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REGULAR ARTICLE

Expeditious Identification of IGBT Switch Fault in Bidirectional Microgrid Inverter Linked to Distributed Energy Resources

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In contemporary power electronics, Insulated Gate Bipolar Transistors (IGBTs) are extremely important for various reasons. IGBTs serve as vital components in microgrid inverters, providing the switching capabilities required to transform DC electricity from renewable sources into high-quality AC power for microgrid (MG) applications. A bidirectional inverter (BDI) is an essential component of a microgrid, allowing for the smooth integration of distributed energy resources (DERs) and supporting both grid-connected and islanded operations. In a bidirectional DC/AC inverter (BDAI), IGBTs play an important role in managing the flow of electricity in both directions. The consequences of bidirectional inverter's IGBT failures on a microgrid might vary from small power quality concerns to more serious interruptions in stability and system performance. Therefore, IGBT should operate without failure. This paper illustrates a method for identifying an early IGBT switch failure (ISF) in a bidirectional microgrid inverter that is linked to a photovoltaic (PV) and battery energy storage system (BESS). An analysis of the inverter output current signal using the Fast Fourier Transform (FFT) has been undertaken to discover faults. Afterwards, the impacts on the DC, fundamental current component, and harmonic distortions have been investigated for various levels of fault. A successful detection of the ISF has been attempted, based on the best-fit features. An ISF detection algorithm also has been proposed.

Keywords: Bidirectional DC/AC inverter (BDAI), Distributed energy resources (DERs), Fast fourier transform (FFT), IGBT, Fault recognition, Microgrid.

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1. INTRODUCTION

Microgrid (MG) is a localized collection of electrical sources and loads that can function independently or in cooperation with the main power grid. MGs rely significantly on distributed energy resources (DERs) [1] to work properly. In contrast to a centralized paradigm where electricity is created at a big, frequently remote facility and transferred over long distances to end-users, DERs refer to a decentralized strategy for generating and supplying energy. A popular and successful strategy for developing a dependable and adaptable energy solution is combining photovoltaic (PV) systems [2] with battery energy storage systems (BESS) [3].

The use of power electronic converters is growing as a result of semiconductor device advancements, low volume, and affordable prices [4]. The vast majority of applications utilize voltage source inverters (VSIs) [5]. In MGs, to improve power controllability and energy efficiency many applications employ bidirectional inverters (BDIs) that are capable of transferring power into or from the AC mains [6, 7]. The high-power handling capabilities, efficiency, and diversity of IGBTs [8] across a wide range of applications make them indispensable in today's power electronics and greatly contribute to the development of dependable and energy-efficient electronic systems.

Voltage source converters (VSCs) are now being utilized in a lot of HVDC systems [9, 10]. In 2012, K. Nguyen-Duy et al. presented a single open circuit fault (OCF) in the bidirectional switch of the matrix converter (MC) system [11]. The authors of [12] propose a rapid diagnostic method for OCF in a nonsensical inverter. A novel method for detecting OCF in the single and double IGBT modules of grid-side converters (GSC) was proposed by J. Zhang et al. in 2020 [13]. M. T. Fard et al. in [14] presented the OCF in the current source inverter (CSI). Methods for identifying OCF in the IGBT-based inverter were presented by S.S. Moosavi et al. in 2019 [15]. A short

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circuit failure (SCF) detection technique for an islanded inverter was presented by S. F. Zarei et al. [16]. In 2024, the authors illustrated the failure recognition methodology of the IGBT switch in VSC [17].

However, there have been no noteworthy attempts to identify early IGBT switch failure (ISF) in a bidirectional inverter of MG. This paper proposes a unique approach for detecting early IGBT switch failure (ISF) in BDAIs. The ISF has been identified using the Fast Fourier transform (FFT). FFT [8, 18, 19] belongs to the frequency-domain analysis category. The frequency-domain analysis is more accurate than the time-domain analysis in differentiating between various transitory forms.

