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Experimental Evaluation of Rogowski Coil Performance for Locating PD in Energized Overhead Covered-Conductor Feeder

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Abstract: An experimental analysis is performed to evaluate Rogowski coil performance for PD (partial discharge) location on overhead CC (covered-conductor) distribution lines. The measuring set-up is arranged in high voltage laboratory. A multi-end measuring method is chosen as a technique to locate PD source point on the line. A power transformer is used to energize one end of the CC line by the AC voltage source. The performance of Rogowski-coil is tested in noisy environment. The tests are carried out concerning different measurement conditions such as off-line and on-line PD measuring systems. The results obtained from the laboratory measurements confirm the capability of the Rogowski-coil in order to measure and locate the high frequency PD source on the CC line in consistent with energizing AC source. Chirp detector is used as a signal-processing tool in order to extract the PD signals and then apply the locator algorithm.

Key words: Partial discharge, Rogowski coil, overhead covered-conductor, distribution network, PD sensors.

1. Introduction

Overhead CC (covered-conductor) distribution lines have been used in Finland for more than 40 years. From the statistical data on CC overhead lines installed in Finland, there are around 0.9 fault cases per year per 100 km as reported in Ref. [1]. This low value of fault cases supports the application of CC overhead lines in the forest area as in Finland.

One of the major problems associated with CC line that is still of concern is initiation of PD (partial discharge). This happens when an insulator is not functioning, as it should be due to structural damage or pollution on the insulator surface. The other main reason is especially after leaning of a tree on the line. PDs are observed and it is usually an early indicator of imminent failure of the insulator. If the PD on the CC is undetected for a certain period of time, it will lead to various faults to the distribution network connected to the CC.

Early detection and replacement of damaged CC line will save a lot of unnecessary repair costs and annoying electricity cuts to the paying consumer [2]. Currently, there are two types of measurement techniques carried out to test if there are any faults along the CC line. They are on-line and off-line measurements. With the on-line measurement, the power line continues working as normal and no disruption of service is required. The methods currently available are using VHF (very high frequency) antennas, infrared sensors, capacitive coupling and Rogowski coil [3].

In this work, Rogowski coil is chosen as a PD sensor because it is a non-destructive method to detect PD. Also due to its structure of not having an iron

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core, it is non-saturated. Therefore, the Rogowski coil features a very good linearity due to the absence of magnetic materials [3]. Furthermore, its circuitry is simple and the cost is low [4].

PD measurement with AC (alternating current) source supplied on the line is always affected by EMD (electromagnetic disturbances) and noise. Different location of PD measurement will be affected by different types of noise. The noise can be classified as follows: DSI (discrete spectral interference) caused by radio broadcast signal, periodical pulse shaped disturbances from power electronic equipments, stochastic pulse shaped disturbance due to lightning or switching operations, and white noise which is broadband interference caused by the measuring instrument itself [5-8]. Using a PD sensor with the suitable frequency bandwidth, then followed by post processing for de-noising, is the best way to eliminate noise problem in PD measuring signal.

As the Rogowski is capable of extracting the PD signals, their location can be found using travelling wave fault locator principles [9]. The single-end travelling wave locator function can not be used for locating the distance of PD source. However, the multi-end travelling wave locator (two synchronized measuring method) gives better accuracy for PD location but it needs information about wave propagation speed over the feeder, which is a function in the feeder parameters and tower configuration. In order to avoid using the travelling speed, multi-end fault locator of three synchronized measuring method can be applied.

The reported experiments for testing Rogowski coil were performed to investigate its high frequency characteristics and therefore to model the coil [2-8]. Such evaluation is not sufficient to test its enhancement in locating PD sources. Furthermore, the evaluation should be done considering practical considerations such as testing the performance with the fundamental AC source.

In this paper, experiments are accomplished to test the Rogowski coil performance with considering 20 kV AC voltage level via power transformer. Overhead CC feeder is installed in the High Voltage Laboratory and then the Rogowski coils are allocated at different three measuring points. Then, multi-end fault locator using three measuring points is applied to locate the PD source. The high frequencies are extracted using the chirp detector and therefore the time stamping can be done to apply the multi-end fault locator function. For the off-line measurements, the PD signal is generated using pulse calibrator where the overhead CC is not energized. For on-line measurements, hand-made twisted coil earthed via capacitor is used to generate life PD pulses in accordance with energizing the overhead CC via power transformer.

