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REGULAR ARTICLE

Identification of GTO Switch Fault in Voltage Source Inverter in PV Integrated Microgrid

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Microgrid inverters (MGIs) employing gate turn-off thyristor (GTO) technology are used in both grid-tied and off-grid microgrids (MGs), where they are essential for controlling power flow and maintaining system stability. The ability of GTOs to withstand high voltages and currents is crucial in power conversion systems that require substantial power levels. GTOs in voltage source inverters (VSIs) are used to convert DC electricity from renewable energy sources, such as photovoltaic (PV) systems, wind turbines or energy storage systems, into AC power that is suitable for use in MGs. An MG's GTO switch failure (GSF) in three-phase (3Ph) VSI can result in several issues, such as diminished power production, safety issues, unstable voltage and frequency, loss of grid connection, overcurrent or overvoltage situations, and operational downtime. Minimizing the impact of such issues on MG operations requires careful maintenance, monitoring, and fault detection techniques. An approach to determine GSF in a PV system-connected 3Ph VSI for the MG application is demonstrated in this study. To identify GSF, a Fast Fourier Transform (FFT) based analysis of the 3Ph VSI's output current signal has been conducted.

Keywords: Fast Fourier Transform (FFT), Fault detection, GTO, Microgrid, PV system, Voltage source inverter (VSI).

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1. INTRODUCTION

With the incorporation of renewable energy sources (RESs), microgrids (MGs) [1, 2] have become a significant advancement in contemporary power systems. MGs make the electricity system more ecologically friendly and sustainable by utilizing renewable energy sources (RESs) and encouraging energy efficiency. To increase energy resilience, encourage self-sufficiency, and encourage environmental stewardship, PV systems [3] are crucial parts of MGs. They provide a clean, dependable, and sustainable source of electricity. By producing power throughout the day, when demand is frequently highest, PV systems can assist in reducing peak demands within the MG. As a result, there is less need to use the main grid to obtain power during peak hours, which lowers electricity bills and eases the burden on the grid.

Advanced semiconductor devices, low volume, and reasonable pricing are driving an increase in the use of power electronic converters [4]. VSIs [1] are essential to microgrid systems because they improve their efficiency, stability, and capacity to incorporate RESs. MGs frequently run in two modes: grid-connected, when they are synchronized with the main grid, or islanded when they are not linked to it. VSIs regulate power flow and uphold grid stability when connecting or detaching from the main grid, making it easier for the grid to switch between different modes smoothly. VSIs are used in the great majority of applications [5]. The DC output from RESs is converted to smoother AC electricity by a VSI [1, 6, 7]. For the VSI to adjust its output power following network requirements, a controller is also required [8, 9].

GTO-enabled microgrid inverters (MGIs) are used in both off-grid and grid-tied microgrid situations. MGIs using GTOs [10] as switches are utilized for high-power region applications. GTOs are appropriate for high-power applications because they have high current and voltage ratings.

I. Jlassi et al. in [11] proposed VSI's IGBTs and current sensors failure detection for PMSM drives. S.S. Ghosh et. al demonstrated the process for identifying IGBT switch failures in voltage source converter (VSC) in [3, 12]. X. Guo et al. in [13] presented an effective diagnostic method for the current source inverter (CSI) short circuit failure (SCF). M.T. Fard et al. introduced open circuit failure (OCF) in the CSI [14]. In 2020, J. Zhang et al. presented a unique technique for identifying OCF in the grid-side converters (GSC) single and double IGBT modules [15]. In 2024, authors illustrated the IGBT switch fault in bidirectional MGI [16]. For an islanded inverter, S.F. Zarei et al. [17]

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identified an SCF detection method.

The identification of GSF in a 3Ph VSI of MG has, however, received little attention. This study suggests a novel method for GSF detection in 3Ph VSI of MG. With the use of the Fast Fourier transform (FFT) [3, 18, 19], the GSF has been determined. The FFT is a potent technique for frequency domain analysis of signals in electrical fault investigation.

