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Review

A Detailed Review of Partial Discharge Detection Methods for SiC Power Modules Under Square-Wave Voltage Excitation

Ghulam Akbar, Alessio Di Fatta *, Giuseppe Rizzo, Guido Ala, Pietro Romano * and Antonino Imburgia

L.E.PR.E. High Voltage Laboratory, Department of Engineering, University of Palermo, 90133 Palermo, Italy; ghulam.akbar@unipa.it (G.A.); new.rizzo1984@gmail.com (G.R.); guido.ala@unipa.it (G.A.); antonino.imburgia01@unipa.it (A.I.)

* Correspondence: alessio.difatta@unipa.it (A.D.F.); pietro.romano@unipa.it (P.R.)

Abstract: Silicon carbide (SiC) power modules are increasingly being used in high-voltage and high-frequency applications due to their superior electrical and thermal qualities. However, the issue of the partial discharge (PD) phenomenon raises serious reliability difficulties resulting in insulation failure, performance degradation, and potential device collapse. This paper provides a thorough assessment of the current PD detection strategies in SiC power modules. The issues provided by SiC devices' distinct operational features, such as high switching frequencies and higher voltage stresses, which hinder PD detection and mitigation, are widely investigated. This review compares the effectiveness, benefits, and limitations of various detection methods, emphasizing the need for better strategies to ensure long-term reliability and performance. This study gives an in-depth overview of the numerous forms of PD phenomena that occur in power modules, including internal and surface discharges, as well as how they appear under various detection systems. It examines the performance of several methods for power module technologies such as SiC. To address these PD issues, this article proposes ways to improve reliability and detection accuracy.

Keywords: SiC modules; PD detection methods; square wave excitation

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1. Introduction

Partial discharges (PDs) are a major issue with high-voltage power modules. These modules include weak points that might induce PDs, leading to more significant concerns including breakdown [1]. Identifying the position of a PD is crucial for enabling greater voltages in power modules and advancing location technology [2]. PDs tend to grow as the frequency of the electrical impulses rises. As a result, understanding partial discharge behavior is critical. To analyze PD behavior, sinusoidal waveforms are typically used, particularly when dealing with pulse width modulation (PWM) waveforms operating at a frequency of 50 or 60 Hz [3,4]. Partial discharge (PD) detection is widely used in big power equipment, such as transformers, to monitor insulation health and avoid failures. However, PD detection in power modules, such as silicon carbide (SiC) modules, is critical because of their high operating frequencies and small construction. While the fundamental idea of PDs—small electrical discharges that occur around insulating weaknesses—is the same in both circumstances, the specific issues in power modules differ. For example, rapid switching rates and thermal strains in power modules complicate PD detection yet are required for long-term dependability. Due to the combination of characteristics provided by silicon carbide SiC, it is ideal for a wide range of electronic industrial applications. When compared to other semiconductors with wide energy gaps, the SiC technology is placed at the forefront of renewed interest in semiconductor material and device development due to its physical characteristics, such as a strong electric field, high saturation drift velocity, and superior thermal properties [5–8]. The high breakdown field, high temperature, and other promising characteristics of SiC material make SiC MOSFETs very attractive as high-power switching device choices [9]. SiC devices do not show significant degradation under high temperature and high voltage stress [10]. SiC MOSFETs enable more efficient, compact inverters by reducing power losses as compared to Si IGBTs and super junction MOSFETs [11]. A SiC power device's particular resistance is expected to be substantially lower, roughly 100–200 times, than a silicon device with a comparable rating [12,13]. The much lower thermal minority carrier production in SiC material implies lower leakage currents, enabling higher operating temperatures and a higher threshold for power dissipation-induced self-heating in devices. Furthermore, SiC has a thermal conductivity three times higher than Si, and, at room temperature, it is even higher than that of copper. Because of these properties' enhanced power, SiC devices are expected to be used in high-voltage applications such as electric power plants, electric cars, and trains [13]. Therefore, in the last decade, the development of high-voltage power modules has been encouraged [14,15].

The comparison of properties of different types of Wide Band Gap devices is shown in Table 1.

Table 1. Comparison of the properties of different types of Wide Band Gap devices [4–6].

Property	Si	SiC	GaN	Ga_2O_3	Diamond
Band Gap Energy	1.1	3.2	3.4	4.7	5.5
Breakdown Field (106 V/cm)	0.3	3	3.5	8	13
Electron Mobility (103 cm^2/V.s)	1.3	.9	1.5	.3	2
Saturation Drift Velocity (107 cm/s)	1	2	2.5	2	1.5
Thermal Conductivity (W/cm.k)	1.5	3.7	1.3	.1	22.9

Silicon (Si) has long been the preferred material in power electronics due to its well-understood characteristics and low cost. Silicon carbide (SiC) is suited for high-voltage, high-temperature, and high-power applications due to its large band gap and breakdown field, which is ten times greater than that of silicon. Its thermal conductivity enables more effective heat dissipation, making it ideal for power electronics in electric vehicles and other industrial applications. Gallium Nitride (GaN) GaN, with a band gap and a high saturation drift velocity, allows for quick switching and great efficiency in power conversion devices. Diamond's greater thermal conductivity provides for efficient heat dissipation, yet manufacturing constraints currently prevent its widespread application in power electronics.