2. Rogowski Coil as a PD Sensor

Rogowski coil was introduced to measure the magnetic fields since 1912. It has been widely used for measuring fast, high-level pulsed currents in the range of a few mega-amperes rather than in power systems [2]. With the improvement of today’s microprocessor-based protection relays and measurement devices, the Rogowski coils become more suitable for those applications and have generally been used where other devices can not help [3]. It has become an increasingly popular method of measuring current within power electronics equipment due to their advantages of low insertion loss and reduced size as compared to an equivalent CT (current transformer) [4]. They are the preferred method of high frequency current measurements having more suitable features than CTs (current transformers) and other iron-cored devices. Features of the Rogowski coils, which make them particularly useful for transient measurements, stem from their inherent linearity and wide dynamic range.

The Rogowski coil configuration and its equivalent simulated circuit is shown in Fig. 1. The physical geometry size of Rogowski coil used in this work is listed in Table 1. This model and its parameters have been experimentally verified in Ref. [8] where the model showed good performance up to 29 MHz.

3. Experimental Measurement

The experimental setup shown in Fig. 2 was arranged in the HV (high voltage) laboratory at Aalto University School of Science and Technology, Finland. Using a single-phase power transformer, a feeder with two overhead CC cables is only installed due to shortage of the CC cables. The overhead CC line was laid at a certain height (approx. 8 m) above the ground level, and each feeder was terminated through capacitor 500 pF to the ground. Rogowski coils are looped around the CC cable to measure the PD pulse propagation to both sides of the CC lines. In the experimental setup, the power transformer is energized to build up the AC voltage up to 11.5 kV/phase (20 kV system). A fast DSO (digitizing oscilloscope), model Lecroy 9384TM is used to capture waveforms of the Rogowski coils. The sampling frequency used in measurements is 2.5 GHz.

The noise is generated using energized three-phase power transformer 20 kV/410 V AC where it was under certain test conditions to generate broadband interference white noises. Two concepts are used to experimentally generate the PD signals. They are:

(1) Pulse calibrator, for calibrating the PD measuring system, and to inject a PD source into CC line during off-line measurement (without energized 11.5 kV power source);

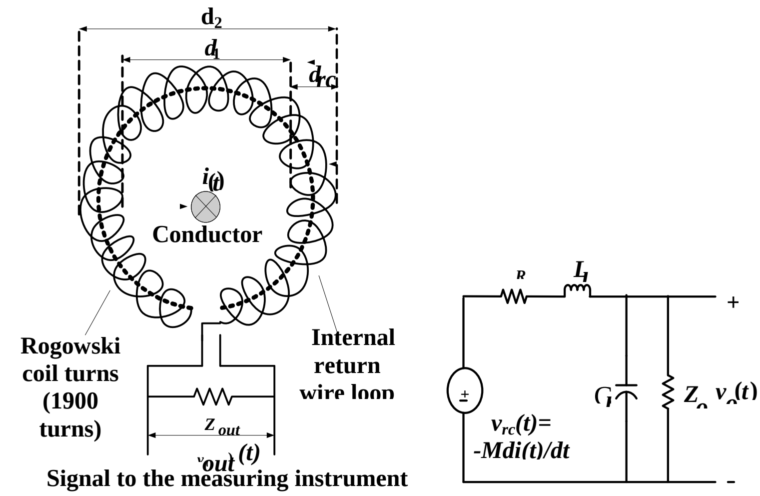


Fig. 1 The Rogowski coil. (a) Geometry and construction; (b) Equivalent circuit (lumped parameters model).

Table 1 Geometry of the Rogowski coil.

Geometrical parameters	Specifications
Inner diameter, *a*	101 mm
Outer diameter, *b*	109 mm
Transducer diameter, d_{rc}	8 mm
Number of turn, *N*	1900

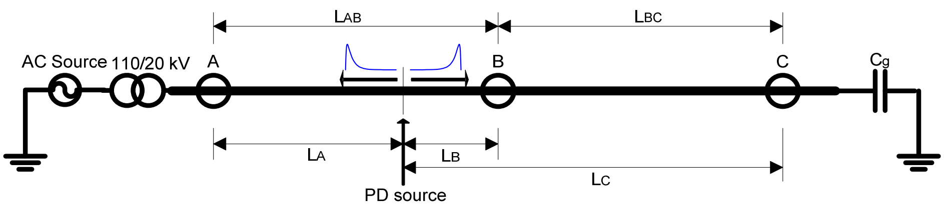


Fig. 2 The experimental configuration.

(2) Twisting a coil around the CC and connected by 1000 pF capacitor, to create a PD source during on-line measurement (Energized 11.5 kV power source).

