A Compact Detector for Flexible Partial Discharge Monitoring of 10-kV Overhead Covered Conductor Lines

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***Abstract* — The availability of accurate and cost-effective solutions for the real-time monitoring of overhead covered conductors (CC) is now becoming an important tool for the reliability and condition assessments of this class of electrical lines. This is even more crucial due to the possibly large number of conductors and the wide geographical spread of the electrical network. This letter proposes a smart and compact detector for partial discharge (PD) based monitoring, matching the above needs and offering a flexible and cost-effective solution with some important features, including a non-invasive sensing, a field energy harvesting function, and a low-power working operation. The detector has been designed and implemented, proving its effectiveness on real cases involving PD-affected 10 kV CC lines.**

***Index Terms*—Overhead covered conductor lines, partial discharge monitoring, low power, Rogowski coils, frequency down-conversion, energy harvesting.**

I. INTRODUCTION

OVERHEAD covered conductor (CC) lines are fundamental elements of power networks, and they can be massively found in rural, forest, and some urban areas. Because of their low cost, their maintenance and condition monitoring should be carried out at a reduced budget cost [1]. Nevertheless, the failure of CC lines can be catastrophic, especially in forest areas, as forest fires can inflict significant economic damage that is much higher than the cost of the CC lines themselves.

Traditionally, technicians have used visual and ultrasonic-based devices to inspect CC lines to detect partial discharge (PD) [2], which is a major cause of insulation deterioration and thus a crucial indicator of future failure. However, this detection method is insensitive to internal PDs, and is also time-consuming, laborious, and unsafe to use for widely distributed CC lines. Recently, an alternative traveling wave (TW)-based high-frequency PD detection technique has been proposed in [3-5]. Such technique allows detecting PDs occurring within a power network remotely, thus enhancing the efficiency and effectiveness of the PD inspection. Practical applications of this technique to monitor the PD activities of numerous CC lines remains however challenging, mainly due to the following two reasons. On one side, embedded solutions for the TW detection are based on devices equipped with expensive and power-consuming high-speed data acquisition interfaces (e.g., devices with a sampling rate of at least 20 Msps is needed [1]). The above feature unavoidably increases the overall cost of the equipment, thus limiting its application to the problem at hand due to budget cost. On the other hand, these detection devices have specific power supply requirements and may need a potential or current transformer, which can limit the specific location where they can be deployed.

To overcome these drawbacks, this work proposed a compact PD detector that can achieve low-cost flexible on-line PD monitoring of CC lines, thereby avoiding laborious manual inspections. Non-invasive Rogowski coils are used to detect PD signals, and the frequency of a detected signal is down-converted to eliminate the need for power-consuming and expensive high-speed acquisition and processing chips. An inductive energy harvester is developed, collecting the power directly from CC lines and allowing the PD detector to work at optimal sites where power supply may be unavailable. Finally, a low-power working procedure is devised that uses a low load current to reliably activate a PD detector mounted on a CC line.

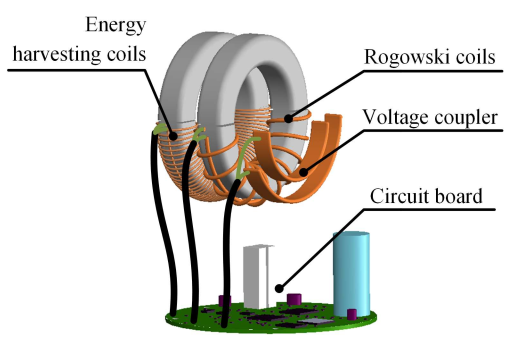

Fig. 1. Components of the partial discharge detector.

