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Published in:
2023 58th International Universities Power Engineering Conference (UPEC)

DOI:
10.1109/UPEC57427.2023.10294468

Publication date:
2023

Document Version
Author accepted manuscript

Citation for published version (Harvard):
Ibem, CN, Farrag, ME & Aboushady, AA 2023, Open circuit fault diagnosis technique for inverter switches and gate drive malfunction. in *2023 58th International Universities Power Engineering Conference (UPEC).* IEEE, 2023 58th International Universities Power Engineering Conference, Dublin, Ireland, 29/08/23. https://doi.org/10.1109/UPEC57427.2023.10294468

Open Circuit Fault Diagnosis Technique for Inverter Switches and Gate Drive Malfunction

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***Abstract*—Open circuit faults (OCFs) in voltage source inverters (VSIs) can significantly affect their performance and reliability. In this paper, a novel fault diagnosis technique (FDT)is presented for the detection and classification of two types of OCFs in VSIs: gate drive malfunction (GDM) and open switch fault (OSF). the effect of these OCFs on the output current of the VSI is analysed, this shows that they can be identified and distinguished using the average and root mean square (RMS) ratio of the current parameters. The proposed FDT is simple to implement and can identify switch faults with quick response, without the need for additional equipment. In this work the authors adopted the ensemble bagged tree classification method to detect and classify the GDM and OSF, the results show the credibility of the proposed technique in identifying different open circuit faults.**

***Keywords*— Inverter, Fault diagnosis, gate drive malfunction, open switch fault, ensemble bagged tree.**

I. INTRODUCTION

Inverters are an integral component in various industrial applications, including renewable energy systems, backup power supplies, and variable drive speed systems [1]. Inverter failure can result in unplanned shutdowns and negative economic impacts. Voltage source inverters (VSIs) are popular due to their high efficiency, ability to drive multiple motors, and lower cost compared to current source inverters (CSIs) [2], [3]. However, studies have shown that VSIs are prone to faults, particularly in motor drive and wind energy conversion systems [3]. One key component of VSIs is the insulated gate bipolar transistor (IGBT) which is widely used due to its favourable operational characteristics, but they are also known to be prone to faults [4]. These faults can be caused by factors such as ageing, environmental conditions, and thermal stress on the IGBT or bond wire. These faults can be divided into short circuit (SC) faults and open circuit (OC) faults [5]. SC faults are usually catastrophic and must be promptly isolated or mitigated. Most protection schemes are designed to address SC faults by using specialized circuitry to minimize their impact. OC faults, on the other hand, do not immediately lead to system shutdowns, but they can degrade output quality and stress other components, potentially resulting in secondary failures [3], [5]. Therefore, it is important to detect OC faults early to prevent these secondary failures. Maintaining the reliability of IGBTs in VSIs is important for many applications, and fault diagnosis (FD) is an effective tool for achieving this goal.

There has been significant research on fault diagnosis techniques (FDT) and fault tolerant schemes for open circuit faults in power electronics systems. These techniques and schemes often follow a similar structure for fault identification and classification in voltage source inverters (VSIs) as shown in Fig 1. This structure typically involves the sensing of system parameters, feature extraction, fault identification, and classification. The system parameters that are typically sensed include current, voltage, and temperature. These parameters are then analysed, and fault signatures are extracted, which are used for fault identification and classification. OC faults in VSIs can be classified into two categories as shown in Fig. 2: gate drive malfunction (GDM) and open switch fault (OSF) [4], [6], [7]. GDM occurs when the gate driver is unable to send signals/pulses to the switch, resulting in an open IGBT switch while the complimentary diode is still connected. One example of a GDM fault is when the gate voltage falls below the required level, causing the IGBT to remain in the off state. OSF occurs when both the IGBT switch and diode are open. One example of an OSF fault is when an IGBT fails to turn on due to an open circuit in the collector-emitter junction, It is important to accurately identify and differentiate these OC faults to apply the appropriate maintenance or fault tolerance scheme to the VSI.