Power modules designed for high power density require improved dielectric performance in their insulation systems, particularly in terms of dielectric and thermal response. Silicone gels are used as electrical insulation in power modules because of their excellent thermal, mechanical, and electrical qualities. Most advanced materials are made with epoxy resin; however, research on nanofiller/silicone gel composites is limited. Another issue is research on the behavior of silicone gel under medium-voltage (MV) circumstances [16]. Despite this, silicone gel remains the most used encapsulant in power modules with its good mechanical and thermal properties [17]. Silicone gel, due to its increased flexibility, is more effective at reducing stress from bare dies and bonding wires. When tiny electrical sparks occur inside silicon gels, partial discharge activity can be placed, which can cause the insulation to break down. This could damage the gel's functionality and may lead to malfunctions in electrical systems that employ these gels for insulation. These gels serve to avoid PD activity and keep moisture and air pollutants out of the internal circuitry. As a result, the effectiveness of silicone gel has a significant impact on the lifetime and reliability of power modules [18]. Power electronic devices are encapsulated in silicone gel, which is susceptible to surface discharges that deteriorate it [19]. Surface discharges are a critical vulnerability of IGBT modules since they cause the formation and expansion of surface channels, ultimately damaging the silicone gel. Cavity propagation is powered by discharges caused by surface charge accumulation within the cavity. This was determined by monitoring the time response of the potential along surface discharges in the silicone gel [15]. It has been thoroughly established that positive discharges cause the cavity's volume to rise, whilst negative discharges cause it to decrease. The charge recombination mechanism within the cavity helps to expand and decrease its volume [14–17].

Traditional methods for detecting a partial discharge (PD), such as the error correction method using multiple neural networks for UHF PD localization [20] and the noninvasive electric-field pulse measurement used to diagnose insulation faults in circuit breakers [21], have produced good results in larger power equipment. For example, the author of [20] used neural networks to achieve high accuracy in detecting PDs inside ultra-high-frequency (UHF) signals, which is particularly beneficial for big, high-voltage applications. The author of [21] used an approach that is especially useful since it detects electric-field pulses to discover insulation concerns in high-voltage circuit breakers without requiring invasive testing. However, these classic methods have limits when applied to smaller and more complicated SiC power modules. SiC modules function at substantially higher switching frequencies, quicker voltage changes, and in a smaller size. These features need PD detection systems that can respond rapidly to fast signals while also handling interference from electromagnetic noise in the surrounding environment. Unlike standard methods, our research focuses on statistical analysis and machine learning techniques that are specially tailored to the unique circumstances in SiC power modules.

Square wave excitation with DC bias incorporates both direct current (DC) and switching frequency signals. Simply modifying the material's capacity to store energy (permittivity) or how effectively it conducts electricity (resistivity) may not fix the problem. Modern materials must perform better in both DC and switching frequency electric fields (E-fields). A switching DC field will always influence power modules. The output voltage frequency may reach up to 100 kHz, with a rapid rising time of hundreds of nanoseconds [22,23]. Furthermore, the electric field change rate in medium-voltage silicon carbide (MV SiC) power modules is quite high [24]. Because of these considerations, the advanced materials utilized in MV SiC power modules must be examined for PDs when employing square wave excitation.

2. Standard Measurement Setups for PD Diagnoses in Power Modules

The increased usage of AC-DC converters, particularly in renewable energy, has resulted in new ways of controlling them, primarily using pulse width modulation approaches [3]. In recent years, novel methodologies and procedures have been developed to identify PDs caused by waveforms from current electronic power systems. The standard measurement circuit includes a Tek-tronix signal generator with an output amplitude of ± 10 V and a Trek Model 616 power amplifier that can magnify the input signal by 1000. The amplifier signal was constructed in accordance with IEC 60270, as shown in Figure 1 [3]. One study [25] detected PD signal activity using two independent techniques that assess both the discharge pattern and individual discharge levels.

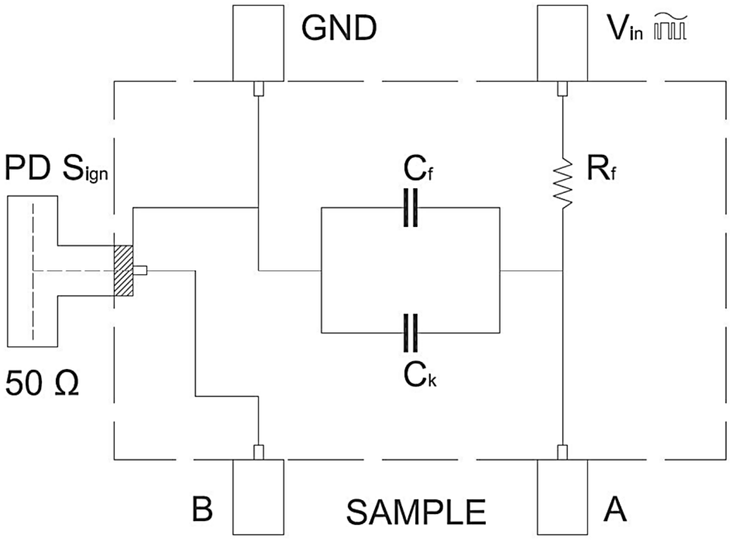

Figure 1. Measurement circuit designed according to the IEC 60270 standard [3].

Research on partial discharge (PD) localization inside IGBT power modules may be divided into two categories: electrical and optical PD monitoring approaches. Studies such as [26,27] examined phase-resolved PD (PRPD) patterns to establish the kind and location of PDs. In these PRPD patterns, the apparent charge of PD events is synced with the AC test voltage, allowing for accurate detection of PD features. As discussed in [28], the PD activity under a 60 Hz sinusoidal waveform typically starts at a higher inception voltage (PDIV) compared to high-frequency PWM waveforms. In the experiments, the PDIV for the sinusoidal case was around 7.6 kV, with continuous PDs detected when the voltage reached around 2.7 kV RMS.