In this article, a bidirectional DC/AC inverter's output phase current has been acquired to identify ISF. To diagnose the ISF, a variety of parameters have been monitored using the FFT, including the DC component (DCC), fundamental component (FC), total harmonic distortion (THD), and sub-harmonics (SHCs) of the output current of the BDAI.

The article is organized in the following manner. DERs linked to BDI are illustrated in Section 2. Section 3 presents the issue statement. In Section 4, the failure recognition methodology has been presented. Specific outcomes and comparative learning have been discussed in Section 5 and Section 6 respectively. The conclusions are outlined in Section 7.

2. DISTRIBUTED ENERGY RESOURCES LINKED BIDIRECTIONAL DC/AC INVERTER

Fig. 1. depicts a schematic representation of the grid-connected PV system, including a unidirectional DC/DC converter (UDDC), a bidirectional DC/DC converter (BDDC), a BESS, and a bidirectional DC/AC inverter (BDAI). The PV system has a 100.7 kW rating and is linked to a 66 kV grid. A DC/DC converter has been employed to connect the PV system to the HVDC bus. The UDDC is used by the Maximum Power Point Tracking (MPPT) control to extract the maximum amount of power from the PV system. A controller that combines a Battery Control System and a Power Conditioning System is also employed here.

To identify ISF in the BDAI, the BDAI's output current has been thoroughly monitored for both normal and faulty circumstances of the IGBT switch.

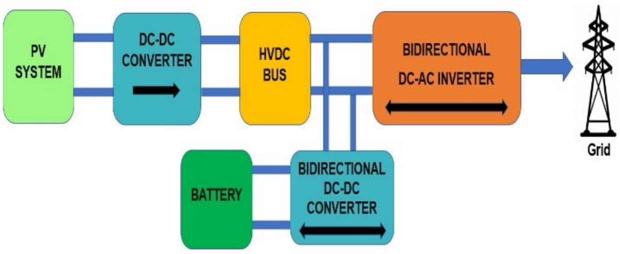

Fig. 1 – Schematic diagram of the grid-connected PV system, including a unidirectional DC/DC converter (UDDC), a bidirectional DC/DC converter (BDDC), a BESS, and a bidirectional DC/AC inverter (BDAI).

The BDAI's output current has been measured under typical circumstances and at various failure percentages (%) of the ISF.

3. ISSUE STATEMENT

In this study, the IGBT-based BDAI is linked to DERs and the electric grid. The BDAI's IGBT switch fault is taken into account for fault analysis. A very unexpected issue is the IGBT switch fault. The problem is characterized as one that leaves the path open following the failure. It may happen as a result of an excessive current increase that raises the temperature and causes IGBT switch burnout also it may happen as a result of a voltage spike that breaks down insulation. It breaks the circuit that alludes to opening the passage in both situations.

IGBT switch protection is very complicated and challenging, which means that when a fault occurs, the heat accumulation during the desaturation phase can destroy it. The developing defect in the very initial phases of an IGBT switch malfunction, the current rate is essentially unrestricted [9].

As a result, rapid and successful identification of ISF is extremely important. Therefore, an attempt was made in this study to discover the progressive increase in BDAI's IGBT switch failure. It should be emphasized that the designer's selection determines both the amount of defects and the system parameters. ISF detection is essential for preventing damage to the system.

4. FFT-BASED FAULT DIAGNOSIS

The Fourier Transform (FT) and Fast Fourier Transform (FFT) [18] both are mathematical methods that convert a function of time into a function of frequency. One essential tool for signal processing is the FFT, which makes it possible to analyze and manipulate data in the frequency domain effectively. Compared to the FT, the FFT is quicker [8]. To analyze a signal's frequency content and facilitate the identification of particular elements or patterns, FFT is useful.

The BDAI's output current is carefully examined in this investigation to detect ISF in BDAI. To identify the ISF problem, a variety of metrics related to the output current of the BDAI have been observed based on the FFT, including the DCC, FC, THD, and SHCs.