3.1 Off-line PD Measuring System

The first experimental test case of PD source on the CC line is injected using PD pulse calibrator for calibrating the PD measurement system. This measurement is performed without energizing AC power source on the CC line. The distances between each Rogowski coil are set as L_{AB} = 5.2 m and L_{BC} = 4.5 m for the network shown in Fig. 2. Calibrator signals for 5 nC, 10 nC, 20 nC and 50 nC pulse are injected at distance L_B = 0.9 m in section AB. The measured PD signals for each value of calibrator pulse using Rogowski coils A, B, and C in time and frequency domains are shown in Figs. 3-6.

From Figs. 3-6, PD signals measured by Rogowski coils for injected 10 nC, 20 nC, and 50 nC pulse calibrator are more clearly be seen in the time and frequency domains. Meanwhile for injected 5 nC pulse calibrator, the measured signal is seen corrupted by noise due to low level of PD signal. The amplitude of PD signal measured by Rogowski coils varies from 50 mV up to 500 mV depending on injected pulse calibrator value. The frequency range for PD signal is between 500 kHz up to 3 MHz. The other signals are considered as a noise. These frequency ranges of the PD characteristics have been reported in Ref. [8].

3.2 On-line PD Measuring System

The PD source is created on the CC line using a hand-made twisted coil earthed via 1000 pF capacitor where the system is energized using step-up power transformer. Referring again to Fig. 2, different lengths

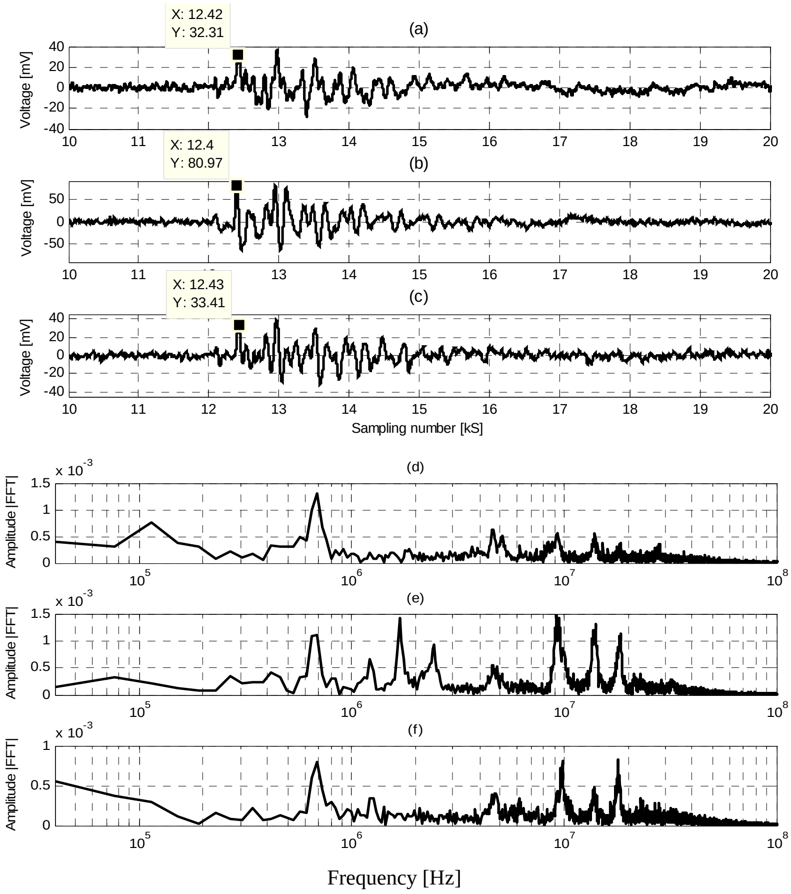
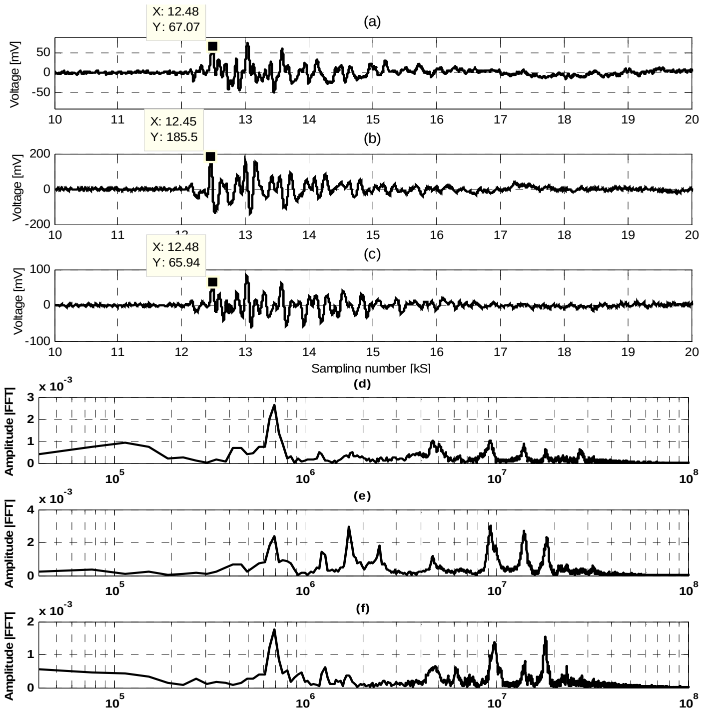
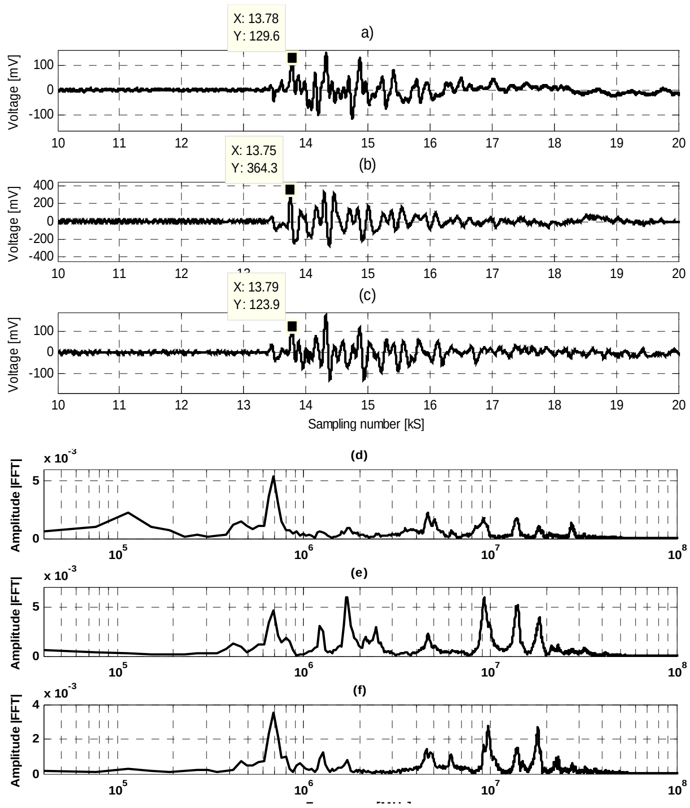


