



An Agile Platform for Partial Discharge Diagnostic Testing and Monitoring in Air-Insulated Substations

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Abstract. Generally, the high-speed oscilloscopes are selected to acquire the real-time data on site for partial discharge diagnostic testing and monitoring in Air-Insulated Substations (AIS). However, it has some disadvantages, such as, the high cost and the inconvenience to carry and install. In this paper, we proposed an agile software defined radio (SDR) platform, the AD-FMCOMMS5-EBZ mounted on the Zynq[®]-7000 SoC ZC706 evaluation kit, as a good solution. We will examine the advantages in the platform that allow developers to quickly prototype partial discharge diagnostic testing and monitoring in Air-Insulated Substations. The tools required in this case are MATLAB[®] and its support packages. As a real-world example of the procedure, we will prototype a platform that determinate partial discharge position directly. The final results verify functionality and performance of the location determination algorithm, and show that the accuracy of the algorithm is acceptable.

Keywords: Partial discharge · Diagnostic testing · Monitoring · Air-insulated substation

1 Introduction

According to IEC-60270, a partial discharge (PD) is defined as a localized electrical discharge that only partially bridges the insulation between conductors and which can or cannot occur adjacent to a conductor [1]. PD can occur at any point within the insulation where the electric field exceeds the local dielectric breakdown strength. PD occurs multiple times and can gradually reduce dielectric breakdown strength.

Partial discharge diagnostic testing and monitoring based on ultra-high-frequency (UHF) sensor array has been applied in air-insulated substations (AIS), especially in location determination of partial discharge sources [2]. Generally, we rely on the high-speed oscilloscopes to acquire the real-time data on

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site. High-end oscilloscopes have high performance, such as the bandwidth in terms of GHz and the sample rate in terms of GSample/s. However, it has some disadvantages, for example, the high cost and the inconvenience to carry and install.

Some software defined radio (SDR) platform, such as the EVAL-AD-FMCOMMS5-EBZ by Analog Devices, as a daughter board, mounted on the Zynq[®]-7000 SoC ZC706 evaluation kit by Xilinx, as a motherboard, maybe a good solution. It could support four transceivers at the same time, and the channel bandwidth is up to 56 MHz. In addition, the tuning range (center frequency) is from 1 MHz (with the help of AD-FREQCVT1-EBZ) to 6 GHz covering high frequency (HF), very high frequency (VHF) and ultra high frequency (UHF), even part of medium frequency (MF) and super high frequency (SHF). Last but not least, the cost is low.

The rest of the paper is organized as follows. The base board, the daughter board and the Communications Toolbox Support Package for Zynq[®]-Based Radio and ADALM-Pluto Radio by MathWorks are described in Sect. 2. The 2-dimension direct position determination algorithm for partial discharge is demonstrated in Sect. 3. Concluding remarks are drawn in Sect. 4.

2 The Agile Platform

2.1 Pre-requisite

The hardware for running PD diagnostic testing and monitoring in air-insulated substations is built with ZC706 evaluation kit, FMCOMMS5 radio hardware and bow-tie antenna array as shown in Fig. 1.

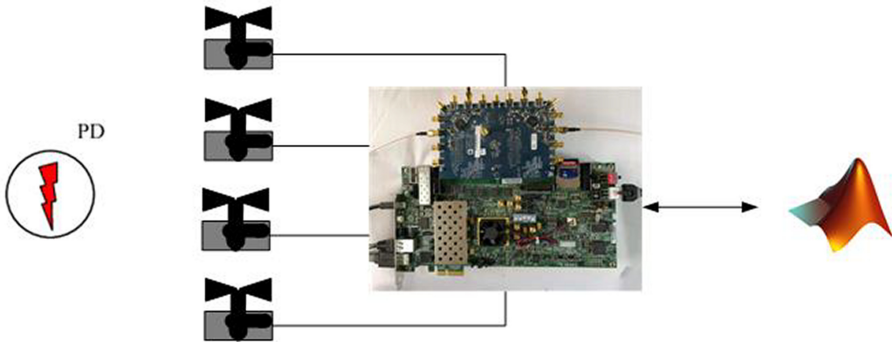


Fig. 1. PD position determination.

The Zynq[®]-7000 SoC ZC706 evaluation kit, as a base board, includes pre-verified reference designs and industry-standard FPGA Mezzanine Connectors (FMC) to allow scaling and customization with daughter boards.