4.1 FFT-Integrated Pattern Creation

The BDAI's collected current signal has undergone FFT analysis in both standard operating conditions and at various ISF percentage levels (% ISF). The analysis to identify the ISF in BDAI utilizes the collected signals of the BDAI output current and the BDAI's captured current signal's FFT window, respectively, as shown in Figs. 2 and 3.

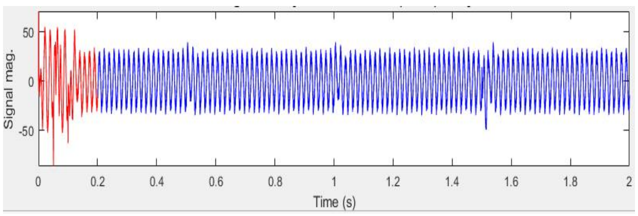

Fig. 2 – Captured output current signal of BDAI

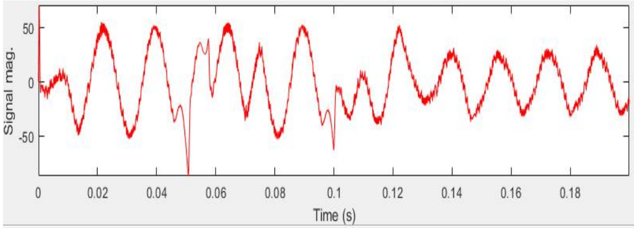

Fig. 3 – FFT window of BDAI's output current

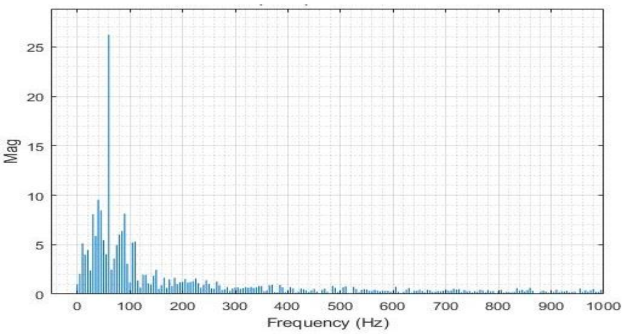

Fig. 4 – Signal spectrum of the BDAI's output current

4.1 Extractions of Low-Frequency Features

4.2.1 Assessment of Fundamental Current Component (FCC)

FCC analysis in the context of FFT is the technique of obtaining the fundamental frequency component (FFC) from an electrical signal. The FFT findings are used here to retrieve the FCC's amplitude and phase information.

The fundamental element has been derived from the BDAI output current for various ISF percentage values in BDAI, and it is displayed in Fig. 5.

Graphical analysis of Fig. 5 clearly illustrates that the principal frequency component of the BDAI's output current and the various percentage values of the ISF are not properly correlated. So, this feature cannot be employed to identify ISF in the BDAI.

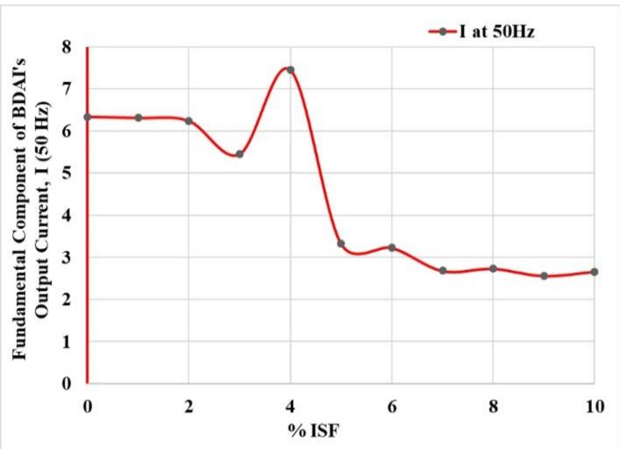

Fig. 5 – FCC versus % ISF

4.2.2 Comprehensive Analysis of THD

THD [18] is a measure of the harmonic content present in a signal. The following can be used to express THD:

$$THD(\%) = \frac{\sqrt{I_2^2 + I_3^2 + ... + I_n^2}}{I_1} \times 100 \quad (1)$$

Here, I_1 and I_2, I_3,……, I_n are the root-mean-square value (RMS) value of the fundamental frequency and the RMS values of every separate harmonic element. The THD values for the analysis of ISF have been retrieved for various percentages of ISF in BDAI, as shown in Fig. 6.