This investigation has assessed the 3Ph VSI's output current to find GSF. The FFT has been employed on VSI's output current to monitor several metrics, comprising the DC component (DCC), fundamental component (FC), total harmonic distortion (THDc), and sub-harmonic currents (SHMCs), in order to determine the GSF.

The article is arranged as follows. Section 2 illustrates the PV system-linked GTO-based 3Ph VSI of MG. Section 3 includes the issue statement. Section 4 describes the approach for identifying GSF. Sections 5 and 6 address the results with discussion and an algorithm to detect GSF, respectively. Section 7 illustrates comparative studies. In Section 8, the conclusions are outlined.

2. GRID-CONNECTED GTO-BASED VSI

A schematic of the grid-connected PV system, a DC-DC boost converter (DBC) operated by Maximum Power Point Tracking (MPPT), a DC-link, 3Ph VSI, and VSI controller is shown in Fig. 1. Here, a PV system of 100 kW is taken into consideration for modelling reasons. The PV system is linked to the main grid of 25 kV. The PV system and grid are connected via a 3Ph VSI alongside a DBC. The MPPT [3] system allows for the automated modification of the duty cycle in order to provide the necessary voltage for the generation of the most power. To provide consumers with a dependable power supply, VSI controllers need to monitor voltage and frequency [1, 20].

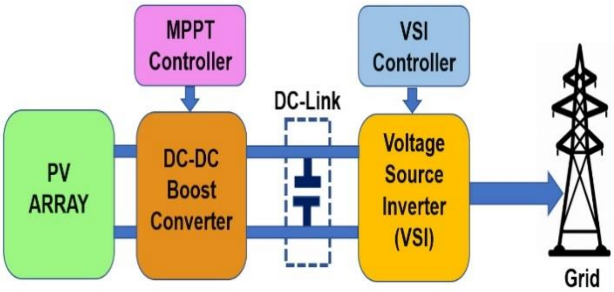

Fig. 1 – Schematic of the grid-connected PV system, a DC-DC boost converter (DBC) operated by Maximum Power Point Tracking (MPPT), a DC-link, 3Ph VSI, and VSI controller

To ascertain whether GSF is present in the VSI, the VSI's output current has been thoroughly monitored at normal and during various percentages of GSF (%GSF) conditions.

3. DESCRIPTION OF THE PROBLEM

In this research, the PV system and the electric grid are linked together through GTO-based 3Ph VSI. For fault analysis, the GTO switch fault of the VSI is factored in. The fault situation pertaining to the GTOs in the inverter circuitry is referred to as GSF. During the GSF the effective internal resistance of the GTO switch changes. Depending on the fault's severity and the configuration of the system, a GSF in the inverter can have several effects. The issue is defined as a condition that, after the failure, leaves the circuit open. The GTO switch itself may malfunction for several causes, including ageing, overvoltage, overcurrent, and overheating.

A VSI's GSF can result in a variety of unfavourable outcomes, such as distortions of the voltage and current, overvoltage or undervoltage situations, overcurrent, thermal stress, loss of control, system outages, and safety hazards.

Consequently, it is crucial to identify GSF swiftly and efficiently. Furthermore, an effort was undertaken in this study to detect the gradual rise in VSI's GSF. It is important to note that the system characteristics and the extent of faults can only be determined by the designer of the system.

VSI systems may include preventative measures like defect detection algorithms to lessen the impact of GSF which can ensure the VSI system's dependable and secure functioning.

4. DIAGNOSIS OF FAULTS BASED ON FFT

Abrupt variations in voltage, current, or frequency are common signs of failures in electrical systems. It is possible to identify these variations and identify the underlying problems in the system by employing Fourier Transform (FT) or Fast Fourier Transform (FFT) [3, 16, 18, 19] to analyze the frequency content of signals. FFT's computing efficiency makes it the preferred method in practice, particularly for digital signal-processing applications. As it is substantially quicker than the regular FT and efficiency-optimized, the FFT is appropriate for real-time signal processing and analysis [3].