Fig. 1. Fault diagnosis structure

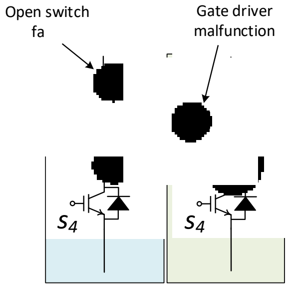

Fig. 2. Type of open circuit fault

II. OPEN CIRCUIT FAULT DIAGNOSIS METHODS

Fault diagnosis of inverters is crucial for ensuring the reliable and safe operation of inverter-based systems. Various approaches exist for inverter fault diagnosis, they include model-based, signal-based, and data-driven methodologies [3].

Model-based techniques primarily utilize the discrepancy between the analytical model and the real system after faults for fault detection. This approach includes establishing the mathematical model of the inverter, monitoring the current or voltage, and performing diagnosis by mapping the residuals to the fault indicators. Different models like the Switching State Function Model

(SSFM), State-Space Model (SSM), Mixed Logical Dynamic Model (MLDM), and Model Reference Adaptive System (MRAS) have been used. The switching state function model was used by authors in [8] to establish an estimated phase voltage and analyze switching states to detect gate drive malfunctions.[9] introduces a State-space model-based FDT where the Luenberger observer is employed to observe the stator current in the dq-frame, and if the residual exceeds a threshold, a fault can be detected. The drawbacks of the model-based approach are that it requires a precise analytical model and may not be able to detect unknown faults or disturbances that are not considered in the model.

Data-driven approaches utilize machine-learning techniques to detect and localize faults by extracting fault features and training artificial neural networks on these features. These methods do not require a precise system model but will need a robust feature extraction of fault signals for their performance. [10] employs a random vector functional network in combination with the three-phase current for fault identification and classification of GDM. High accuracy was achieved with a sample current time window length above 60 ms (around 3-4 cycles). In [11], [12] a wavelet analysis with support vector machine and fuzzy algorithms was proposed respectively for open circuit fault detection by opening the gate signal to the switches under investigation. Changes occurring in the three-phase current wavelet coefficients were used for fault identification and classification. This technique identified single and double switch faults. Wavelet parameters such as energy and entropy have been combined with machine learning algorithms for fault identification [13]. However, the data-driven approach is complex and the need for a large amount of data for training and validating machine learning algorithms are major concerns.

Signal-based techniques use variations in voltage or current signals between normal and faulty states to identify faults in an inverter. These signals include the current trajectory pattern, mean current, reference value, and current distortion. Various techniques have been proposed in the literature, including average current trajectory analysis based on the park vector technique by [14], [15]. However, this method is load-dependent, and to address this issue, [16] introduced the dc normalized current. Similarly, the mean current technique proposed by [17] can identify single and double-switch faults, while the root mean square (RMS) technique proposed by [5]identifies the faulty arm and switch using the normalized mean current. However, this technique cannot detect multiple switch faults and is prone to challenges affecting the normalization technique used in other approaches. Moreover, [4] developed an FD method for identifying OSF in the voltage source inverter based on measuring the RMS and average voltage output. Although this method can identify single and multiple switch faults, it requires the rated RMS voltage input at the start of the FD and cannot identify triple-switch faults. [3]criticized this method's effectiveness at low currents and approaching zero. Overall, the signal-based approach is simple and easy to implement in control units with minimum calculation required. Recent research focuses on signal and data-driven methods due to their simplicity and potential.

The literature review reveals drawbacks of existing fault diagnosis techniques for inverters, such as false alarms, complexity, lack of robustness, and the need for additional hardware. Most fault diagnosis techniques focus on gate drive malfunction (GDM), with limited research on open switch fault (OSF). No current technique accurately distinguishes between GDM and OSF in voltage source inverters (VSI), which is crucial for maintaining system reliability. In this paper, we introduce a novel fault diagnosis technique (FDT) to identify and differentiate between GDM and OSF open circuit faults (OCFs) in VSIs using output current parameters. Our approach leverages the average and root mean square (rms) ratio of the current and offers a simple implementation, rapid response time, and no need for extra hardware. We adopt the ensemble bagged tree classification method for detecting and classifying single or double GDM or OSF OCFs.

III. ANALYSIS OF THREE-PHASE INVERTER OPEN CIRCUIT FAULT

A. *Inverter model*

This paper uses a two-level VSI system which can be seen in Fig 3. A pulse width modulation (PWM) control is used to operate six IGBT switches connected to the RL load at the output. The model's parameter can be seen in Table A1.