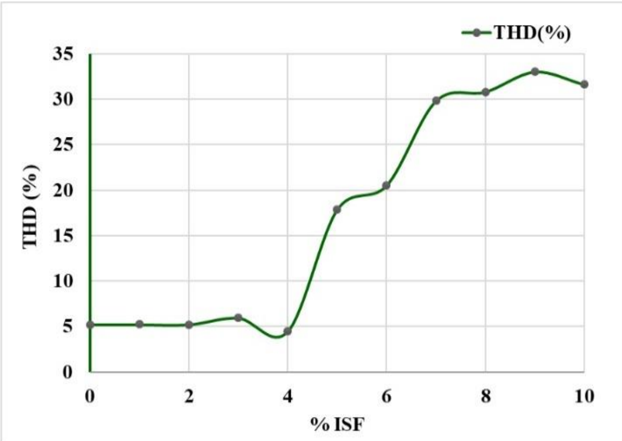

Fig. 6 – THD (%) versus % ISF

It illustrates that although ISF percentage values vary, THD(%) values remain constant up to 2% of ISF. An additional finding from Fig. 6 indicates that the THD(%) value increases along with the percentage of ISF in BDAI up to 3%. However, the THD(%) value steadily drops until 4% of ISF after 3% of ISF. Following 4% of ISF, the THD(%) value rises once again until the ISF value reaches 9%. Additionally, the graphical evaluation of Fig. 6 does not offer substantial evidence for the diagnosis of ISF.

4.2.3 Assessment of Current Subharmonics

From the recorded BDAI output current, sub-harmonics (SHCs) have also been retrieved. From the collected signal, every subharmonic component has been carefully examined for various ISF percentage values. Fig. 7 demonstrates how all sub-harmonic values vary in tandem with an increase in the percentage of ISF.

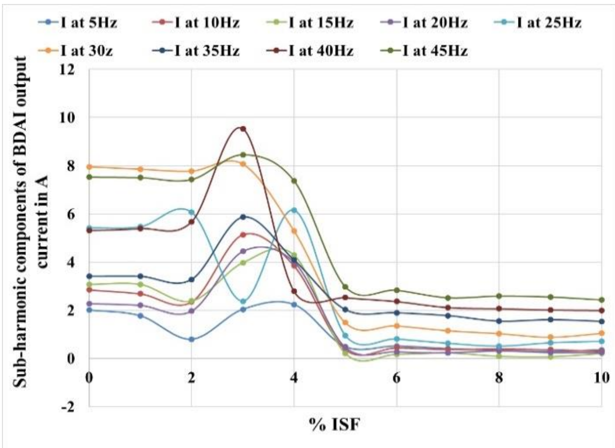

Fig. 7 – SHCs versus % ISF

5. SPECIFIC OUTCOME

The early portion of this study comprised FFT-based signal monitoring for several parameters such as the FCC, THD, and SHC of the BDAI's output current. However, no meaningful results from these assessments can be achieved that may be utilized to detect ISF in BDAI.

Meanwhile, the standard deviation values (SDV) and mean values (MV) for the variation in values of all the sub-harmonics for various ISF percentages have been acquired and are shown in Fig. 8 for ISF analysis.