According to [28], a comparison of the data obtained revealed that no discharges with a sinusoidal waveform were recorded. However, when the system was given a PWM waveform, substantial discharge activity was detected. These experiments closely simulated actual IGBT working conditions. Although existing standards do not require the use of discontinuous waveforms in testing, the authors believed that evaluating the sample's behavior under a PWM signal would yield more accurate results. The article [28] concluded that high-frequency PWM PD detection is more effective for power modules because it gives a more realistic and sensitive evaluation of PD activity than the typical 60 Hz sinusoidal waveform. This makes PWM-based testing more appropriate for current power electronics, where quick switching and high voltage strains are typical.

Understanding the effects of different excitation waveforms, particularly square wave excitation, is critical when detecting PDs in SiC power modules. This approach is becoming increasingly important due to its prevalence in high-voltage applications since it poses unique problems and opportunities for successful PD detection. In the following part, we will look at how each detection technique operates under square wave voltage excitation, emphasizing its unique strengths and limits.

3. PD Detection in Power Modules Under Square Wave Voltage Excitation

Approximately 77% of PD detecting voltage is 50/60 Hz AC voltage, with square wave excitation and switching source DC SSDC voltage accounting for just 17% and 6%, respectively [24]. The power module does not use AC voltage in direct bonded copper (DBC). Detecting PD under AC voltage does not fully show the power module's operation [29]. The SiC power module's ultra-high dv/dt, weak PD signals, and pulse width modulation PWM excitation-induced interferences can create significant electromagnetic interference EMI difficulties [30,31]. The power module's ultra-high dv/dt, PWM, and EMI are also responsible for the absence of PD detection during square wave excitation. While research on PDs in MV power modules is limited, comparable assessment methods have potential applications in this industry [32]. However, not all PD testing techniques have been applied directly to MV power modules, and their universality and underlying concepts remain informative [29].

In the following, four methods for detecting PDs using square wave excitation are illustrated.

3.1. Optical Methods for PD Detection

The optical detection approach uses emitted light from PD events, which has strong EMI immunity under square voltage. It consists of photomultiplier tubes (PMTs), silicon photomultipliers (SiPMs), fluorescent fibers, and a Charged Coupled Device CCD camera.

3.1.1. Photomultiplier Tube Method (PMT)

The PMT method is the most often used method for detecting PD under the square wave method, with the measurement setup shown in Figure 2 [33,34]. An MV SiC power module, high voltage pulse power supply, high voltage amplifier, or super cascade structure may be used to generate square wave excitation. When a PD event occurs, the PMT immediately detects the weak light produced by Ultraviolet UV. But the power module and PMT must be placed in a dark space. To remove any influence from the surrounding light, the module is put in a dark room. Because of its extreme sensitivity to light, the photomultiplier tube may even pick up on weak signals, such as the dim light emissions from partial discharge activity. It would be challenging to precisely detect the tiny light signals produced by a PD if the module were not put in a dark area since other light sources, such as sunlight or room lighting, might produce noise or erroneous readings during the detection process. A PD occurs on both the rising and falling edges of the square wave excitation. The PD pulses are immediately recognized, and they closely correspond to voltage fluctuations.

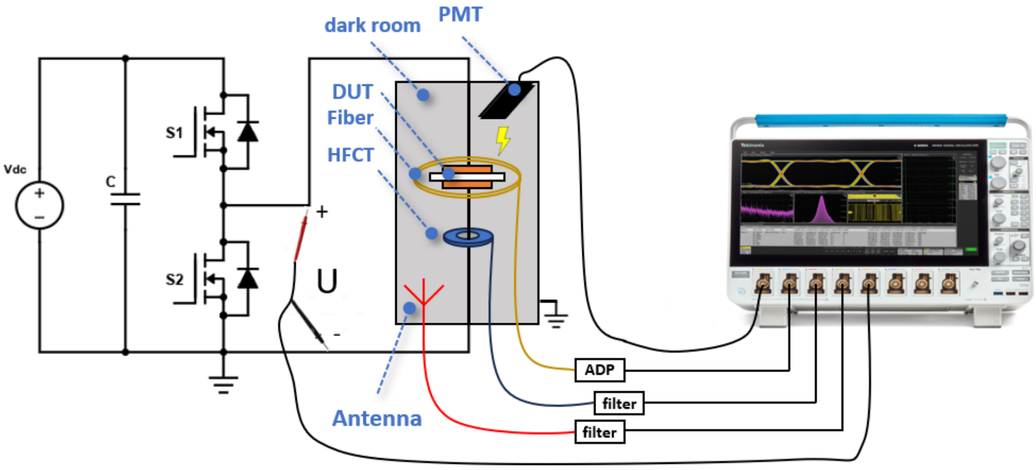

Figure 2. PD under square wave excitation via the optical detection method [33].

In Figure 3, a replica of a typical 1.55 kV, 5 kHz switching, and 20% duty cycle waveform finding for the PMT under square wave excitation is shown. Each negative pulse is a light emission event, showing the presence of a PD at 1.55 kV, 5 kHz switching, and 20% duty cycle as described by [35].

