Research Article

A SiPM-Based Trinal Spectral Sensor Developed for Detecting Hazardous Discharges in High-Voltage Switchgear

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Electric discharges seriously threaten the safety of high-voltage switchgear. In this paper, a spectrum-based optical method is proposed for hazardous discharge monitoring. A SiPM-based trinal spectral sensor is developed with good performances in terms of sensitivity, defect resolution, and risk evaluation. Experiments carried out on two types of artificial discharges (i.e., partial discharge and arc discharge) demonstrate that the light intensities coupled in the three spectral bands account for different proportions and the ratio among the three components generally experiences a regular change with increase in severity of discharge. The typical spectral ratio values are then acquired for hazard rating of discharge and recognition of discharge types with high confidence.

1. Introduction

Gas-insulated switchgear and metal-enclosed switchgear have high reliability, low maintenance, and compact size and thus are widely used in a power grid. However, some unavoidable insulation defects derived from manufacture, transportation, assembly, or operation can result in partial discharge (PD) and even electrical arc under a high electric field, which leads to degradation of the insulation system and even results in insulation failure. With regard to PD, the monitoring detections developed based on the discharge-associated effects such as current flow, electromagnetic (EM) wave, and acoustic wave [1] have been used for many years, but their applications are still constrained by the common knotty issues in practice including the aperiodic noises distributed in the whole frequency range of detection, the indefinable criteria for fault recognition [2, 3]. For arc discharge, arc light detection is used for relay protection [4], but it cannot respond to weak light emission from PDs. In fact, hazardous discharges with releases of low or high energy are accompanied by light emissions with different spectra. By utilizing the spectral information, the type and severity of discharge can be estimated without any complex signal processing and algorithms. However, the PD light emission lasts for a very short time (several picoseconds) [5] with low light intensity. A coupling device with high sensitivity, a wide spectral response, and a high-time resolution is needed. In this case, the vacuum photomultiplier tube (PMT) is used in detecting PD lights, but its irreducible size, high driving voltage bias, and high electromagnetic interference (EMI) susceptibility restrict its applications in online PD monitoring.

With the development of the silicon solid-state photovoltaic technology, single-photon-level photosensitive devices have been produced with micropackaging [6]. As the promising alternatives to PMT, the state-of-the-art micro solid-state photoelectric devices such as avalanche photodiode (APD) and silicon photomultiplier (SiPM) [7, 8] can serve as the substrate of the multispectral sensor with micro size (~μm²), high quantum efficiency (up to ~40%), and excellent EM interference immunity (~1pC) [9]. In this paper, a trinal spectral sensor array is developed based on
SiPM which presents good properties in sensitivity and linearity as well as pulse resolution. By experiments, it is indicated that different types of discharge shows different light intensity ratios among the three spectral sensitive ranges. Based on this fact, a risk evaluation method is proposed to distinguish the hazardous discharges with low or high energy such as partial discharge and arc discharge, which makes it possible to combine the status monitoring and fault protection of switchgear equipment.

2. Working Principle of a Sensor

2.1. SiPM-Based PD Sensor. Unlike vacuum PMT, SiPM integrates high density of microcells of APD in a microchip with millimeter-level size. Each APD unit is activated as a photon is received and generates a self-sustained avalanche ionization, which is called Geiger discharge [8]. By integrating the ionization current of APD units and converting the current into a voltage signal, the photon counting can be achieved as the conventional PMT performs. The basic principle of SiPM is shown in Figure 1.

The signal-to-noise ratio (SNR) and device current noise (DCR) of the SiPM sensor are impacted by the voltage bias applied; thus, seeking an appropriate applied voltage is essential for PD detection. For the practical PD detection, the applied overvoltage was determined experimentally. Figure 2 shows the general SNR of the SiPM sensor as a function of applied overvoltage. Finally, the applied overvoltage was set at 2.0 V.

The 3.07 × 3.07 mm² SiPM (SensL-MicroFJ-30035-TSV) is used as the single unit of the sensor array.