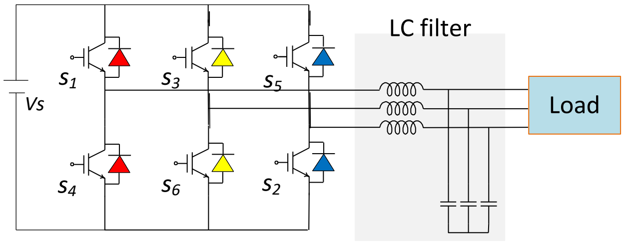

Fig. 3. Inverter model

B. *Fault analysis*

In this section, the effect of GDM and OSF on the output current will be critically analyzed. To illustrate the current path in the inverter during I > 0 and I < 0, the same leg switches S1 and S4 will be used. I > 0 can be described as when current flows from the source to the load and I < 0 is the reverse.

At normal conditions there are two signal commands on a inverter single leg, they are 01 and 10. When I < 0 the current passes through either D1 or S4. This depends on the switching command, If the switching command is 01 the current will flow through S4 back to the source. When the command signal is 10 the current flows through D1 back to the source. This scenario can be seen in Figs 4(a) and (b) respectively. When I > 0, the current will either flow through D4 or S1 depending on the switching operation if the signal is 10 the current path is S1 and if the signal is 01 the current path will be D4. This can be observed in Figures (c) and (d) respectively. The corresponding output current waveform of a balanced three-phase VSI is sinusoidal and can be seen in Fig 5. The waveform changes during faulty conditions, and the effect on the waveform will be determined by the type of fault.

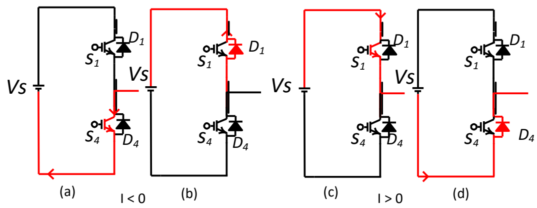

Fig. 4. The current path in normal condition

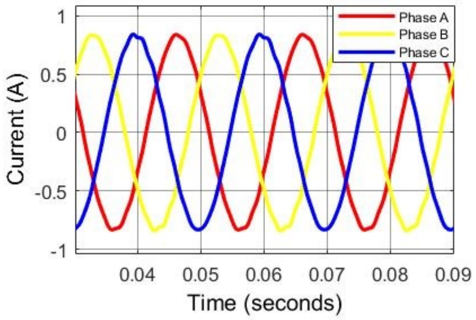

Fig. 5. Current at normal condition

a) *Gate drive malfunction analysis*

GDM creates an open circuit on the transistor switches only, S1 GDM will be used to illustrate the effect of GDM on the current path which can be seen in Fig 6. In Fig 6(a) and (b), it is observed the current pathway during I < 0 is not affected thus, current can flow through S4 or D1. However, during I > 0 as shown in Fig 6(c) and (d) current cannot flow through S1 but D1 can still conduct. The corresponding effect on the output current waveform can be seen in Fig 7. The positive half cycle of Phase A is not present, but the negative half cycle is and positive dc offset is introduced to Phases B and C.

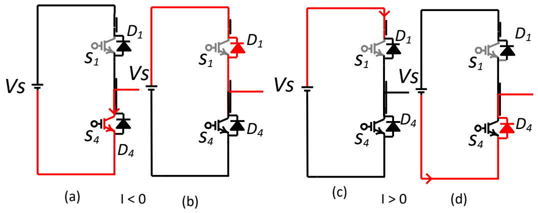

Fig. 6. Current path during gate drive malfunction

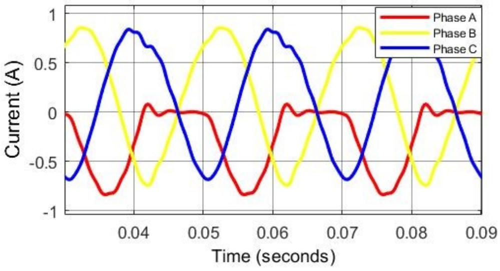

Fig. 7. Three-phase current under gate drive malfunction

b) *Open switch fault analysis*

In open switch fault (OSF) both the transistor and the diode are faulty as can be seen in Fig 8. Fig 8(a) and (b) show the current path when I < 0. The current can only go to the source through the S4 transistor if turned on. It will not go through D1 because D1 is faulty in this scenario. During I > 0, as shown in Fig 8(c) and (d), the current will flow from the source to the load through D4 but cannot flow through S1 because S1 is faulty. The effect on the three-phase output current waveform can be seen in Fig 9. We can also observe the positive half cycle of the phase A waveform is not present.