The EVAL-AD-FMCOMMS5-EBZ, as a daughter board, is a high-speed analog module designed to showcase dual AD9361 devices in 4×4 multiple-input multiple-output (MIMO) applications. This platform is intended to enable the prototyping and development of many software defined radio applications, such as angle of arrival systems. Up to one thousands user-programmable registers make it an agile platform [3, 4]. In many cases, multiple bits or bytes work together to serve a particular function, for example, those used to configure automatic gain control (AGC). Analog Devices provides complete drivers for both bare metal/No-OS (operating systems) and Linux when using the evaluation board.

ADALM-Pluto Radio is a software-defined radio active learning module available from Analog Devices that can generate RF analog signals from 325 MHz to 3800 MHz at up to 61.44 megasamples per second (MSPS) with a 20 MHz bandwidth.

The bow-tie antenna, as shown in Fig. 2, is selected as antenna element [5]. The reflection coefficient (S_{11}) is shown in Fig. 3.

In MATLAB[®], Add-ons extend the capabilities by providing additional functionality for specific tasks and applications, for example, connecting to hardware devices and additional algorithms.

By installing the Communications Toolbox[™] Support Package for Xilinx[®] Zynq[®]-Based Radio (MATLAB R2019b and later versions), we can execute MATLAB[®] script to prototype and verify PD diagnostic testing and monitoring systems [6].

By installing the Communications Toolbox[™] Support Package for Analog Devices[®] ADALM-Pluto Radio (MATLAB R2018a and later versions), we can run MATLAB[®] script to calibrate the FMCOMMS5 radio channels and the bow-tie antenna array [7].

2.2 Setup and Procedure

Firstly, we connect the ZC706 evaluation kit and FMCOMMS5 radio hardware by an Ethernet cable. And then, we configure the host computer to work with the Xilinx[®] Zynq[®]-Based Radio Support Package. Finally, we open the MATLAB[®] script for PD diagnostic testing and monitoring.

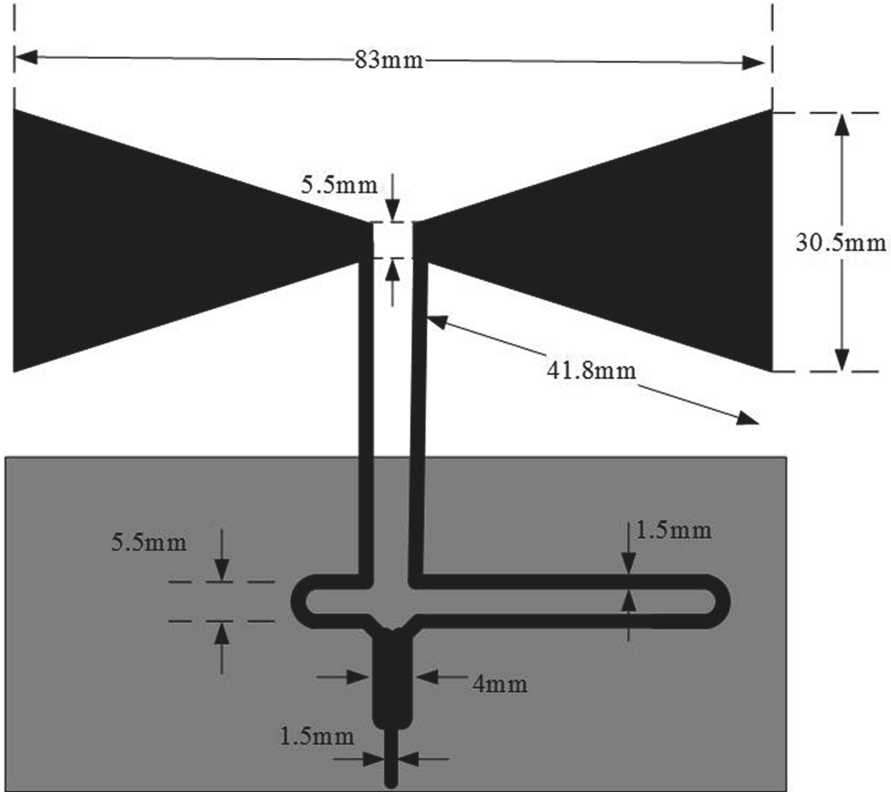


Fig. 2. Bow-tie antenna.