Fig. 3 Rogowski coil response for injected 5 nC pulse calibrator; (a), (b), (c) in time domain, (d), (e), (f) in frequency domain for Rogowski coils A, B and C respectively.



Frequency [Hz]

Fig. 4 Rogowski coil response for injected 10 nC pulse calibrator; (a), (b), (c) in time domain, (d), (e), (f) in frequency domain for Rogowski coils A, B and C respectively.



Frequency [Hz]

Fig. 5 Rogowski coil response for injected 20 nC pulse calibrator; (a), (b), (c) in time domain, (d), (e), (f) in frequency domain for Rogowski coils A, B and C respectively.

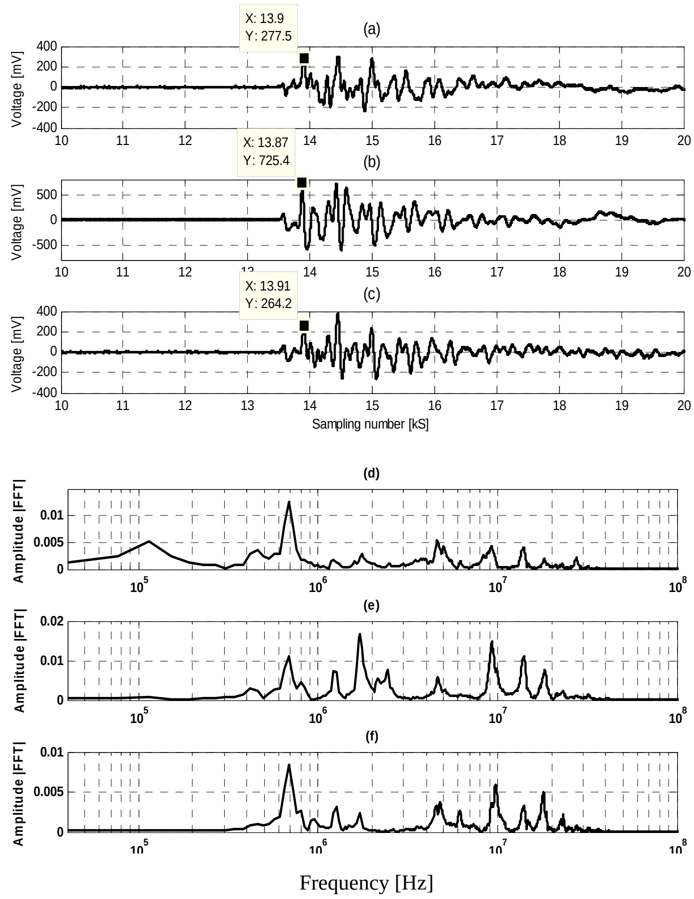


Fig. 6 Rogowski coil response for injected 50 nC pulse calibrator; (a), (b), (c) in time domain, (d), (e), (f) in frequency domain for Rogowski coils A, B and C respectively.

between Rogowski coils are considered for this setup that L_{AB} = 4.7 m and L_{BC} = 5.0 m. The PD source is set at L_B = 2.5 m in section BC. The Rogowski coils measured signals for above-mentioned PD measurements in time domain and frequency domain at points A, B, and C are shown in Fig. 7. It is revealed that dominant frequency contents in the on-line PD measurement with AC source are in the frequency range from 3 MHz -10 MHz, which is little bit higher than case of PD measurement using pulse calibrator. Injecting a PD calibrating pulse will be different from a PD due to an earthed coil through capacitor. These different ranges of PD signal frequency produced by two different measurements is expected. The maximum amplitude of PD signal measured in this setup is found at 2.5 V which is almost 5 times higher than measured PD signal due to injected 50 nC calibrator pulse. This is because the Rogowski coil response depends on how strong the PD signal passing through it. The noise level for on-line measurement with AC source could not be clearly seen in FFT plot due to higher PD amplitudes created in this setup. Noise affected by power line source and energized 20 kV/410 V AC transformers can be seen in time domain plot and it will be clear in the next section.

4. PD Time Localization Using Chirp Detector

FM (frequency modulation) is a technique implemented in communication systems to send information from one point to another by changing the instantaneous sinusoidal carrier frequency linearly with the message. In communication applications, the frequency modulation has the advantage of more robustness against noise effect with increased bandwidth

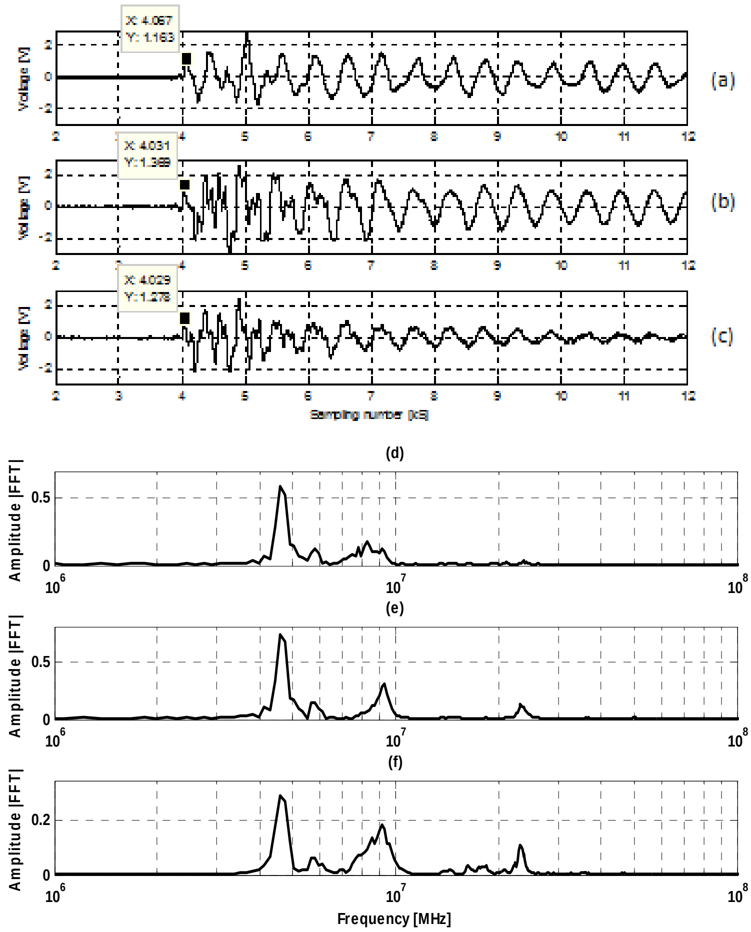


Fig. 7 Rogowski coil response with energized AC power source; (a), (b), (c) in time domain, (d), (e), (f) in frequency domain for coils A, B and C respectively.