In order to identify GSF in VSI, this study closely examines the VSI's output current. Many metrics associated with the VSI's output current such as DCC, FC, THDc, and SHMCs, have been monitored based on the FFT to find the GSF issue.

4.1 Pattern Creation using FFT Integration

Under typical working conditions and at different %GSF, the collected output current of VSI has been subjected to FFT analysis.

The VSI's collected output current is shown in Fig. 2. In Figure 3, the FFT window of the acquired output current of the VSI is shown. In Figure 4, the output current of the VSI is shown in the FFT window.

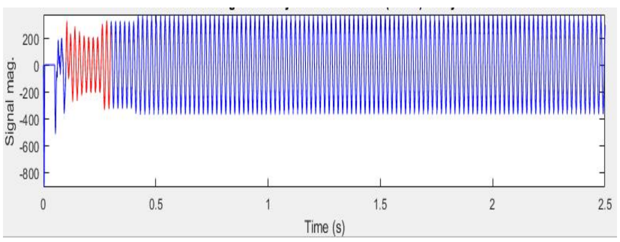

Fig. 2 – Collected output current signal of VSI

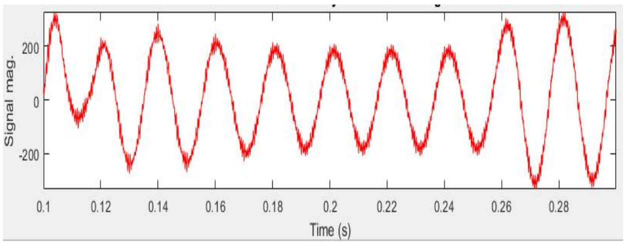

Fig. 3 – FFT window of VSI's output current

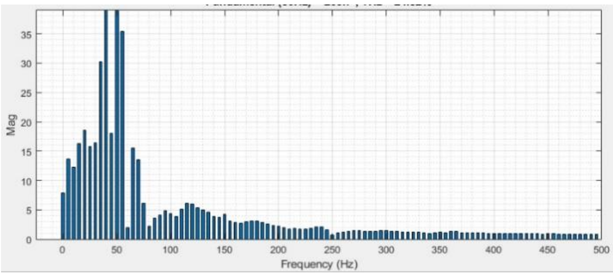

Fig. 4 – Spectrum of the VSI's output current

4.1 Retrieving of Low-Frequency Characteristics

4.2.1 Analysis of the DCC

FFT-based analysis has been used to recover the DCC of the captured output current of VSI's for a range of percentage fault levels of the GSF (%GSF).

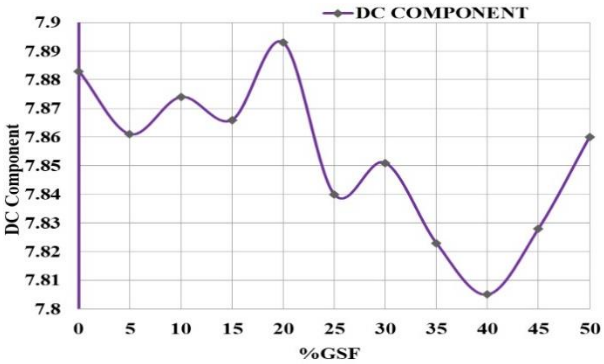

Fig. 5 – DCC versus %GSF

Fig. 5 suggests that the DCC and GSF are not statistically associated with one another. As a result, this characteristic cannot be used to identify GSF in the VSI.

4.2.2 Analysis of the FC

To extract the fundamental frequency component from the VSI's output current signal, FC analysis is done based on FFT. Here, the amplitude and phase information from the FC is obtained using the FFT results.

The FC values, which have been derived from the VSI's output current for various %GSF numbers, are displayed in Fig. 6.

The FC of the VSI's output current and the different %GSF are not adequately related, as a graphic study of Fig. 6 makes evident. Consequently, it is not practical to use this feature to identify GSF in the VSI.