As shown in Fig. 4, for phase calibration among the four FMCOMMS5 radio channels, we connect the power splitter from the Transmitter (TX) port of Plu-toSDR to the four receiver channels of FMCOMMS5, and then estimate and correct the phase offset among the channels.

We could display sinusoidal signals in the time domain to check whether all signals are in synchronization after IQ rotation as shown in Fig. 5.

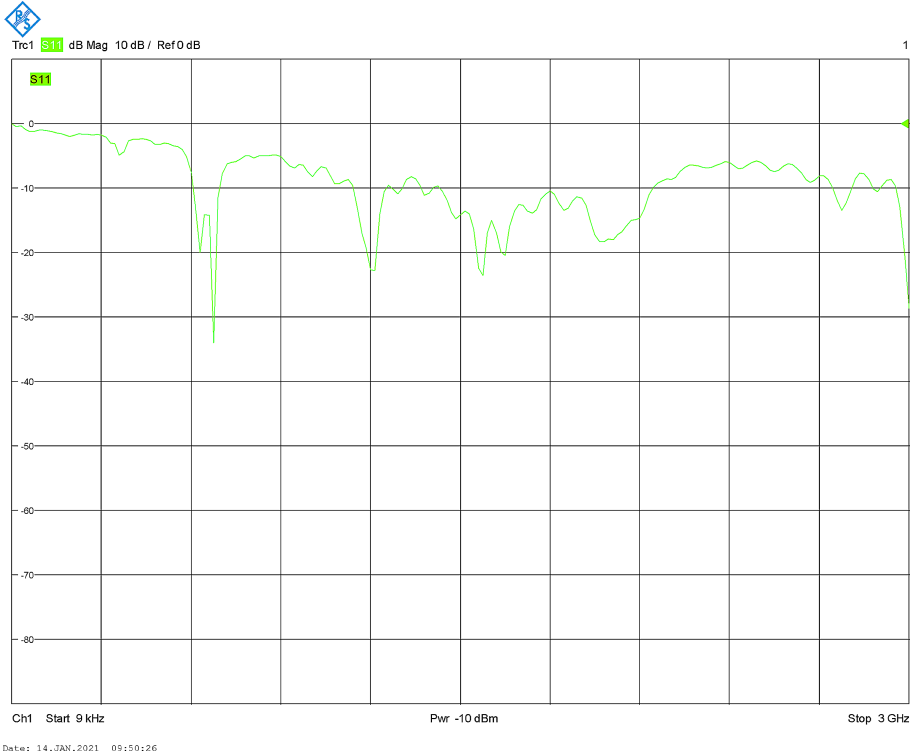


Fig. 3. Reflection coefficient.

As shown in Fig. 6, to calibrate bow-tie antenna array, we connect the power splitter from the four antenna elements to the Receiver (RX) port of the PlutoSDR, and then generate signal at the Transmitter (TX) port of the PlutoSDR, to estimate and correct the phase offset among the antenna elements.