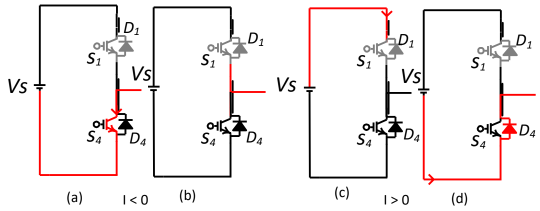

Fig. 8. Current path during open switch fault

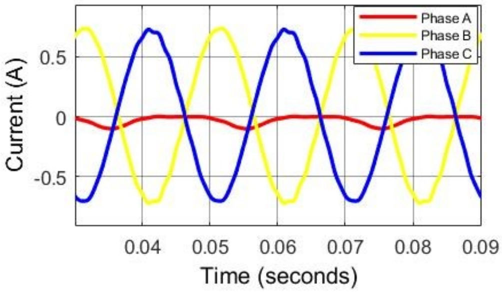

Fig. 9. Three-phase current under open switch fault

IV. PROPOSED FAULT DIAGNOSIS METHOD

As established in the previous section, the output current is affected during GDM or OSF conditions. This paper proposes an FDT for open circuit fault using the VSI three-phase current as a detection parameter. Thus, the characteristics of the sinusoidal signals can be evaluated and analysed during healthy and faulty conditions. This paper has chosen the average and rms current for fault identification. The proposed fault identification structure can be seen in Fig 10. The performance of the inverter model rms and the average current waveform was evaluated under normal, GDM, and OSF conditions in Fig 11. The inverter model was simulated over a period of 5 cycles from 0s to 0.1s, with a GDM or OSF introduced at 0.02s. The results for the rms current under these conditions are shown in Fig 11(a) and (b). During normal operation (0 - 0.02s), the rms current is balanced across all three phases. However, when a GDM is introduced, the faulty phase exhibits a drop from 0.58A to 0.4A, while the other two phases drop to approximately 0.55A. In the case of an OSF, the faulty phase shows a significant drop from 0.58A. The average current under normal, GDM, and OSF conditions can be seen in Figs 11(c) and (d). During normal operation (0 - 0.02s), the average current of all three phases is zero. When a GDM is introduced, the faulty phase changes from 0 to -0.2A, while the other two phases change to approximately 0.14A. In the case of an OSF, the faulty phase exhibits a change in average current to -0.03A. These differences between normal and faulty conditions can be used as indicators of a fault. The magnitude of the drop and average polarity can be used to differentiate between GDM and OSF and identify the faulty switch.

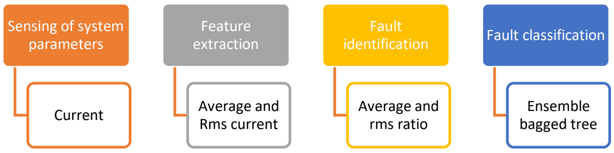

Fig. 10. Proposed fault diagnosis structure

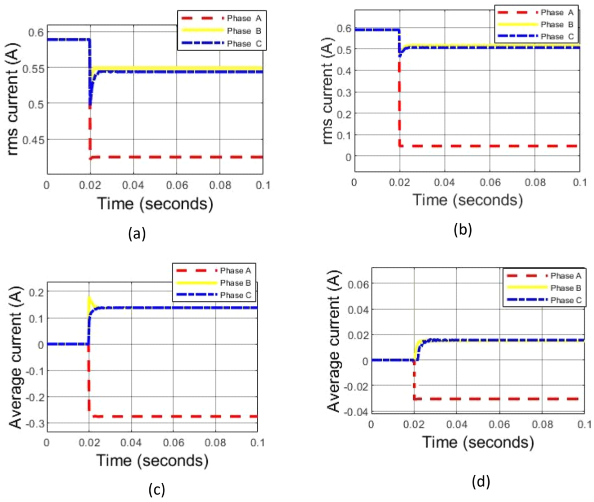

Fig. 11. (a) rms current during GDM (b) rms current during OSF (c) Average current during GDM (d) Average current during OSF