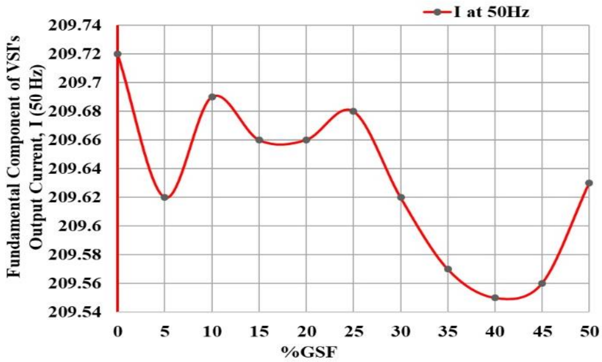

Fig. 6 – FC versus %GSF

4.2.3 Analysis of THD$_C$

The harmonic content of a signal is measured by THD [3, 16]. THD of the current signal can be expressed as the following [16]:

$$THD_C(\%) = \frac{\sqrt{I_2^2 + I_3^2 + \ldots\ldots + I_n^2}}{I_1} \times 100 \qquad (1)$$

where, the fundamental frequency's root-mean-square (RMS) value is represented by I_1 and the RMS values of each individual harmonic component are termed as I_2, I_3, …, I_n. As seen in Fig. 7, it displays the THDc readings for the investigation of GSF were obtained for different %GSF in VSI.

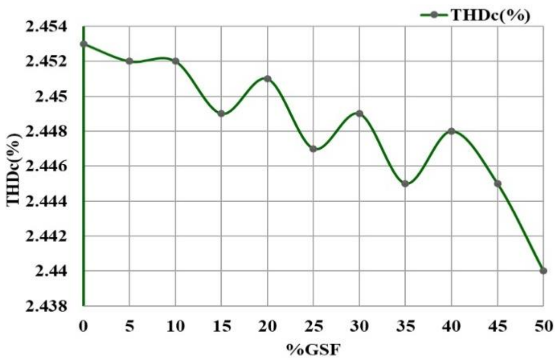

Fig. 7 – THD$_C$ (%) versus %GSF

It shows that THDc(%) values fluctuate along with changes in GSF percentage values.

Furthermore, the graphical examination of Fig. 7 provides inadequate validation for the GSF diagnosis.

4.2.4 Analysis of Subharmonic Currents (SHMCs)

Additionally, the SHMCs have been obtained from the acquired output current of the VSI. The obtained signal's SHMCs have all been carefully examined for varying %GSF values. Figure 8 illustrates that when the percentage of GSF increases, all SHMCs values change.

Upon closely examining Figure 8, it becomes evident that the subharmonic component of the VSI's output current at 45 Hz, denoted as I at 40 Hz, decreases gradually until the percentage GSF reaches 20 %. So, this statistical feature can be employed for the detection of GSF in VSI.