requirements. A frequency-modulated wave can be written generally in the form,

$$s(t) = A\cos\left(2\pi f_0 t + 2\pi k \int_0^t m(\tau)d\tau\right) \tag{1}$$

where $m(.)$ is the message information that will cause frequency variations of the sinusoid, and k is a sensitivity factor. The instantaneous frequency of the waveform given above is

$$f_i(t) = f_0 + km(t) \text{ Hz} \tag{2}$$

In Refs. [10, 11], this transform has been used to evaluate the performance of chirp detector to localize earth faults in MV networks based on travelling wave fault locator. Theoretically, a sudden frequency chirp (or frequency modulation) occurring in the Rogowski coil voltages can be extracted using a frequency demodulator and therefore an exact time of the chirp can be identified. In order to evaluate this information, the chirp detector is applied on the off-line PD signal for injected 20 nC calibrator pulse shown in Fig. 5 and the corresponding detected chirp is shown in Fig. 8. The noise impact is clear in this figure. Fig. 9 shows the detected chirps for the on-line measurements shown in Fig. 7. It is confirmed also the noise impact and the difficulty to time localization of the PD signals. Therefore, the measured signals are de-noised before applying the chirp detector and the corresponding results are shown in Figs. 10 and 11 for off-line and on-line measurements, respectively. The de-noising is carried out using DWT (discrete wavelet transform) as illustrated in the Appendix.

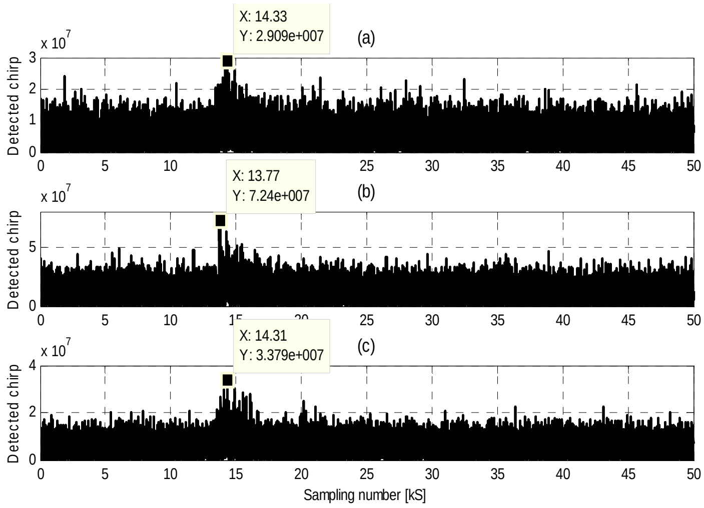


Fig. 8 Detected chirp of PD signal without de-noising measured at Rogowski coils A, B, and C, for injected 20 nC calibrator pulse.

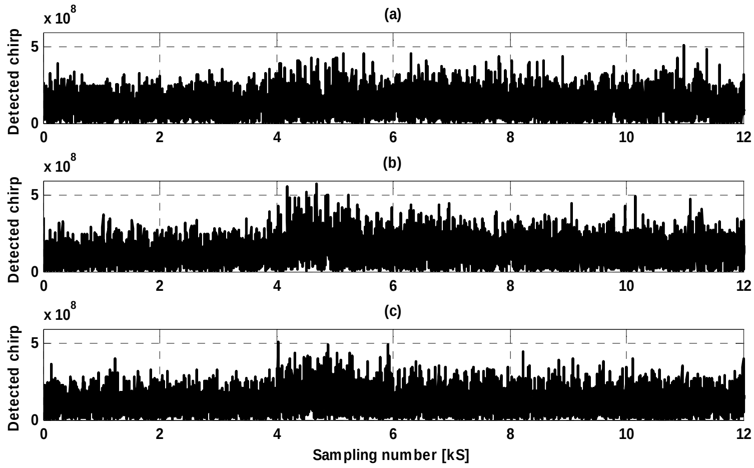


Fig. 9 Detected chirp of PD signal without de-noising measured at Rogowski coils A, B, and C for on-line measurement with energizing AC source.

5. Locator Algorithm

PD source location technique is proposed based on multi-end synchronized measuring points of high frequency impulse PD signals measured by Rogowski coils. The time stamping task is carried out using the chirp detector as discussed in the previous section.