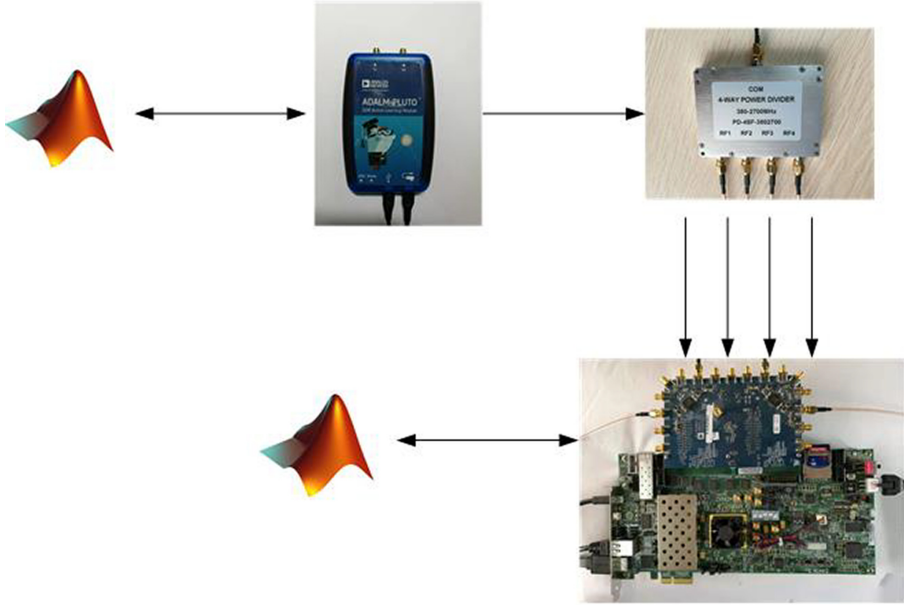


Fig. 4. Phase calibration for EVAL-AD-FMCOMMS5-EBZ.

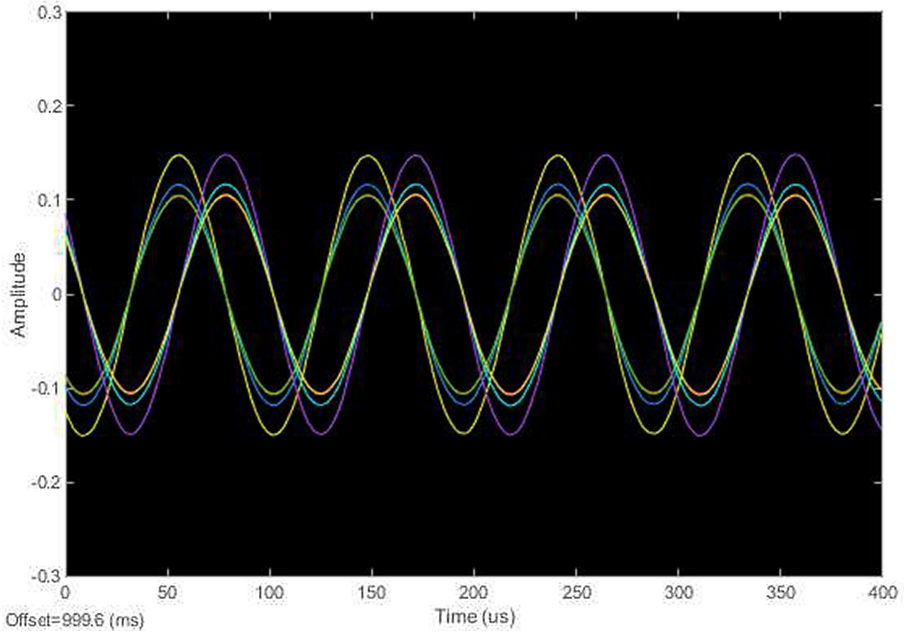


Fig. 5. Four channel signals are in synchronization.