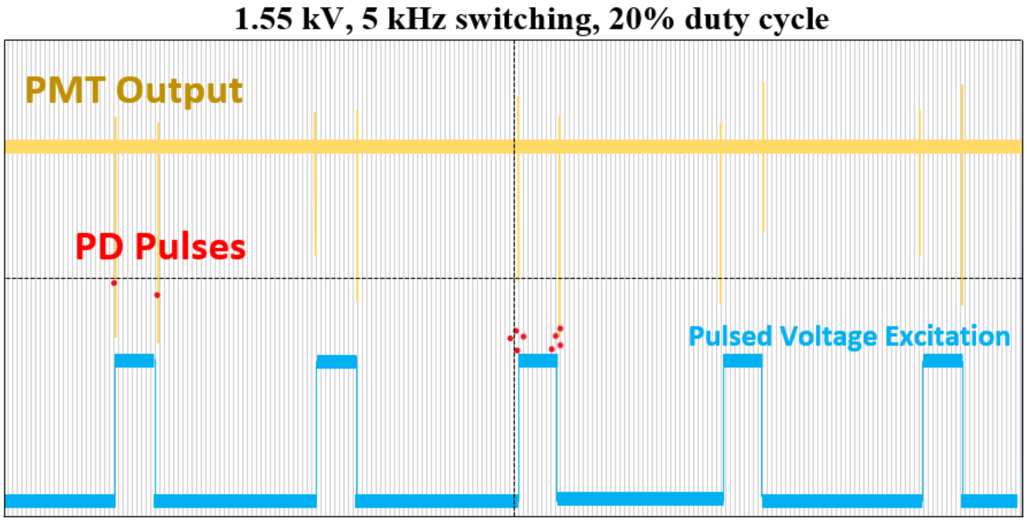

Figure 3. Typical waveform results of PMT under square wave excitation [35].

3.1.2. Silicon Photomultiplier Method (SiPM)

SiPM optical detection might be a viable option for detecting PD events [36]. The technology has been successfully applied to converters and might potentially be utilized for power module PD detection in the future [37]. SiPM is a photon-sensitive sensor of the millimeter scale with several sensitive components. Each sensitive element combines a photodiode and a quenching resistor for Geiger mode operation. Figure 4 shows that the light generated by a PD event can introduce the pulse voltage across the quenching resistor. The advantages provided by this device can be summarized as compact size, high gain, good sensitivity, and complete immunity to electromagnetic interference [37]. Hence, the SiPM may be easily integrated with the power module to provide online monitoring.

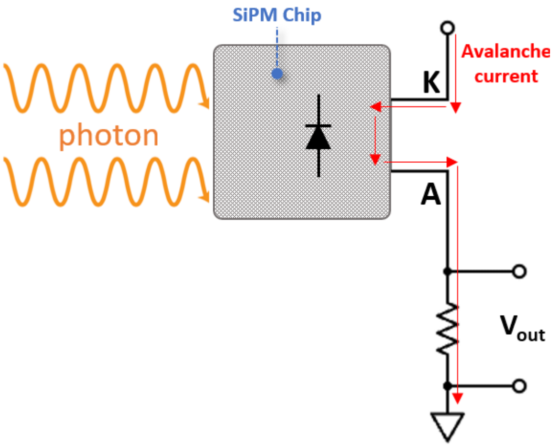

Figure 4. SiPM-based PD sensor working principle [37].

3.1.3. Fluorescent Fiber Method

Fluorescent fibers can detect light from partial discharges (PDs) [36]. Fibers feature core components that absorb light when exposed to it [38]. When fluorescent fibers absorb light, they emit a particular glow known as fluorescence. This implies that they can absorb light and then release it as visible light. Furthermore, the fibers are surrounded by a transparent cladding, a translucent layer that allows the fluorescent materials to collect light from all directions. This architecture makes the fibers particularly effective in collecting and detecting light produced by partial discharges. Fluorescent fibers absorb light, produce fluorescence, and use their transparent outer layer to efficiently gather light, making them ideal for sensing light from partial discharges, as shown in Figure 5 [38].

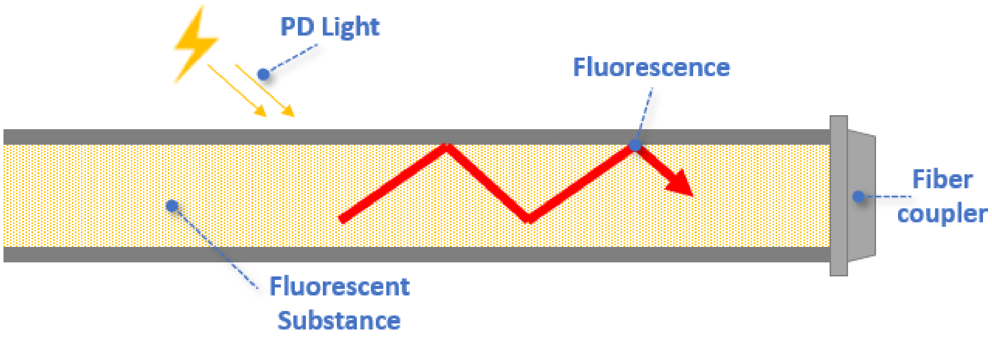

Figure 5. Working principle of fluorescence fibers [38].

3.1.4. Charged Coupled Device (CCD) Method

The CCD camera is an image sensor that is the most used instrument in insulation design to determine the PD location in power modules [39]. Using a high-voltage, two capacitor banks (each 4.95 nF) were connected to a test item to create square voltage pulses, as shown in Figure 6 [39]. Positive and negative voltages from various high-voltage sources were used to charge the capacitors. They can produce bipolar (two-direction) and unipolar (one-direction) pulses with varying DC levels at frequencies up to 500 Hz by varying the charging voltages. The Lambert HiCAM 500 CCD camera, equipped with a dual-stage image intensifier and Nikon Nikkor AF-S Micro 60 mm f/2.8G lens, was used to identify PD locations [39]. As shown in Figure 7, a single image was created by computing the arithmetic mean from 1000 recorded frames [39].