V. FAULT DIAGNOSIS

Drawing from the evaluation of average and rms current measurements previously discussed, these parameters can act as indicators to detect a faulty switch and determine the fault type. Consequently, a proposed signal-data-based diagnostic approach is introduced to identify the fault type and the faulty switch. To collect information on the inverter's status, the root mean square (rms) and average current values are calculated for each phase over one cycle using Equations (1) - (4). The simulated inverter, under both healthy and faulty conditions, produces rms and average current values to obtain fault signatures. Nonetheless, there are limitations in using each parameter individually for fault detection. While the rms can locate the faulty phase in the inverter, it cannot determine the specific faulty switch. Conversely, relying solely on the average current enables the identification of the faulty switch but cannot distinguish between one faulty phase and a normal condition. This paper proposes the combination of both parameters for a robust FDT.

To tackle the load dependency issue, this paper adopts a normalization technique that utilizes the ratio of average to rms current for each phase.

The sample data presented in Table A2 contains the generated data to be fed into a machine-learning algorithm for classifying the fault type and the malfunctioning switch under various loads. Table 1 lists all possible open switch faults and their respective fault labels, which will be employed to train the classifiers.

$$I_{avg} = \frac{1}{T}\int_0^T i(t)\,dt \qquad \text{Eq. 1}$$

$$I_{rms} = \sqrt{\frac{1}{T}\int_0^T i^2(t)\,dt} \qquad \text{Eq.2}$$

This can be represented in discrete form as:

$$I_{rms} = \sqrt{\frac{1}{N}\sum_{n=0}^{N-1} i^2\,(n)} \qquad \text{Eq.3}$$

$$I_{avg} = \frac{1}{N}\sum_{n=0}^{N-1} i(n) \qquad \text{Eq.4}$$

A. Ensemble classification

Ensemble learning is a supervised machine learning technique with a strong capacity for accurately predicting classification labels. This approach combines classifiers in series or parallel to enhance classification accuracy, generalizability, and robustness compared to using a single classifier. There are various types of ensemble methods, and this paper focuses on the bagging tree method. Bagging tree combines decision tree classifiers, resulting in a decrease in variance and bias, thereby improving overall accuracy. To boost the classifier output, this paper employs 30 learners within the bagged tree method.

VI. SIMULATION ANALYSIS AND RESULT

In this study, a three-phase DC-AC inverter was simulated under GDM and OSF scenarios. A simulation model was developed, incorporating the three-phase inverter under investigation and an ensemble classifier block fed with current root mean square (rms) and average measurements. The classification model applied ensemble classifications for the average/rms data samples, which were obtained from simulating the inverter during 12 scenarios of GDM and OSF. The flow chart of the proposed diagnosis technique is shown in Fig 13. The current output of the inverter is measured, and the average and rms values are calculated. These values are then sent to the trained classifier for classification, which identifies the type of fault (i.e., GDM or OSF) and the specific switch involved. The output of the classifier is indicated as a fault label representing the fault case, with full details provided in Table 1. The simulation analysis and results of the investigated technique are presented in this section, including a comparison of the performance and accuracy of different classifiers.

Table 1 Fault type labels

Fault type labels			
Fault type	Fault label	Fault type	Fault label
Healthy	0	S1 OSF	7
S1 GDM	1	S3OSF	8
S3 GDM	2	S5 OSF	9
S5 GDM	3	S4OSF	10
S4 GDM	4	S6 OSF	11
S6 GDM	5	S2 OSF	12
S2 GDM	**6**		

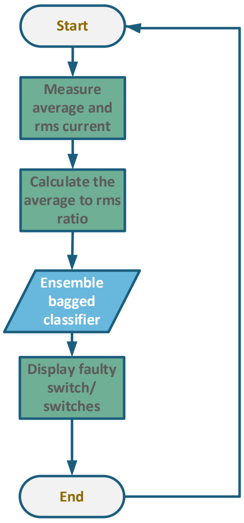

Fig. 12. Proposed FDT flow chart

A. *Load variation*

The average to root mean square (rms) ratio is an important factor in maintaining the stability of the system during load changes and avoiding misinterpretations of these occurrences. The time-domain waveforms of the phase currents during GDM and OSF along with the fault detection and average to rms ratio, can be seen in Figures 13a and b during various load changes. In Fig 13a, the three-phase load/impedance decreases from 9.5 Ω to 4.4 Ω at t = 0.1 seconds, causing an increase in the currents. The amplitude of the current increases from 0.8 A to 1.5 A, representing a variation of approximately 87%. At the same time, the average to rms ratio remains unchanged despite the load variation, indicating the absence of false alarms during this load change. A similar scenario can be seen in Fig 13b during GDM.