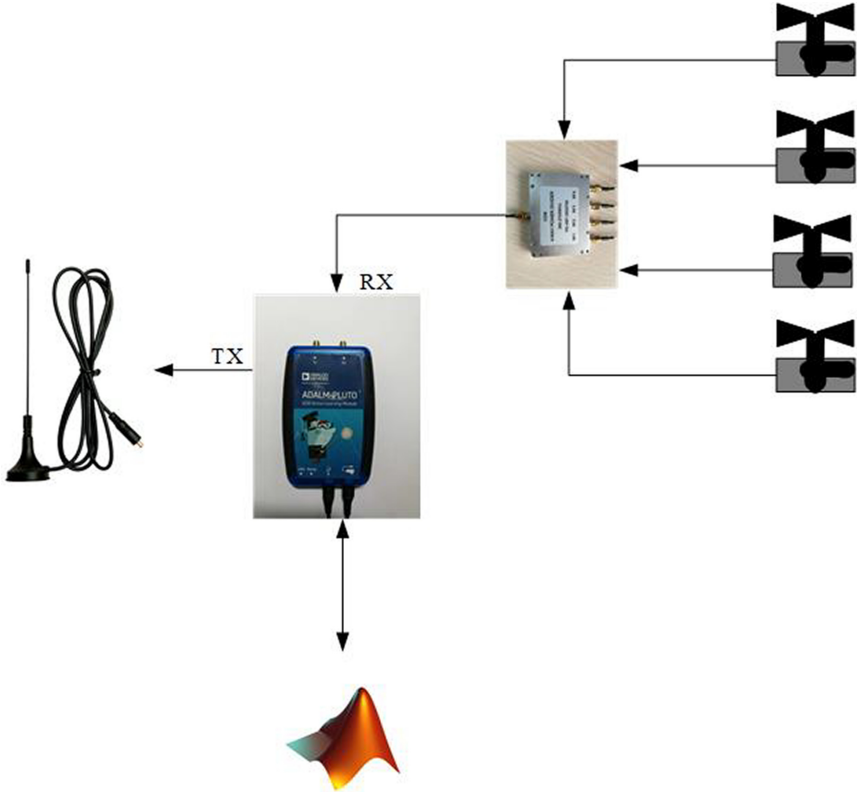


Fig. 6. Phase calibration for bow-tie antenna array.

Carefully disconnect the power splitter from the Tx port of PlutoSDR to the FMCOMMS5 without powering off the ZC706 evaluation kit, and connect the bow-tie antenna array to the four channels of the FMCOMMS5 using equal length SMA cables.

2.3 Verifying Algorithms in MATLAB

The first step, in designing a PD diagnostic testing and monitoring algorithm, is to access some source data. We can use the Zynq[®] SDR Rapid Prototyping Platform. Analog Devices provides a MATLAB System object[™] that is capable of receiving data from the FMCOMMS5 platform over Ethernet.

The System object[™] allows us to select a tuning frequency and sampling rate, collect receive samples using the radio hardware, and bring the receive samples directly into the MATLAB workspace as a MATLAB variable. The required code is very short. A few lines of code to set up the FMCOMMS5, a

few more to set up the MATLAB System objectTM `sdrReceiver`. A sample of the code is shown as follows

```

1 DOARx.SDRDeviceName = 'FMCOMMS5';
2 DOARx.IPAddress = '192.168.3.2';
3
4 RadioBasebandRate = 1e6;
5 RadioFrameLength = 4000;
6
7 sdrReceiver = sdr_rx( DOARx.SDRDeviceName, ...
8   'IPAddress',          DOARx.IPAddress, ...
9   'BasebandSampleRate', RadioBasebandRate, ...
10  'GainSource',         'Manual', ...
11  'Gain',                20, ...
12  'SamplesPerFrame',    RadioFrameLength, ...
13  'ChannelMapping',     [1 2 3 4], ...
14  'OutputDataType',     'double');

```

A few lines of code to capture I/Q samples and write them to a MATLAB variable. A sample of the code is shown as follows

```

1 [data, valid, ~] = sdrReceiver();

```

A few lines of code to phase calibration for EVAL-AD-FMCOMMS5-EBZ. A sample of the code is shown as follows

```

1 data = zynqRadioDOAEstimation...
2 AmplitudeNormalization(data);
3
4 % Calculating the phase offset
5 % between 2 channels
6 [angle1, angle2, angle3] = zynqRadioDOAEstimation...
7 FindPhaseDifference4Channels(data);
8
9 % IQ Rotation to reduce the phase offset
10 % between all channels to 0
11 data = zynqRadioDOAEstimation...
12 RotateIQ4Channels(data, angle1, angle2, angle3);

```

A few lines of code to release the System objectTM `sdrReceiver`. A sample of the code is shown as follows

```

1 release(sdrReceiver);

```

3 Experiments

As shown in Fig. 7, we consider two stations ($L = 2$) placed at one side of a 10 (m) \times 10 (m) square and a single PD source placed at the square center. Each station is equipped with a uniform linear array (ULA) of two antenna elements ($M = 2$) whose broadside towards the square center.

The channel response from the PD source to each station is calibrated in advance, and the propagation speed is assumed to be $c = 3 \times 10^8$ [m/s].