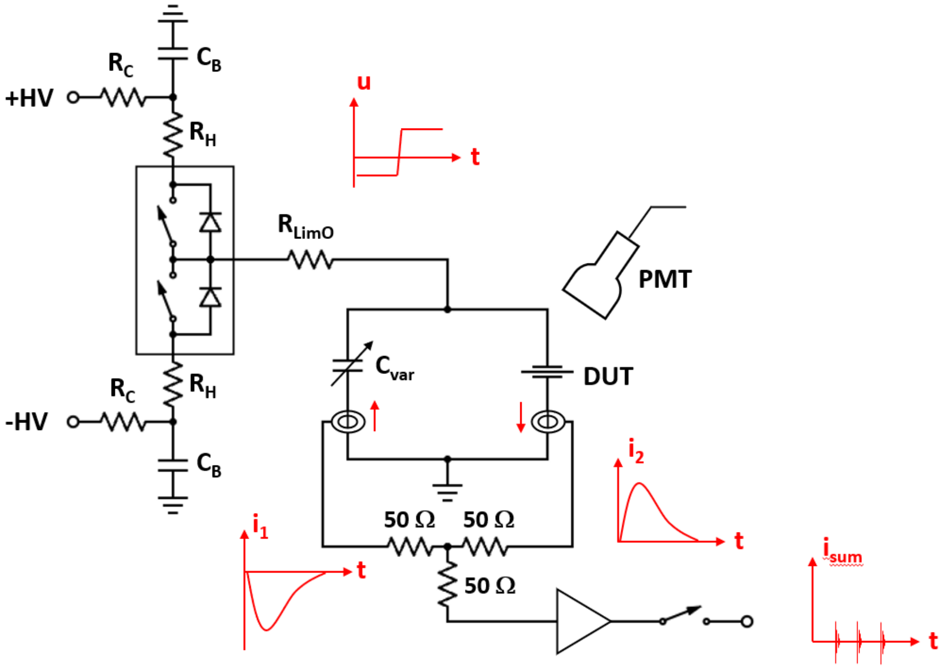

Figure 6. Schematic for PD setup for square voltage pulses [39].

However, this approach fails to synchronize with the voltage signals, leaving out important details like frequency, rise time, and fall time.

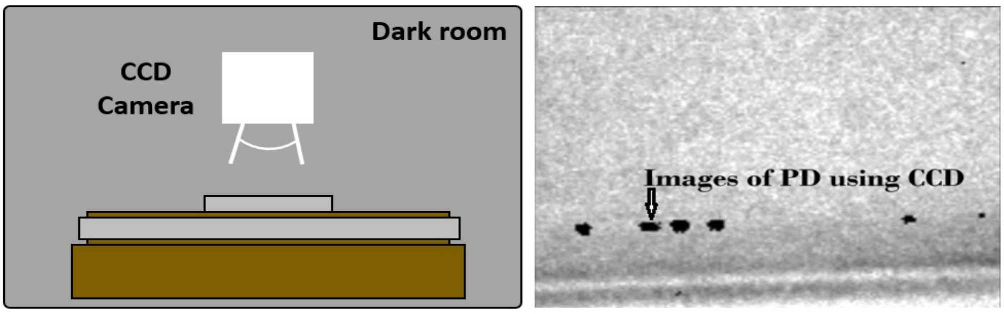

Figure 7. CCD images [39].

- Advantages: These techniques include high sensitivity to PD events and good resistance to electromagnetic interference (EMI), which is useful in loud surroundings.
- Disadvantages: It requires dark circumstances to eliminate light interference; it requires costly and sophisticated installations; and it is best suited for scientific settings.

3.2. Electromagnetic Detection Method

High-frequency electromagnetic signals produced by PD events may be detected by the antenna as they radiate and spread over the surrounding area. Additionally, it may be utilized to identify partial power module discharge.

3.2.1. Antenna Method

To eliminate switching noise, the antenna is connected to a high-pass filter. In partial discharge detection systems, the type of antenna employed is critical. Creating tiny antennas for PD detection is far more difficult than designing antennas for specific frequencies, such as WiFi antennas that function at 2.4 GHz and 5 GHz. The antenna must have a large bandwidth to successfully receive and send PD signals at various frequencies. This means that it should be able to operate well across a wide range of frequencies, rather than just one [40]. Furthermore, to detect the faint signals produced by PD events, the antenna must have a high gain. A high gain allows the antenna to pick up these feeble signals more effectively. However, attaining a wide bandwidth and high gain with a single antenna can be hard [40]. Antennas for successful PD detection must be carefully constructed to balance the need for wide bandwidth and strong gain with minimum switching noise. Loop antennas exist in a variety of basic shapes, including circles, squares, rectangles, rhombuses, and ellipses, which are specified by the geometry of the conductive wire that forms the closed loop, as shown in Figure 8. These forms influence the antenna's radiation pattern and impedance properties, making them appropriate for a variety of communication and signal applications [4546].

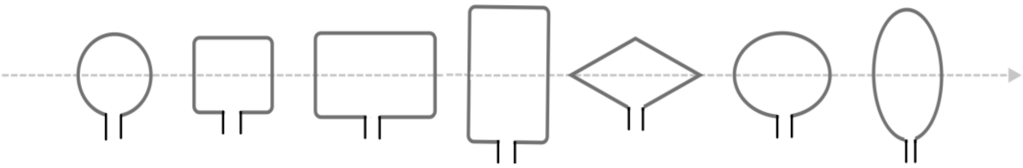

Figure 8. Basic shapes of loop antennas for PD detection [46].