2.2. Trinal Spectral Sensor Array. Based on the circuit of the single unit, a multichannel sensor readout circuit can be developed with three units including a DC power supply, a SiPM array substrate, and a multichannel analog amplifier, as shown in Figure 3.

The width of the PD pulses (i.e., the time constant) coupled by the unit can be adjusted by changing the impedance in the transimpedance amplifier.

According to the discrepancies in the integral spectral distributions, three ion beam sputtering (IBS) optical filter sheets with different spectral responses are chosen for multispectral detection, i.e.,

- **Band1** filter (UV): 260 nm~380 nm UV shortpass; absolute transmission \(T_{abs} > 66\%\), average transmission \(T_{avg} > 74\%;\) optical depth of \(10^{-3}\) (OD3)
- **Band2** filter (VIS): 370 nm~670 nm VIS bandpass; \(T_{abs} > 86\%, T_{avg} > 90\%;\) OD3 level
- **Band3** filter (NIR): 745 nm~1980 nm NIR longpass; \(T_{abs} > 85\%, T_{avg} > 90\%;\) OD3 level

Figure 4 shows the transmissions of three optical filters and the photon detection efficiencies (PDEs) of SiPM in the three spectral bands. With the three optical filter sheets installed in front of three independent SiPM sensors in the array, three regions of different sensitive spectra are built. The structure and picture of the trinal spectral PD sensor array are shown in Figure 5.

Figure 6 gives the typical waveforms of the light pulses synchronously coupled by the three spectral regions of the sensor. It indicates that for a specific discharge, the light
pulses coupled by the three spectral units have the same pulse width (~100 ns) but different magnitudes. In practical detection, all the discharge events can be recorded as \([\text{phase (time)}, \text{magnitude (relative intensity)}]\).

To verify the effective detection distance of this sensor, the attenuation of the coupled light intensity with distance between the sensor and PD source is obtained experimentally in a dark background, as shown in Figure 7. It indicates that the effective detection distance exceeds 4 m which is enough for coupling the discharge light inside the actual equipment. The life cycle of SiPM is determined by the APD unit. APD is with a life cycle of \(\sim 10^5\) hours, thus ensuring the sufficient life cycle of the SiPM-based sensor.

### 3. Experimental Setup

To explore the availability of the SiPM-based trinal spectral sensor in discharge diagnosis, a simulation experiment system is built, as shown in Figure 8(a). This system consists of a high-voltage test chamber, a high-frequency current transformer, a trinal spectral sensor, a 100 kV/100 kVA AC transformer, a high-voltage probe (P6015A, 40 kV peak), a multichannel PD detector, and a digital oscilloscope (LeCroy WaveSurfer 64MXs-B, 600 MHz, 10 GS/s). An epoxy resin insulator is placed between a rod electrode and a plate electrode, which is employed as the discharge model, as shown in Figure 8(b). In the experiment, the ambient temperature is 27°C and the relative humidity is 45%.

### 4. Results and Analysis

#### 4.1. Stochastic Detection Pattern

##### 4.1.1. Partial Discharge

In this section, the statistical characteristics of the light pulses emitted by PDs in the UV, VIS, and NIR ranges are obtained by means of stochastic detection. As an AC electric field is applied, the time lag and intensity of discharge vary periodically with the phase of AC voltage, based on which phase-resolved partial discharge (PRPD) pattern analysis was proposed for PD diagnosis and defect recognition in insulation systems under AC HV. The PD data in a certain number of applied voltage cycles are plotted on the phase axis in one voltage cycle. This analysis provides the physical properties and stochastic behaviors of the discharges. In this case of light pulse detection, the applied voltage peak \(U\), corresponding phase degree \(\phi\), and light pulse magnitude \(I\) are simultaneously recorded for thousands of AC cycles with optical detection to plot PRPD.

The signal processing procedure is briefly described as follows.