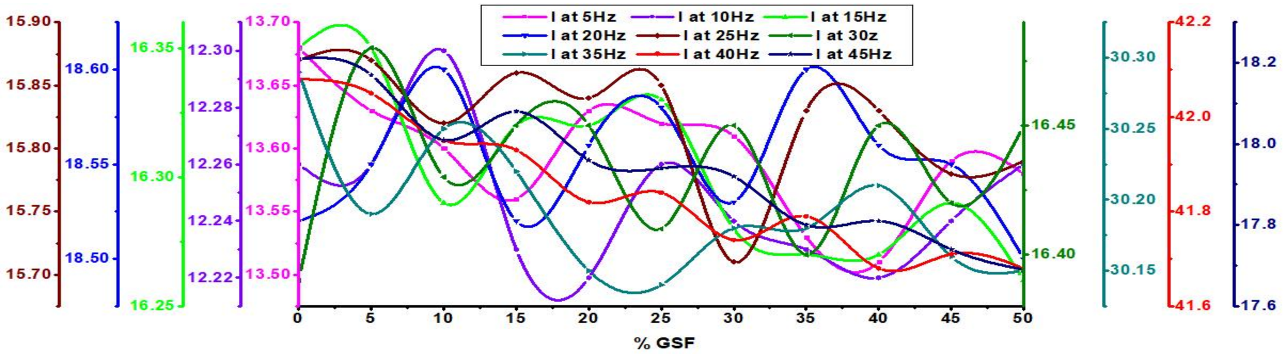

Fig. 8 – SHMCs versus %GSF

5. RESULT AND DISCUSSION

This study's initial phase involved FFT-based signal monitoring for many metrics, including the DCC, FC, THDc, and SHMCs of the output current of the 3Ph VSI. However, only the subharmonic component of the VSI's output current at 45 Hz, indicated as I at 40 Hz, progressively drops until the percentage GSF hits 20 %, as can be seen from the graphical analysis of Fig. 8. Thus, it is shown that GSF (up to 20 % of GSF) in VSI may be identified simply by continuously monitoring the SHMC, I at 40 Hz. Also, the percentage of GSF in the VSI can be calculated using the recommended approach.

6. ALGORITHM FOR GSF IDENTIFICATION

The following is a GSF detection algorithm:
(a) First, obtain the output current of the VSI.
(b) Considering the VSI's output current, find I at 40 Hz through FFT.
(c) Inspect the data of SHMC, I at 40 Hz.
(d) Check to find out whether GSF is present.

7. COMPARISON ASSESSMENT

A comparative analysis of several inverter defect identification methods with the suggested approach is illustrated in Table 1.

Table 1 – Comparison Assessment

Ref.	Identifying Faults	Fault Finding in %
[11]	IGBT and current sensor fault in VSI	No
[13]	SCF in CSI	No
[14]	OCF in CSI	No
[15]	OCF in IGBT modules of GSC	No
[17]	SCF in islanded inverter	No
Proposed method	GSF in VSI	Yes

8. CONCLUSION

In this study, a statistical evaluation using FFT on the output current of the VSI was performed under both optimal and faulty conditions to identify GSF in 3Ph VSI, and the values of the relevant parameters were seen to be changing.

The study additionally indicated that the method suggested makes it possible to compute the GSF percentage in the VSI.

Thus, by constantly tracking the SHMC values at 40 Hz, it has been observed that this FFT-based approach effectively detects GSF (up to 20 % of GSF) in 3Ph VSI.

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Ідентифікація несправності перемикача GTO в інверторі джерела напруги в інтегрованій фотоелектричній мережі

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Мікромережеві інвертори (MGI), що використовують технологію затворного тиристора (GTO), використовуються у мережевих внутрішніх та зовнішніх мікромережах (MG) , де вони важливі для керування потоком електроенергії та підтримки стабільності системи. Здатність GTO витримувати високі напруги та струми має вирішальне значення в системах перетворення електроенергії, які потребують значних рівнів потужності. GTO в інверторах джерел напруги (VSI) використовуються для перетворення електроенергії постійного струму з відновлюваних джерел енергії, таких як фотоелектричні (PV) системи, вітряні турбіни або системи накопичення енергії, у потужність змінного струму, яка підходить для використання в MG. Збій перемикача GTO (GSF) MG у трифазному VSI може призвести до кількох проблем, таких як зниження виробництва електроенергії, проблеми з безпекою, нестабільна напруга та частота, втрата з'єднання з мережею, ситуації перевантаження по струму або перенапруги та простої в роботі. Зведення до мінімуму впливу таких проблем на роботу MG вимагає ретельного обслуговування, моніторингу та методів виявлення несправностей. У цьому дослідженні продемонстровано підхід до визначення GSF у підключеній до фотоелектричної системи 3Ph VSI для застосування MG. Щоб ідентифікувати GSF, було проведено аналіз вихідного струмового сигналу 3Ph VSI на основі швидкого перетворення Фур'є (ШПФ).

Ключові слова: Швидке перетворення Фур'є, Виявлення несправностей, GTO, Мікромережа, Фотоелектрична система, Інвертор джерела напруги, VSI.