B. *Response time and switching frequency variation*

Figs 14 and 15 show the time-domain waveforms of the phase currents, fault detection, and average/root mean square (rms) ratio response time and during the switching frequency variation for GDM and (OSF). The inverter switching frequency is increased from 5 KHz to 20 KHz at t = 0.05 seconds, a change of approximately 400%. Despite the significant change in the switching frequency, the value of the average/rms ratio remains unchanged. This demonstrates that there are no false alarms during operation when the switching frequency is altered.

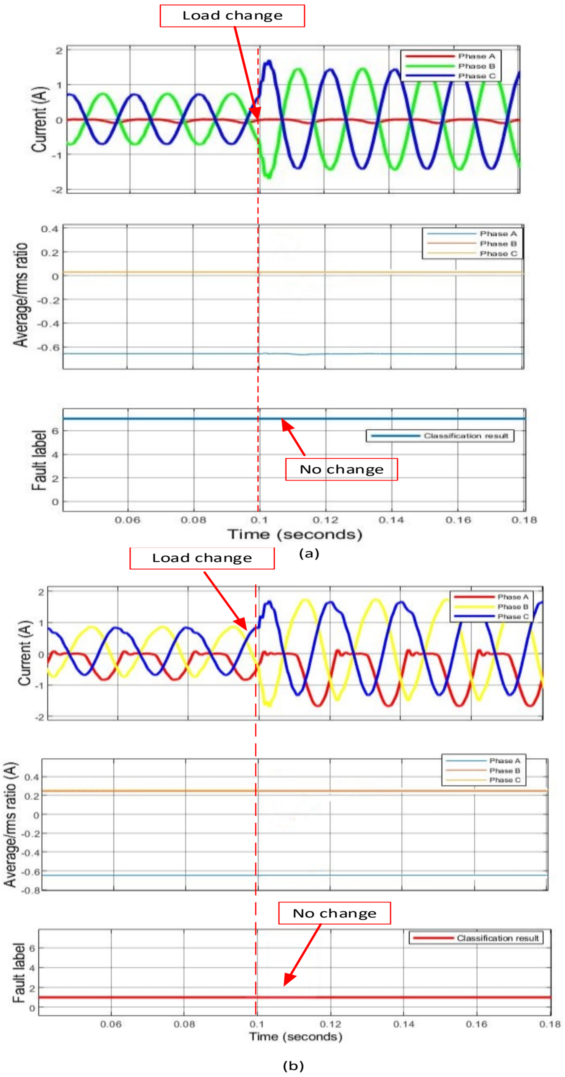

Fig. 13. Proposed FDT response on load variation during (a) OSF (b) GDF

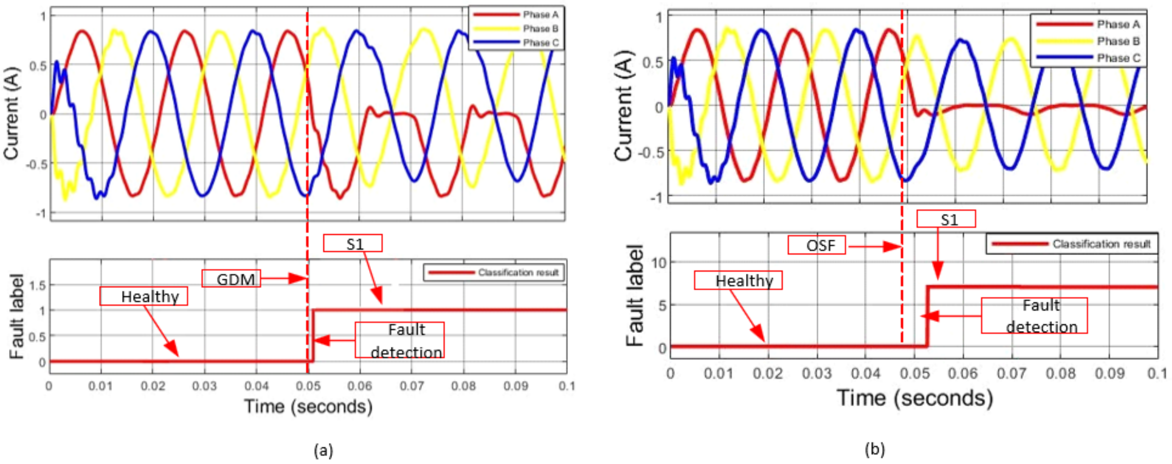

Fig. 14 Response time for (a) GDM (b) OSF

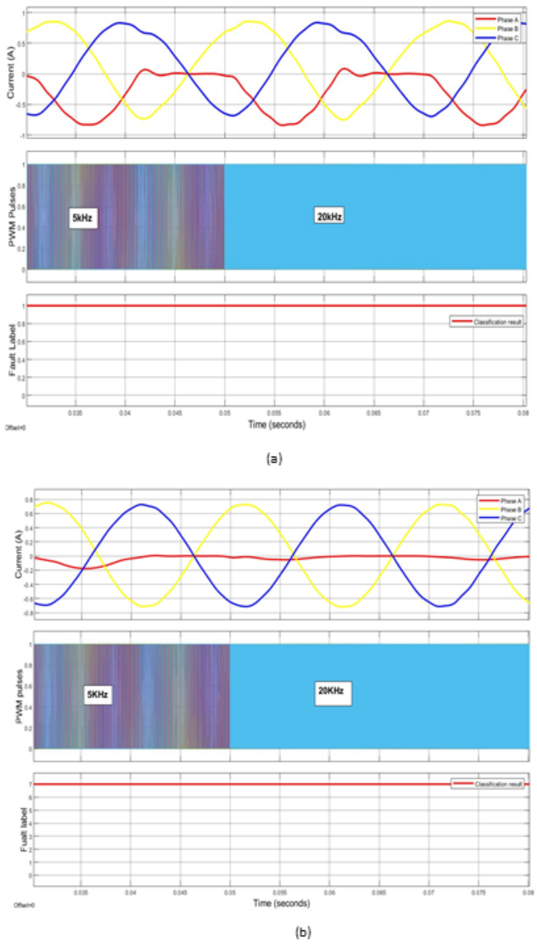

Fig. 15. Effect of varying switching frequencies on proposed FDT for (a) GDM (b) OSF

VII. CONCLUSION

In conclusion, this research paper has shed further light on the impact of gate drive malfunction and open switch fault on the output current of an inverter. A novel approach combining signal-based and data-driven fault diagnosis techniques was proposed and tested successfully for distinguishing between 12 scenarios of gate drive malfunction and open switch fault and identifying the affected