II. IMPLEMENTATION OF THE PD DETECTOR

This section describes the in-house-developed on-line PD detector for overhead CC lines. Figure 1 shows its main

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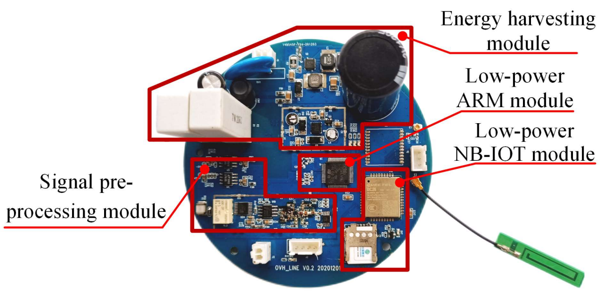

Fig. 2. The circuit board.

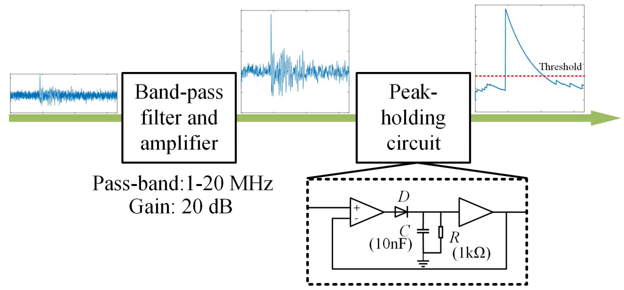

Fig. 3. Signal preprocessing of the partial discharge signal.

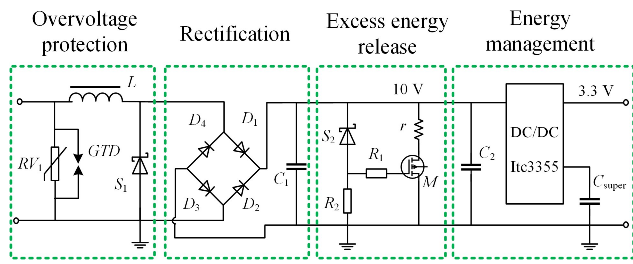

Fig. 4. Equivalent circuit diagram of the energy harvesting module.

components: energy harvesting coils, Rogowski coils, a voltage coupler, and a circuit board. The energy harvesting coils power the circuit board from the CC lines, while the Rogowski coils and voltage coupler are used to non-invasively detect the PD and the power frequency phase, respectively. The circuit board consists of four parts: (i) an energy harvesting module; (ii) a signal preprocessing module; (iii) a low-power advanced reduced instruction set computer (RISC) machine (ARM) module (STM32L476RG, ST); and (iv) a low-power narrow band Internet of things (NB-IOT) module (BC26, Quectel), as shown in Fig. 2. It is important to point out that the most expensive device among the previously discussed components is the ARM module, which costs around 14 USD. Also, the chosen Rogowski coil has been selected to properly work on 10-kV CC lines (its inner diameter is 40 mm).

A. PD detection

Rogowski coils with a passband frequency from 0.2 to 50 MHz is used to detect PD signals due to their superiority of high sensitivity and non-invasive placement. Preprocessing the captured PD signal is done via a band-pass filter, a low-noise amplifier, and a peak-holding circuit, as shown in Fig. 3. First, the filter is used to reduce noise, and the amplifier are used to amplify the PD signal. Second, the peak-holding circuit is used to down-convert the high-frequency PD signal to generate a demodulated signal that can be sampled by the STM32L476RG ARM with a reduced sampling rate of 5 Msps. Finally, the information about the peak amplitude and the time-of-arrival of the PD pulse are extracted via a simple thresholding method. The threshold is defined as (m+3σ), where m and σ are the mean and the standard deviation of the sampled signal, respectively. The estimated time-of-arrival is then converted into a phase value, providing the information about the exact location of the pulse within a given period of the sinusoidal power signal, which is detected by the voltage coupler.