3.2.2. Down Mixing Partial Discharge Detection

The ultra-high frequency (UHF) technique will be interfered with by the switching noise's mostly distributed spectrum below 3 GHz, although greater signal sampling and processing speed oscilloscopes are required for higher detecting frequencies (>3 GHz). The super-high-frequency (SHF) down-mixing PD detection system is suggested as a solution to this problem, shifting the SHF signal's frequency down to less than 1 GHz [41].

The suggested PD signal system is very clear and achieves a greater signal-to-noise ratio, as seen in Figure 9 [47].

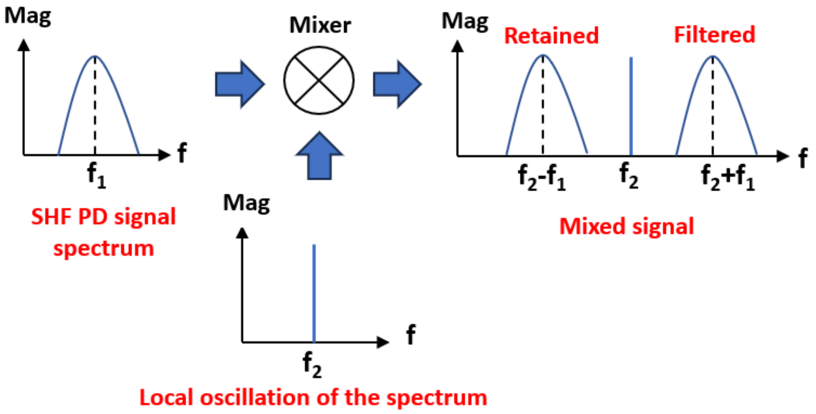

Figure 9. Results of the SHF antenna before and after mixing under square wave excitation [47].

- Advantages: Good flexibility to industrial conditions, effective in high-speed switching applications, and acceptable noise resistance.
- Disadvantages: Susceptible to disturbance in high-EMI situations; requires precise antenna design to maintain bandwidth and sensitivity.

3.3. Electrical Detection Method

When charges accumulate and then merge in specific locations, partial discharge occurs. High-frequency transient currents are produced during this discharge process by the movement of electrons. These currents can be detected by using high-frequency current transformers.

3.3.1. High-Frequency Current Transformer (HFCT)

One tool for measuring abrupt changes in electric currents is the high-frequency current transformer (HFCT). It is made especially to identify partial discharges, which are tiny electrical problems. It contributes to the safety and dependability of electrical systems by detecting these discharges. The HFCT has significant challenges due to displacement-current interference that arises during square wave stimulation. When working with AC voltage, this instrument is frequently used to detect PDs.

The HFCT is a sensor that measures PDs using electrical means. It is an external sensor since it does not communicate directly with the system. The HFCT detects current signals from PD events [41]. The sensor is positioned on the ground wire from the PD source to measure the current signal. If the sensor is properly fitted, the voltage signal it detects (V_{out}) will correspond to the phase of the input current. The HFCT is a tiny round transformer that detects electromagnetic waves in the current passing through the PD ground wire. Figure 10 depicts the geometry of the HFCT, with the cable passing through a hole in the sensor [41].

The square wave stimulation's displacement current interference may cause the PD signals to become distorted by confusing the HFCT measurements. Accurately detecting and measuring real partial discharge events can be challenging due to interference, which might introduce noise or other signals that mix with the PD signals. Because of this, the data gathered could not accurately represent the system's status, which could result in inaccurate interpretations of the electrical conditions. As a solution to these problems, a distortion-less extraction method (DEM) is suggested in [42].

Figure 10. HFCT used for PD detection [41].

As can be seen in Figure 11, the displacement current is ultimately subtracted from the unfiltered current waveform to obtain undistorted genuine PD signals. However, this method cannot be used to handle waveforms under nanosecond transition times.

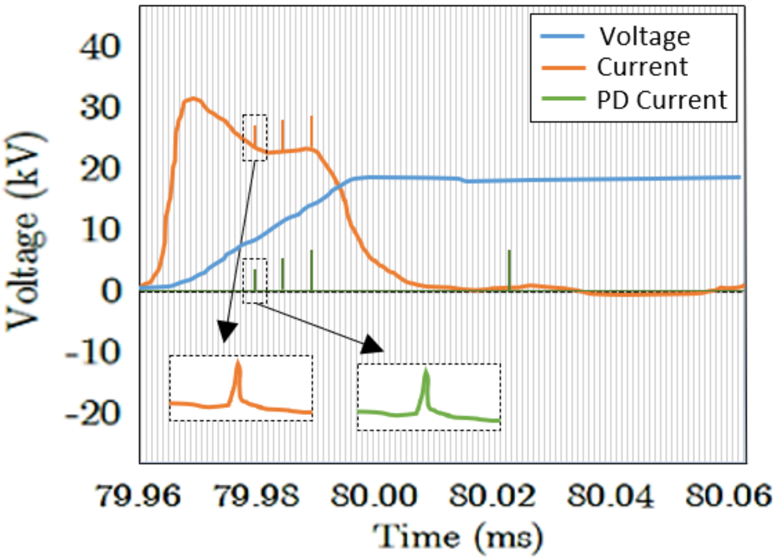

Figure 11. Effect and waveform of DEM [42].