switch. The diagnosis method demonstrated resilience to false alarms through the use of switching frequency variation and load-changing analysis and had a detection time of approximately one-quarter of the fundamental period. The introduction and verification of a new normalization method based on the average to root mean square (rms) ratio, and the utilization of the ensemble bagged classification method for fault classification, were key contributions of this research. Additionally, the simplicity of the fault diagnosis technique and the lack of required additional sensors make it easy to implement and cost-effective for manufacturers.

VIII. APPENDIX

Table A1 Model parameters

Parameters	Values	Parameters	Values
DC supply	100 V	RL Load	10Ω, 10e-3 H
Fundamental frequency	50 Hz	Modulation index	0.8
Carrier frequency	10 kHz	LC Filter	C= 25e-6, L =4.05e-3

IX. REFERENCES

[1] M. Ayyakrishnan, "Fuzzy Control Based Double Switching Fault Tolerant Control on Four Switch Voltage Source Inverters," J. Electr. Eng. Technol., vol. 17, no. 2, pp. 1031–1038, 2022.

[2] S. Lee, F. Chen, T. M. Jahns, and B. Sarlioglu, "Review on Switching Device Fault, Protection, and Fault-Tolerant Topologies of Current Source Inverter," 2021 IEEE 13th Int. Symp. Diagnostics Electr. Mach. Power Electron. Drives, SDEMPED 2021, pp. 489–495, 2021.

