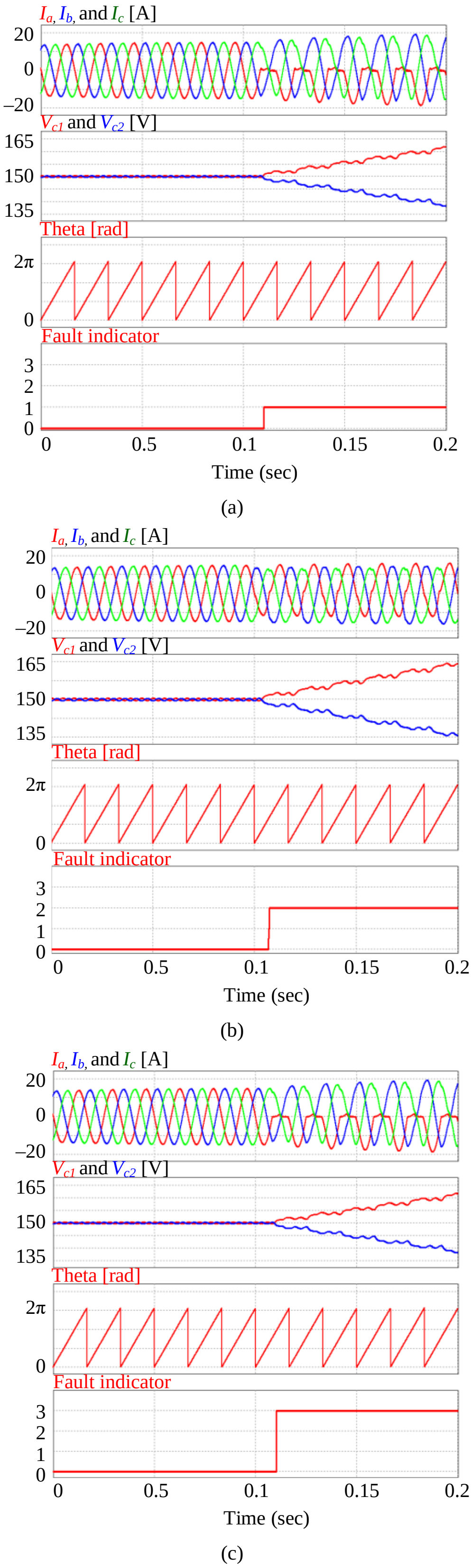

Fig. 7. Simulation result of an open circuit fault for the data used for training the ANN at fault in (a) S_{a1} (a) S_{a2}, and (a) S_{a3}

considering the remaining faulty cases.

Subsequently, in Fig. 7b, it is illustrated that an open circuit fault has occurred at the upper clamped IGBT S_{a2}. This fault scenario is characterized by the fault occurrence specifically at the zero crossing point and a relatively slower voltage difference between the top and bottom capacitors compared to the open circuit fault at S_{a1}. Despite these specific conditions, the proposed fault detection method demonstrates its effectiveness by accurately detecting and identifying this fault. The fault indicator is assigned to the corresponding label (2), which signifies the presence of the fault. Additionally, in this case, the voltage difference between the top and bottom capacitors exhibits a relatively slower rate compared to the previous fault case. These unique conditions may pose challenges to fault detection methods due to the specific characteristics and timing of the fault. However, the proposed fault detection method overcomes these challenges and effectively detects and identifies the open circuit fault at S_{a2}.

In Fig. 7c, it can be observed that a fault has occurred at S_{a4}, and the proposed fault detection method successfully detects and identifies this fault by assigning it the label (3). The similarity between this case and the case when an open circuit fault occurred at S_{a1}, is the effects on the average current angle. Despite the similarity in the fault effects, the proposed fault detection method effectively detects and identifies the fault in the system. This demonstrates the method's ability to operate quickly and accurately, regardless of the specific fault location within the power converter system.

The successful detection and identification of all faulty cases highlight the robustness and versatility of the proposed method. Despite the variation in the average current angle, the fault detection system remains effective in detecting faults in the power converter system. This capability ensures that faults can be promptly addressed, minimizing any potential disruptions or damages. The proposed fault detection method's ability to detect and identify faults accurately and swiftly across different fault locations within the system is crucial for maintaining the reliability and safety of power converter operations. By efficiently recognizing fault patterns and distinguishing them from normal operating conditions, the proposed approach enables timely interventions and preventive measures to be taken, enhancing the overall performance and longevity of the power converter system.

IV. CONCLUSIONS

Fault detection in power converters is a critical aspect of power converters, and efficient fault detection can significantly improve system performance to tolerate faults. In this paper, a creative and effective fault detection method is proposed. The proposed method perform ANN for the different cases of the open circuit faults in HANPC topology for IPMSM dive systems. The proposed method depends on calculating the average and normalized values of the three-phases currents, difference in DC-link voltage, and current angle. The proposed method effectively detects the faults at multi cases and accurately identified each case. The proposed method is verified in simulation results.

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