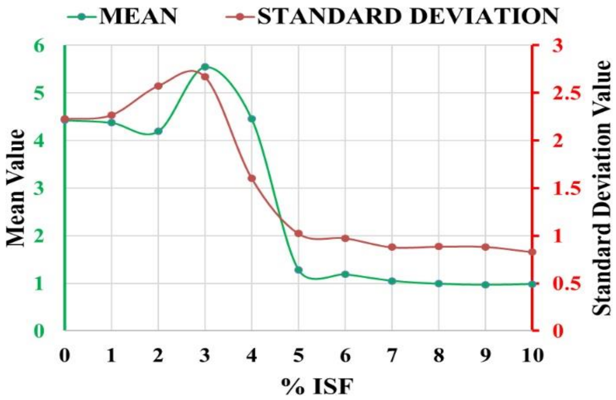

Fig. 8 – MV and SDV of the sub-harmonics versus % ISF

From the graphical assessment of Fig. 8, it can be clearly observed that the SDV of the sub-harmonics obtained from the BDAI's output current increases to 3% of ISF thereafter it decreases as the ISF increases to 10%. As a result, it can be discovered that the earlier identification of ISF (up to 3% of ISF) in BDAI is only achievable by closely monitoring the SDV of the subharmonics.

6. COMPARATIVE LEARNING

Table 1 presents a comparison investigation of several inverter fault detection approaches with the suggested strategy.

Table 1 – Comparative Analysis

Ref.	Identifying Faults	% of the Fault Detection Capacity
[11],[12]	OCF in MC and nonsensical inverter	No
[13]	OCF in IGBT modules of GSC	No
[14],[15]	OCF in CSI and IGBT inverter	No
[16]	SCF in islanded inverter	No
Proposed method	ISF in BDAI	Yes

7. CONCLUSION

The statistical evaluation utilizing FFT on the BDAI output current has been conducted in this study to identify ISF. Both in ideal and flawed circumstances, it was noted that the values of parameters vary.

From the comparative learning, it was also found that the suggested technique further enables the calculation of the ISF percentage in the BDAI.

Furthermore, it was discovered that the FFT-based fault detection approach effectively detects ISF early in BDAI. Therefore, early ISF identification in BDAI is possible by constant monitoring of the subharmonics' SDV. The system may therefore be properly protected from costly damages by using the suggested approach.

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Оперативна ідентифікація несправності перемикача IGBT у двонаправленому мікромережевому інверторі, пов'язаному з розподіленими енергетичними ресурсами

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У сучасній силовій електроніці біполярні транзистори з ізольованим затвором (IGBT) надзвичайно важливі з різних причин. IGBT служать життєво важливими компонентами інверторів мікромережі, забезпечуючи комутаційні можливості, необхідні для перетворення електроенергії постійного струму з відновлюваних джерел у високоякісну енергію змінного струму для додатків мікромережі (MG). Двонаправлений інвертор (BDI) є важливим компонентом мікромережі, що забезпечує безперебійну інтеграцію розподілених енергетичних ресурсів (DER) і підтримує як підключену до мережі, так і автономну роботу. У двонаправленому інверторі постійного/змінного струму (BDAI) IGBT відіграють важливу роль в управлінні потоком електроенергії в обох напрямках. Наслідки збоїв двонаправленого IGBT інвертора в мікромережі можуть варіюватися від невеликих проблем із якістю електроенергії до більш серйозних перебоїв у стабільності та продуктивності системи. Тому IGBT повинен працювати без збоїв. Ця стаття ілюструє метод виявлення ранньої несправності перемикача IGBT (ISF) у двонаправленому інверторі з мікромережею, який підключено до фотоелектричної (PV) системи зберігання енергії від акумулятора (BESS). Для виявлення несправностей було проведено аналіз сигналу вихідного струму інвертора за допомогою швидкого перетворення Фур'є (ШПФ). Після цього було досліджено вплив на постійний струм, фундаментальний компонент струму та гармонійні спотворення для різних рівнів несправності. Була спроба успішно виявити ISF на основі найкращих характеристик. Також був запропонований алгоритм виявлення ISF.

Ключові слова: Двонаправлений інвертор постійного/змінного струму (BDAI), Розподілені енергетичні ресурси (DER), Перетворення Фур'є (FFT), IGBT, Розпізнавання несправностей, Мікромережа.