[3] K. Hu, Z. Liu, Y. Yang, F. Iannuzzo, and F. Blaabjerg, "Ensuring a Reliable Operation of Two-Level IGBT-Based Power Converters: A Review of Monitoring and Fault-Tolerant Approaches," IEEE Access, vol. 8, no. May, pp. 89988–90022, 2020.

[4] Y. O. Ajra, H. Al Sheikh, N. Moubayed, and G. Hoblos, "Fault Diagnosis of Open Switch Failure in Voltage Source Inverter Using Average and RMS Phase Voltages," 2021 Int. Conf. Innov. Intell. Informatics, Comput. Technol. 3ICT 2021, pp. 250–255, 2021.

[5] M. A. Khelif, A. Bendiabdellah, and B. D. Eddine Cherif, "A combined RMS-mean value approach for an inverter open-circuit fault detection," Period. Polytech. Electr. Eng. Comput. Sci., vol. 63, no. 3, pp. 169–177, 2019.

[6] S. M. Dabour and M. I. Masoud, "Open-circuit fault detection of five-phase voltage source inverters," 2015 IEEE 8th GCC Conf. Exhib. GCCCE 2015, no. 1, pp. 1–4, 2015.

[7] Z. Li, B. Wang, Y. Ren, J. Wang, Z. Bai, and H. Ma, "An average model-based transistor open-circuit fault diagnosis method for grid-tied single-phase inverter," Proc. IECON 2018 - 44th Annu. Conf. IEEE Ind. Electron. Soc., vol. 1, pp. 993–998, 2018.

[8] D. Zhou and Y. Tang, "A Model Predictive Control-Based Open-Circuit Fault Diagnosis and Tolerant Scheme of Three-Phase AC-DC Rectifiers," IEEE J. Emerg. Sel. Top. Power Electron., vol. 7, no. 4, pp. 2158–2169, 2019.

[9] R. Maamouri, M. Trabelsi, M. Boussak, and F. M'Sahli, "Mixed model-based and signal-based approach for open-switches fault diagnostic in sensorless speed vector controlled induction motor drive using sliding mode observer," IET Power Electron., vol. 12, no. 5, pp. 1149–1159, 2019.

[10] Y. Xia, B. Gou, Y. Xu, and G. Wilson, "Ensemble-based Randomized Classifier for Data-driven Fault Diagnosis of IGBT in Traction Converters," Int. Conf. Innov. Smart Grid Technol. ISGT Asia 2018, pp. 74–79, 2018.

[11] M. Fei, L. Ning, M. Huiyu, P. Yi, S. Haoyuan, and Z. Jianyong, "On-line fault diagnosis model for locomotive traction inverter based on wavelet transform and support vector machine," Microelectron. Reliab., vol. 88–90, no. June, pp. 1274–1280, 2018.

[12] R. B. Dhumale and S. D. Lokhande, "Comparative Study of Fault Diagnostic Methods in Voltage Source Inverter Fed Three Phase Induction Motor Drive," IOP Conf. Ser. Mater. Sci. Eng., vol. 197, no. 1, 2017.

[13] P. Achintya and L. Kumar Sahu, "Open circuit switch fault detection in multilevel inverter topology using machine learning techniques," PIICON 2020 - 9th IEEE Power India Int. Conf., 2020.

[14] A. M. S. Mendes and A. J. Marques Cardoso, "Voltage source inverter fault diagnosis in variable speed AC drives, by the average current Park's vector approach," in IEEE International Electric Machines and Drives Conference, IEMDC 1999 - Proceedings, 1999, pp. 704–706.

[15] B. Lu and S. K. Sharma, "A literature review of IGBT fault diagnostic and protection methods for power inverters," IEEE Transactions on Industry Applications. 2009.

[16] K. Rothenhagen and F. W. Fuchs, "Performance of diagnosis methods for IGBT open circuit faults in phase three-phase voltage source inverters for ac variable speed drives," Proc. Eur. Power Electron. Appl. Conf., pp. 1–10, 2005.

[17] Z. Jian-Jian, C. Yong, C. Zhang-Yong, and Z. Anjian, "Open-Switch Fault Diagnosis Method in Voltage-Source Inverters Based on Phase Currents," IEEE Access, vol. 7, pp. 63619–63625, 2019.