(i) Convert the occurrence time of each PD \(t_i\) into the phase angle degree \(\phi_i\) in the same cycle of AC applied voltage by using

\[
\phi_i = 2\pi \left( t_i \cdot T^{-1} - \left[ t_i \cdot T^{-1} \right] \right) \tag{1}
\]

where \(T\) is the period time of a AC cycle.

(ii) Determine the length of window \((l)\) according to the PD intensity in unit time, and count the number of PDs in the \(i\)-th window \((N_i)\) and calculate the average magnitude in the \(i\)-th window \((I_i)\) by using

\[
I_i = \frac{1}{N_j} \sum_{j=1}^{N} I_j \tag{2}
\]

Then, the PRPD pattern can be drawn by plotting each point \((\phi_i, I_i, N_i)\) recorded over a certain time in a fixed cycle of applied voltage. Figure 9 demonstrates the PRPDs and phase-resolved average light intensity curves for the three spectral bands at different applied voltage levels. With increase in applied voltage, the intensities and active phase
ranges of the light pulses increase gradually. The behaviors of PDs at negative half cycles show obvious differences to those at positive half cycles in terms of PD repetitive rate and magnitude.

For all cases of different voltages, the light intensity in the visible spectral band accounts for the majority, while that in the near-infrared band accounts for the least proportion, but with increase in applied voltage, the ratio among the integral light intensities in the three bands varies within a limited range. This rough proportionality remains unchanged in the whole PD active range from inception to prebreakdown.

4.1.2. Arc Discharge. In the experiment, the arc discharge is generated with a rod-epoxy-plate electrode. The arc length is controlled by changing the distance between the rod electrode and epoxy insulator. The time-domain signals of the light emission in the full spectral band for the three arc length conditions (i.e., 0.5 cm, 1.0 cm, and 2.0 cm) are recorded as shown in Figure 10. Arc discharge is intermittent with a fixed active period (i.e., active frequency) which is determined by the arc length. With increase in arc length, the active frequency of arc discharge decreases which is also demonstrated in the light intensity. If the driven power is high enough, the active frequency is independent of the frequency of the AC voltage.

With the same stochastic detection but different detection window lengths, the scatter patterns of the light pulses in the three bands can be obtained synchronously, as shown in Figure 11. It indicates that the intensity components in the three spectral bands remained unchanged as arc discharge continues but account for different proportions. The proportion of the visible light component increases with increase in arc length, while the proportions of UV and NIR components show the opposite. It is also indicated that the ratio among the three components varies within the limited ranges with variation of the applied voltage level and arc length. This rule is consistent with that of PDs.

4.2. Spectral Ratio Variation. The experimental study shows that the light intensities coupled in the three spectral bands account for the different proportions and the ratio among the three components generally experiences a regular change with increase in severity of discharge, which means that the spectral distributions can reflect not only the PD type but also the PD severity. These trinal spectral characteristics provide us a new approach in insulation diagnosis. To quantitatively investigate the influence of discharge active level on the ratio among the intensities in the three spectral bands, the

Figure 5: The structure and picture of the trinal spectral PD sensor array.

Figure 6: The PD light pulse waveforms detected by the trinal spectral PD sensor.

Figure 7: Light intensity attenuation with detection distance. A stable corona discharge (145 pC) is used as the light source.
Figure 8: Experimental setup: (a) test system; (b) artificial discharge models (PD and arc).

Figure 9: PRPDs and phase-resolved average light intensity curves for the three spectral bands at different applied voltage levels. (a) Applied voltage = 4 kV (scatter plots). (b) Applied voltage = 4 kV (average intensities). (c) Applied voltage = 6.5 kV (scatter plots). (d) Applied voltage = 6.5 kV (average intensities). (e) Applied voltage = 10.5 kV (scatter plots). (f) Applied voltage = 10.5 kV (average intensities).
Figure 10: The time-domain signals of the light emission in the full spectral band for the three arc length conditions.