3.3.2. Double HFCTs

The circuit in Figure 12 [39] uses two current transformers (HFCT1 and HFCT2) that measure current in opposing directions. As a result, they provide opposite polarized readings. This configuration, known as the "double HFCTs approach," makes use of opposing polarities. In this setup, a variable vacuum capacitor (C2) is coupled in parallel to a Differential Bus Coupler (DBC). Adjusting C2's capacitance to match that of the DBC can ensure that the displacement currents (i1 and i2) are the same magnitude. These displacement currents are the currents that flow through the circuit because of the high voltage provided but do not cause a partial discharge (PD) in C2 [39].

HFCT1 and HFCT2 independently measure any partial discharge events. The present output, i3, indicates the true PD signal in the DBC. However, if the capacitance of C2 does not exactly match the capacitance of the DBC or if the characteristics of HFCT1 and HFCT2 change, the signal's accuracy may suffer slightly. These variations can influence the ultimate shape of the PD signal seen in the waveform.

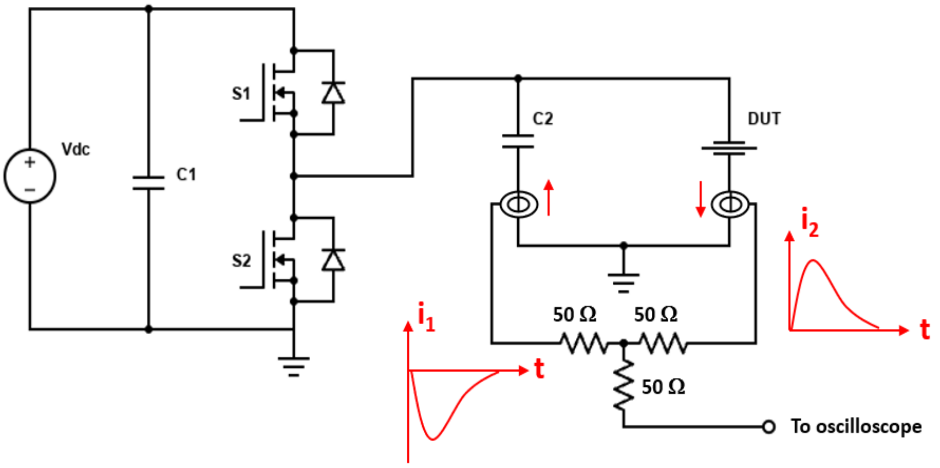

Figure 12. Schematic of the PD measurement setup by the double HFCTs method [39].

- Advantages: Low cost, widespread industrial application, and sensitivity to high-frequency PD signals.
- Disadvantages: Noise-prone, particularly at high switching frequencies common to SiC modules; additional filters may be required in EMI-heavy circumstances.

3.4. Ultrasound Method for Detection

When a PD happens, the electrical field force on the flaw would quickly change, which would result in mechanical vibration. Space charges are compelled to travel concurrently with the electrical field, creating an ion current that collides with other dielectric molecules. Nevertheless, the commercial ultrasound sensors' bandwidth restricts their ability to capture PD pulses with a nanosecond transition time, which are produced by square wave excitation.

According to the recent literature, Optical Fiber Sensors (OFSs) are useful instruments for identifying ultrasonic signals produced by PD events when excited by square waves [26]. As illustrated in Figure 13 [43], the mechanical vibration energy P(n) is transferred to the optical fiber detecting probe upon a PD event, resulting in some vibration on the sensor. In the step-index fiber, the core-cladding contact would cause a significant shift in the light wave's refractive index.

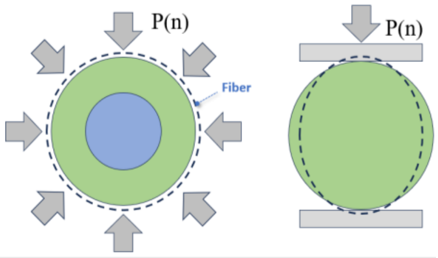

Figure 13. Working principle of fiber sensors [43].

The dielectric constant and refractive index are altered due to atomic displacement and electronic state modifications, which are both brought about by mechanical vibration energy impacting the sensor. The phase of the light wave is altered because of this change in the refractive index. The light intensity signal is then transformed into an electrical signal by a series of modulation and demodulation operations, which enable PD detection. However, this method is vulnerable to environmental interference.

- Advantages: Small and simple to use, non-invasive, suited for field applications.

- Disadvantages: Limited flexibility and might have difficulty with accuracy and noise in real-world scenarios as compared to other approaches.

In the above section, a comparative analysis was given of various PD detection approaches, evaluating them based on a variety of characteristics such as sensitivity, noise resistance, cost, ease of implementation, and scalability. This comparison, as summarized in Table 2, provides a complete understanding of each method's strengths and limitations, shedding light on their applicability for various applications in SiC power modules. Insulating materials are critical to the performance and longevity of modern high-voltage electronic equipment; yet, manufacturing or design flaws can increase electric fields, resulting in partial discharge and other reliability difficulties [44].

Table 2. Comparative analysis of PD detection methods using square wave excitation.