The locator function is as following. Considering the network shown in Fig. 2, for a PD occurs in the section A-B of the conductor line, the PD source distances from sensor A, B and C can be calculated as follows:

$$L_B - L_A = (T_B - T_A)v, \quad L_B - L_C = (T_B - T_C)v$$

$$L_A + L_B = L_{AB} \tag{3}$$

where $T_B - T_A$ is the time difference between sensors B and A and similarly $T_C - T_B$ is the time difference between sensor C and sensor B. Solving the above equations yields to:

$$L_B = \frac{1}{2}\left(L_{AB} + \frac{T_B - T_A}{T_C - T_B} L_{BC} \right) \tag{4}$$

The fault locator algorithm (4) is suitable when the PD location is in section AB as shown in Fig. 1. If the fault is in section BC, the locator equations should be in the form:

$$L_B = \frac{1}{2}\left(L_{BC} + \frac{T_B - T_C}{T_A - T_B} L_{AB} \right) \tag{5}$$

It is clearly seen from the Eqs. (4) and (5) that the PD source location algorithm proposed in this work does not depends on the value of wave propagation speed, v although, the characteristic of wave speed, v on CC

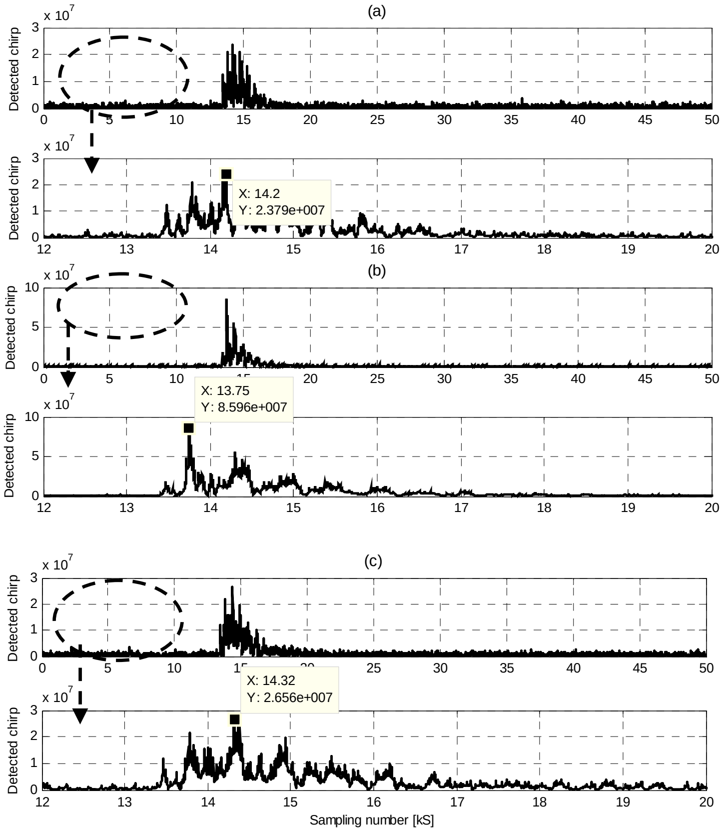


Fig. 10 Detected chirp of denoised PD signal measured for injected 20 nC calibrator pulse.