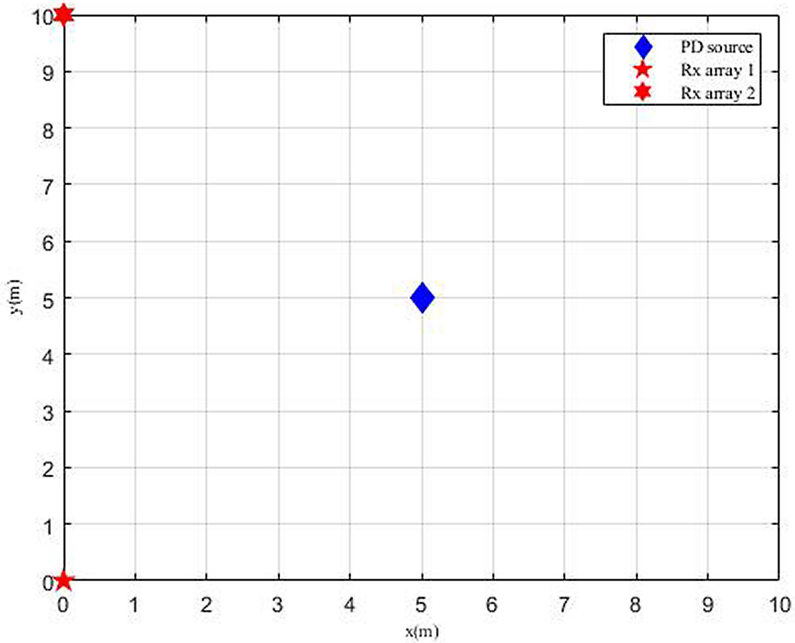


Fig. 7. Laboratory layout.

Following similar coding structures for interacting with the agile platform, we can explore PD position determination as an example of diagnostic testing and monitoring in air-insulated substations [8]. The location determination algorithm was performed in two steps: first, a coarse grid search with 1 (m) resolution over the square generate an initial location estimate; and then, a fine grid search with 0.1 (m) resolution over the neighborhood of the peak detected in the coarse search. The spectrum of the PD source is near 1 GHz, and each location determination is based on single capture of the PD signal for a period of 100 samples ($N_s = 100$).

We performed 500 experiments ($N_e = 500$). The location determination algorithm is executed for each experiment. Then, we evaluate the performance based on the Root Mean Square (RMS) of error given by

$$RMS = \sqrt{\frac{1}{N} \sum_{i=1}^{N_e} (\hat{x}_i - x_0)^2 + \frac{1}{N} \sum_{i=1}^{N_e} (\hat{y}_i - y_0)^2}. \quad (1)$$

where (x_0, y_0) is the PD source location and (\hat{x}_i, \hat{y}_i) is the i -th location estimate.

We plotted one cost function in Fig. 8 for the experiment setup. The cost function has a peak at the location which is close to PD source, the accuracy of the proposed algorithm is acceptable. The RMS of error or miss distance is 0.21 (m).

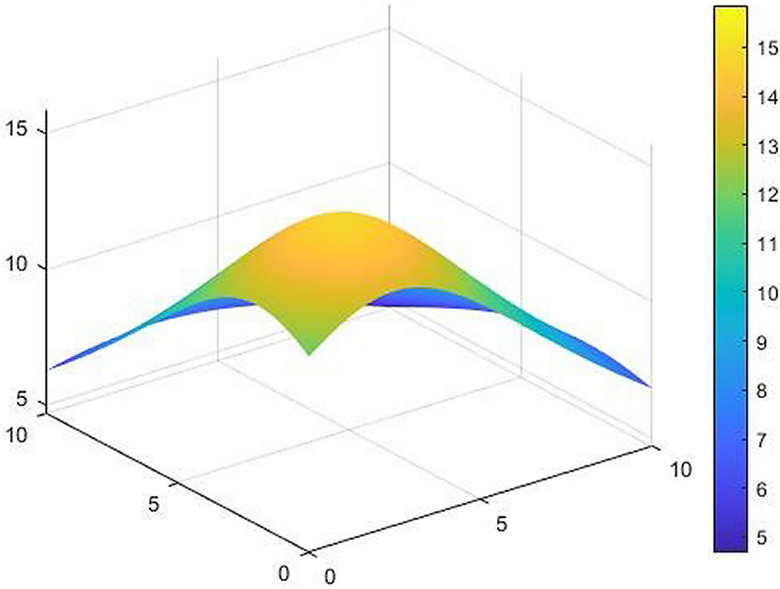


Fig. 8. Cost function for the layout in Fig. 7.

4 Discussion and Conclusions

In this paper, we proposed an agile platform for partial discharge diagnostic testing and monitoring in air-insulated substations. Through experiments in laboratory, the accuracy of the location determination algorithm is shown to be acceptable.

In the future, we will explore other algorithms and implementation of diagnostic testing and monitoring in air-insulated substations by the agile platform.

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