Detection Method	Type of Method	Ref.	Noise Resistance	Cost	Ease of Implementation	Application Feasibility
Optical Methods	PMT SiPM Fluorescent Fiber CCD	[33–35] [36,37] [36,38] [39] [39]	Excellent	High	Complex	R&D, Laboratory Settings (high sensitivity critical)
Electromagnetic Methods	Antenna Down-Mixing	[40,43,45,46] [41 ,47]	Moderate	Moderate	Easier	Industrial Settings (EMI-rich environments)
Electrical Methods	HFCT Double HFCTs	[41,42] [39,41,42]	Low	Low	Moderate	High-frequency environments
Ultrasound Methods	OFS	[26,43]	High	Moderate	Easy	Field Applications (acoustic-based setups)

- Optical Methods: These are usually restricted to laboratory environments and offer great sensitivity and good noise immunity, but they require expensive and complicated setups (e.g., dark rooms). When highly accurate measurements are needed and noise interference is not a significant issue, optical techniques like PMT and SiPM perform well in research and development settings. These methods provide excellent accuracy, which is especially useful in high-sensitivity areas such as research and laboratory settings. Their high cost and complex implementation make them unsuitable for ordinary applications, but they stand out when accurate detection is required.
- Electromagnetic Methods: Because of its ability to adopt different sizes and requirements and reasonable noise resistance, this category is perfect for real-world industrial applications, it may not function well in settings with a lot of electromagnetic interference (EMI). In industrial applications like automotive electronics or renewable energy power conversion, where high-speed photodetector detection is required, electromagnetic methods (especially those based on antennas) are well-suited for widespread implementation. These methods provide moderate accuracy and are ideal for industrial applications, particularly in areas with high electromagnetic interference (EMI). They achieve a compromise between cost and ease of deployment, allowing for simple integration into bigger systems while retaining reliable performance.
- Electrical Methods: Due to their great sensitivity and affordability, these methods are frequently employed in industry. They are more susceptible to noise, though, especially at the high switching frequencies that SiC power modules are known for. While generally scalable, electrical detection techniques like the HFCT are less ideal in EMI-heavy situations without additional noise filtering. The HFCT is a standard technique in industrial maintenance and diagnostics of high-power systems. This category has

lower accuracy than previous methods. However, their low cost and simplicity of implementation make them useful for high-frequency situations where other methods may fail. They are especially effective in conditions where great sensitivity is not required.

- Ultrasound Methods: Although inexpensive and simple to construct, these approaches have limited scalability and are best suited for field applications requiring a compact and non-invasive detection system. They can be effective in detecting localized PD, but they may be less precise than other approaches. With high accuracy, these approaches are simple to implement and suited for field applications, particularly in acoustic-based settings. They can function efficiently in a range of environments, integrating simplicity of use with reliable detecting capabilities.

4. Future Directions

The developments in SiC power modules necessitate equally new PD detection methods. Based on the limitations and issues revealed in this assessment, numerous future directions emerge.

4.1. AI and Machine Learning Integration:

With the growing complexity of PD patterns in SiC modules running at high frequencies, artificial intelligence (AI) and machine learning (ML) algorithms are going to play a very important role in enhancing PD detection and categorization. These systems could discover subtle trends that are difficult to capture using standard methods by training ML models on massive datasets of PD events, enhancing accuracy and response speed. For example, one study [44] developed a technique for automatically identifying and predicting PD flaws utilizing essential properties of PD pulses under DC voltage, concentrating on statistical patterns and attaining 96.3% accuracy with machine learning, particularly support vector machines.

4.2. Hybrid PD Detection Techniques

Considering the shortcomings of individual PD detection techniques, a suggestion is that future research ought to concentrate on creating hybrid systems that integrate several approaches. Combining optical and electromagnetic approaches, for instance, could benefit from both the broad applicability of electromagnetic techniques and the high sensitivity of optical detection. These hybrid technologies have the potential to reduce problems like false positives or environmental interference while offering more accurate, real-time monitoring of PD activity.

In conclusion, despite great advancements in the identification and mitigation of partial discharges in SiC power modules, there are still several technological obstacles that need to be overcome. A multidisciplinary strategy incorporating developments in electronics, signal processing, materials research, and artificial intelligence is needed to address these issues. For SiC power modules used in high-voltage, high-frequency applications to remain reliable and safe over the long term, it will be imperative to continue developing more sophisticated, integrated PD detection techniques.

5. Conclusions

In this review, we conducted a thorough examination of the current PD detection methods for SiC power modules, with a focus on their significance in high-voltage, high-frequency applications. SiC power modules have become increasingly popular in power electronics due to their superior electrical and thermal qualities as compared to older silicon-based devices. However, the reliability of SiC power modules is jeopardized by the occurrence of partial discharges, which can cause insulation breakdown, performance degradation, and, eventually, device failure.

This paper examined several PD detection methods, such as optical, electromagnetic, electrical, and acoustic techniques, and highlighted their strengths and limits when applied to SiC modules. Each detection approach has demonstrated potential for detecting PD activity, but their practical application is dependent on SiC device-specific operating circumstances such as high switching frequencies and voltage stress. For example, optical technologies such as photomultiplier tubes and CCD cameras provide excellent sensitivity and resilience to electromagnetic interference, but they may necessitate elaborate setups and separation from ambient light. Electromagnetic and electrical detection technologies are faster and more scalable for industrial applications, but they are prone to interference from switching noise. Acoustic approaches, while effective in detecting PD locations, frequently struggle with signal-to-noise ratios in real-world settings.

As studies reveal, each approach for detecting a partial discharge (PD) has few advantages when used with SiC power modules, which frequently face extreme conditions. These conditions include fast switching rates, temperature variations, and voltage swings. Because of this, no single PD detection approach can function consistently in every circumstance. We suggest that adopting a mix of methodologies, particularly for the environment in which the SiC power module works, will result in improved and more reliable PD detection. Combining technologies such as acoustic, electrical, and optical PD detection may allow for the development of a system capable of detecting PDs more precisely under various conditions. Future studies should investigate how these technologies might be combined to create a detection system that fits the specific requirements of SiC power modules.

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