B. Energy harvesting

This subsection describes the energy-harvesting module, including inductive coils to collect power from CC lines, and an energy-harvesting circuit to convert and manage the power. The coils consist of 750-turn coils and a high-permeability permalloy core. The energy-harvesting circuit includes four serial functions: overvoltage protection, rectification, excess energy release, and energy management, as shown in Fig. 4 and briefly described below. First, overvoltage protection — implemented with an arrester (RV_1), gas discharge tube (GDT), an inductance, and a stabilivolt (S_1) — is enabled to protect the circuit board from power system transients. Second, the alternating voltage is rectified into direct voltage. Third, an energy release circuit is developed to limit the voltage within 10 V to protect the subsequent circuit, especially when the load current in CC lines is in the range of several hundred amperes. When the voltage exceeds 10 V, the metal-oxide semi-conductor field effect transistor M (SQD50N10-8m9L, Vishay Inter technology) is turned on and the excess energy is consumed by the resistance r. Finally, the harvested energy is distributed to the subsequent circuits or the 120 F supercapacitor (C_{super}) through an energy management chip (LTC3355, Analog Devices Inc.). The above value is designed to allow a maximum voltage drop of 1 mV during each measurement cycle.

C. Low-power management strategy

The measured power consumption of each module in the circuit board is listed in Table 1. The energy harvesting module, NB-IOT module, and ARM module with an analog-to-digital converter (ADC) off consume very low power, whereas the ARM module with the ADC on and the signal preprocessing module consume significantly higher power. To power the PD detector in low-current CC lines, a low-power management strategy is developed, as shown in Fig. 5 and coded into the ARM module. They are activated only if the voltage of the supercapacitor ($U_{supercap}$) exceeds 3.3 V and the interval between two measurements exceeds the set time-delay (5 min). It is important to point out that the time duration of the

TABLE I
MEASURED POWER CONSUMPTION OF EACH MODULE IN THE CIRCUIT BOARD

Module name	Energy harvesting	ARM with ADC on	ARM with ADC off
Power (mW)	9	78	14
Module name	NB-IOT	Signal preprocessing	
Power (mW)	5	232	

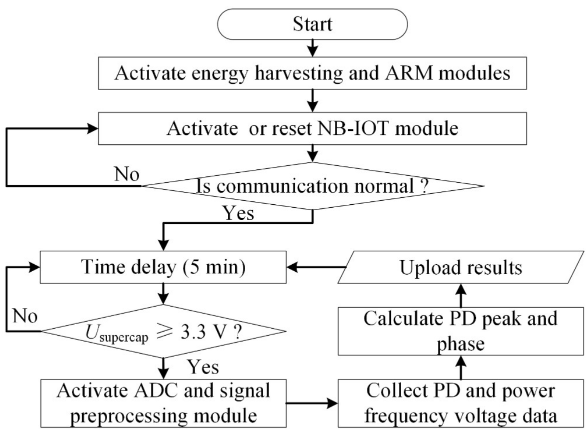

Fig. 5. Low-power working procedure of the partial discharge (PD) detector.

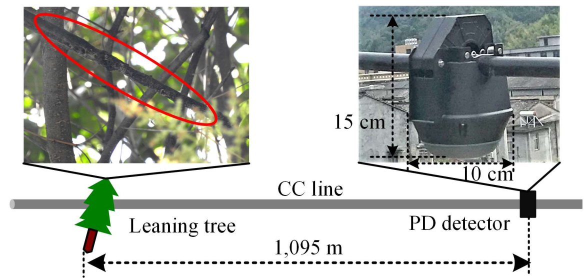

Fig. 6. Case I: on-site partial discharge (PD) monitoring of a 10-kV covered conductor (CC) line affected by a learning tree.

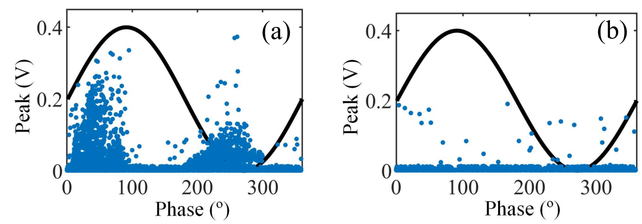

Fig. 7. Case I: partial discharge (PD) events before (a) and after (b) replacement of the PD-affected covered conductor line.