Figure 11: The scatter patterns of the light pulses in the three bands: (a) arc length = 5 mm; (b) arc length = 10 mm; (c) arc length = 15 mm.
proportion of the light intensity in the spectral band $k_i$ is defined as

$$k_i = \phi^{-1} \cdot \left( \frac{I_i}{I_{FULL}} \cdot I_{FULL}^{-1} \right),$$

where $\phi$ is the discharge active phase range, $I_{FULL}$ is the light intensity coupled in the full spectral band.

Figure 12 shows the variations of the three spectral components with applied voltage for PDs. It indicates that the light intensities of the three bands increase monotonically with increasing applied voltage but with different gradients especially in the PD inception stages and prebreakdown stage, as shown in Figure 12(a). With regard to the ratio among the three components, it varies in a very limited range with discharge level ranging from 250 pC to 1.3 nC except for the PD inception stage with relatively low discharge level, as shown in Figure 12(b).
Figure 13 shows the variations of the three spectral components with applied voltage for arc discharge. It indicates that all the light intensities of the three bands experience the up-and-down process with arc discharge length increasing from 2 mm to 25 mm, as shown in Figure 13(a). It can be seen from Figure 13(b) that the variation trend of the light intensity is almost consistent with the driving power of the arc discharge which is deemed as the average energy partially released by light emission in unit time. With regard to the ratio among the three components, it remains almost unchanged with arc length increasing from 2 mm to 25 mm or driving power increasing from 0.4 kW to 2.4 kW.

4.3. Hazard Rating of Discharge. Although the ratios among the three spectral components for PD and arc discharge vary with the applied voltage or discharge level, their distributions have little intersection as shown in Figure 14. For PDs, with increase in PD level, the total proportions of UV and VIS lights decrease from 0.91 to 0.81 and NIR light proportion increases from 0.09 to 0.20, but the ratio of UV light intensity to VIS intensity stays in the range (0.85, 1). For arc discharge, the light intensities in the three bands change with the driving power, but the ratio of UV intensity to VIS intensity stays around 0.3 and is almost unaffected by the variations of arc length and driving power.

Table 1 summarizes the typical spectral ratio values for PD and arc discharges. Actually, the spectrum of discharge light emission is determined by the energy release process and the temperature of the electron. Obviously, the difference of energy level between PD and arc discharge is the underlying causes of the difference in spectral ratios for PD and arc discharge. Therefore, the spectral ratio can be used as the criterion in evaluations of discharge types and discharge risk level with high confidence.

According to the spectral ratio, we can determine the following actions including early prewarning or protection control in practical use.

5. Conclusion

In this paper, a spectrum-based optical method is proposed for hazardous discharge monitoring of switchgear equipment. Based on the fact that the spectrum of discharge light emission is determined by the energy release process and the temperature of the electron, a SiPM-based trinal spectral sensor is developed with good performances in terms of...
sensitivity, defect resolution, and risk evaluation. Experiments indicate that the ratio among the light intensities in the three spectral bands can be used as the criterion in evaluations of discharge types and discharge risk level. For weak and intense PDs, their typical spectral ratios distribute in the ranges of (0.28, 0.44) : (0.62, 0.44) : (0.09, 0.12) and (0.37, 0.44) : (0.43, 0.44) : (0.12, 0.20), and for arc discharge, the ratio distributes in the range of (0.21, 0.22) : (0.70, 0.71) : (0.07, 0.08) and is almost unaffected by the arc length and driving power. In practical use, if a hazardous discharge event is detected, the following actions including early pre-warning or protection control can be taken timely according to the trinal spectral ratio.

Data Availability

The experiment data in this paper are provided in the supplementary materials.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Supplementary Materials

File "data1" concludes the data of light intensities in the three spectral bands at different applied voltages for PDs (Figure 11(a)). File "data2" concludes the data of normalized spectral proportions and discharge level at different applied voltages for PDs (Figure 11(b)). File "data3" concludes the data of light intensities in the three spectral bands at different arc lengths for arc discharge (Figure 12(a)). File "data4" concludes the data of normalized spectral proportions and driving power at different arc lengths for arc discharge (Figure 12(a)). (Supplementary Materials)

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