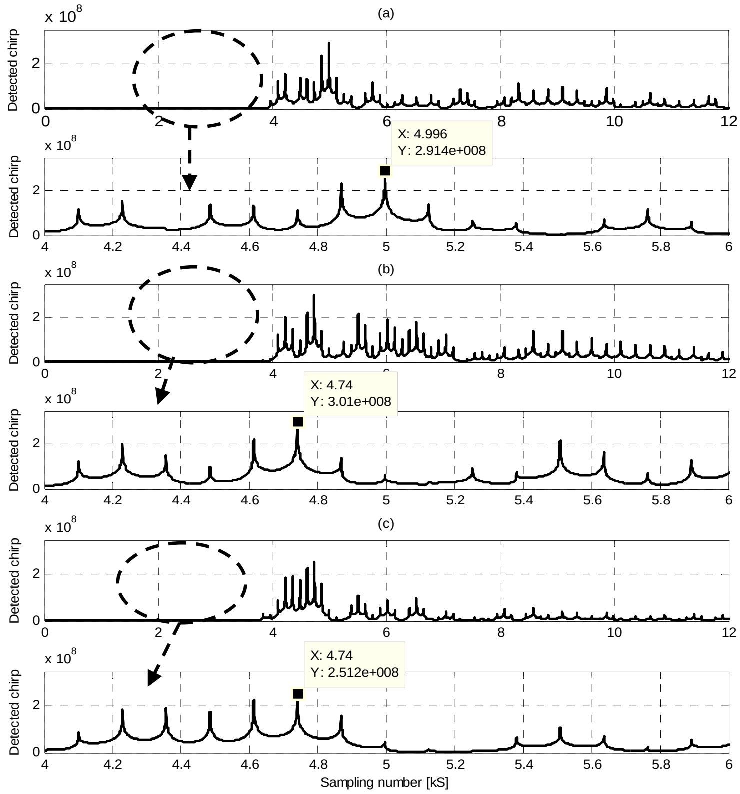


Fig. 11 Detected chirp of denoised PD signal measured for on-line measurement with energizing AC source.

line still give an impact on the arrival times stamping at measuring points. This locator algorithm is valid under circumstances that the measurements are synchronized and the PD faulty section is identified. The identification of faulty section can be based on the values of arrival time and measured voltage at each Rogowski coil. This assumption can be accurate if the allocation between Rogowski coils on the network systems is same.

The criterion to identify the arrival surge generated by the same PD source is the maximum value of the detected chirps shown in Figs. 10 and 11 for off and on-line measurements, respectively. This criterion can help to overcome the de-noising impacts where the low amplitude surges can be removed during the de-noising process. If the PD traveled surge is removed at one of the measuring nodes, it can produce error because the locator will not be applied on measurements of the same PD signal. Therefore, the highest PD surge can help to select the arrivals of the same PD surge source with overcoming such an error that happened because of de-noising process.

Referring to the result of detector chirp in Figs. 10 and 11, the distance of L_B for off-line measurement is found 0.82 m using the locator (2) where the actual distance was 0.9 m in section AB. Meanwhile, the distance of L_B for on-line measurement is 2.5 m using the locator (3) where the actual distance was 2.5 m in section BC.

Due to the experimental distance limitations, the distances used in this work are too short. In order to be able to use any algorithm to localize in this small experiment size, it needs a good time resolution where the sampling frequency is 2.5 GHz, and then sampling time is 0.4 ns. At a wave speed of 2.9×10^8 m/s the distance covered between two adjacent samples is 0.116 m, which is 11 cm, which is acceptable with the network size in meters as in the experiments. This sampling frequency can be reduced when the algorithm used in real network because its size is in kilometers. In other words, low sampling frequency can be used in the field applications due to long distance allocated between sensors.

6. Conclusion

The PD measurement analysis shows that the Rogowski coil used in this work performed well to detect on-line PD signal with energized AC source on the CC line. The PD signals initiated during off-line and on-line measurements have different frequency ranges. The amplitude of PD signal measured by Rogowski coil also depends on the strength of PD source created on the line. This information is important for the design of a wireless PD sensor to detect PD signal. The algorithm for PD source location proposed in this work has more advantages compared to previous locator methods especially the capability of locator without using propagation velocity of traveling wave.

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Appendix: DWT Denoising

In this work, three steps using general wavelet procedure have been performed for de-noising the PD signal. These steps are wavelet decomposition, manipulating wavelet coefficients, and wavelet reconstruction.

(1) DWT decomposition

The DWT is a tool that divides up data, functions or operators into different frequency components, and then studies each component with a resolution matched to its scale [12]. The number *N* of decomposition levels selected should ensure that the DWT decomposition has enough frequency resolution to distinguish PD-associated coefficients from the noise at a certain scale. Nine levels of wavelet decomposition have been selected in this work. Biorthogonal 2.4 (bior 2.4) has been used as mother wavelets.

(2) Threshold determination

The threshold value must have the ability to discard coefficients related to noise and store the PD related ones for signal reconstruction. Therefore, its selection plays an important role in the de-noising process especially for an on-line PD detection and measurement. In this paper, threshold value for each level is determined using:

$$\lambda_j = \frac{\sigma_j}{0.6745\,j}\sqrt{2\log_2 n_j} \tag{A1}$$

where λ_j is the threshold value at level j, σ_j is the standard deviation of the wavelet coefficients and n_j is the length of wavelet coefficients. The automated threshold is implemented in Matlab using Hard Threshold function as it produces better performance shown for the PD signal processes than the Soft Threshold function.

(3) Reconstruction

The PD signal is reconstructed after applying the automated threshold concept on each coefficient detail up to N = 9 levels. The reconstructed PD waveforms after de-noising process can be used for detecting chirps and then for applying the locator.