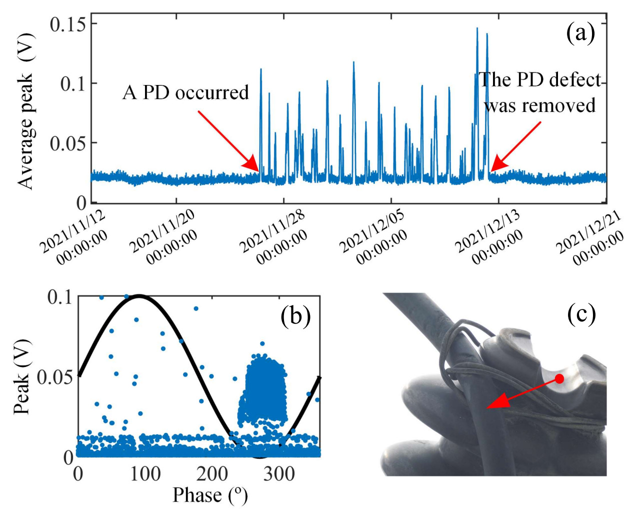

Fig. 8. Case II: historical partial discharge (PD) data (a), phase-resolved PD events (b) and picture (c) of the slipping CC line.

measurement carried out has to be sufficiently larger than the period of the power voltage waveform (i.e., 20 ms). A reasonable value that can be set is 1 s, which corresponds to a duration allowing to cover enough PD pulses for subsequent statistical analysis. For the latter statistical assessment, a specific discussion is included in the next validation section. The low-power working procedure can successfully activate the developed circuit board under a current as low as 4 A.

III. VALIDATION EXPERIMENT

A. Case I: PD caused by a leaning tree

An on-site validation experiment was conducted on a PD-affected 10-kV overhead CC line, as shown in Fig. 6. The PD defect was caused by a leaning tree and the insulation of the CC line was visibly damaged, but no relay protection action was recorded. Since simulation research in [4] and practice experiment in [5] showed that the signal amplitude detected on the non-faulty phase is close to half of that in the adjacent faulty phase due to their coupling characteristics, a PD detector was mounted on the middle phase of the CC line via an insulated boom truck at a distance of 1,095 m from the PD source. The load current on the CC line was 7.4 A, and the PD detector was successfully powered, proving the effectiveness of the developed low-power management strategy. Figure 7 collects the phase resolved PD spectrums of the recorded PD events. The two panels in the Figure correspond to the situation occurring during the PD defect (see the left, panel) and after maintenance and replacement of the PD-affected line (see the right panel). As can be clearly seen, Fig. 7(a) reveals significant PD activities, which disappeared in Fig. 7(b).

B. Case II: PD caused by a CC line slipping from an insulator

Dozens of developed PD detectors were deployed in a rural 10-kV overhead CC line distribution network at intervals of about three kilometers. The intervals depend on the high-frequency attenuation characteristics of the CC line and were determined with reference to the simulation and experiment results provided in [4] and [5], respectively. After a storm, one of the detectors started to detect significant PD activities, as shown in Fig. 8. This information was fruitfully used by the portable PD location system proposed in [5] to localize precisely the damaged point, revealing that the PD source was about 675 meters away from the detector and was caused by a CC line slipping from an insulator, as shown in Fig. 8 (c). After the alert, the staff repaired the CC line and the PD signals subsequently disappeared, thereby confirming that the CC line slipping from the insulator had caused the PD.

IV. Conclusion

This letter proposes a compact detector for flexible on-line PD monitoring of overhead CC lines. The three main benefits of using the proposed detector are: (i) frequency down-conversion of the high-frequency PD signal is achieved via a peak-holding circuit, thus eliminating the need for expensive and power-consuming high-speed acquisition and processing chips; (ii) an inductive energy harvesting circuit is developed to obtain power on-site from CC lines to supply the PD detector, thus increasing the number of sites that can be monitored; (iii) low-power components and working procedures of the detector are developed so that it can be reliably activated by a current value as low as a few amps in the CC line. Validation experiment was conducted on two PD-affected 10-kV CC lines, and the results demonstrate the practical feasibility and effectiveness of the developed PD detector.

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