Assessment of Rogowski Coils for Measurement Full Discharges in Power Transformers †

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Abstract: Science and industry have sought to develop systems aiming to avoid total failures in power transformers since these machines can be working under overloads, moisture, mechanical and thermal stresses, among others. These unconformities can promote the degradation of the insulation system and lead the transformer to total failure. In the incipient stages of these faults, it is common to detect Full Discharges (FDs), which are short circuits between degraded coils. Therefore, several techniques were developed to perform FD diagnosis using UHF, acoustics, and current sensors. In this scenario, this article presents a mathematical model for Rogowski coils and compares two different types of cores: Ferrite and Teflon. For this purpose, FDs were induced in an oil-filled transformer. The sensitivity and frequency response of the Rogowski coils were compared. This analysis was achieved using the Power Spectrum Density (PSD) and the energy of the acquired signals. Additionally, the Short-Time Fourier Transform (STFT) was applied to detect repetitive discharges. The results indicated that the Ferrite core increases the sensitivity by 50 times in the frequency band between 0–1 MHz. However, the Teflon core showed higher sensitivity between 5 to 10 MHz.

Keywords: partial discharges; bushing; insulation systems; infra-red sensors; monitoring systems

1. Introduction

The incidence of discharges in power transformers can be indicative of the deterioration of the machine insulation system. These unconformities can lead the transformer to total failure. They usually appear when the device operates under overload, moisture, mechanical and thermal stresses [1,2].

Partial discharges (PDs) are low energy ionization processes that occur due to a local field concentration in a dielectric material [3]. On the other hand, full discharges (FDs) perform the complete disruption of the dielectric and can occur permanently or in random periods [4–6]. PDs and FDs are characterized as electric unconformities that emit UV radiation, current pulses, acoustic and electromagnetic waves, causing a progressive deterioration of the insulation components. According to Murugan and Ramasamy (2019), the failures of transformer's windings are commonly caused by short circuits due to internal overheating, conductor tilting, conductor bending, clamping system failure, axial instability, and deformations by careless transformer transportation [4]. All these mechanical stresses can impair the wire insulation and lead the transformer to FDs.

Therefore, several techniques were developed to perform discharges diagnosis such as UHF approach [7], acoustic analysis [8], optic acoustics technology [9], or current analysis [10].

Several current sensors have been proposed to perform the discharges identification. For example, the sensitivity of the Inductive Loop Sensor was studied by [11]. The authors proposed a current sensor as a single turn and assessed its sensitivity for partial discharges. High-Frequency Current Transform (HFCT) was used in [12] to estimate the charge emitted by discharges. One of the most traditional topologies is the Rogowski coils (RC), which are widely applied in the industry to perform current measurements [13]. This type of sensor has a toroidal core wound by wires.

Finally, this article proposes a comparison between two different types of cores for Rogowski coils: Ferrite and Teflon. Additionally, the mathematical model of the coils was presented, and their electrical parameters were calculated. In experimental tests, full discharges were induced in an oil-filled transformer, and the current signals produced by the Rogowski coils were compared using Power Spectrum Density (PSD) [2]. The Short-Time Fourier Transform (STFT) [6] was applied to detect repetitive discharges. The results indicated that the Ferrite core demonstrate, high sensitivity in the frequency band between 0 - 1 MHz. Nevertheless, the Teflon core showed higher sensitivity between 5 MHz to 10 MHz, which can be a promising alternative to noisy environments since narrow bands can avoid interference.

The outline of this manuscript is: Section 2 presents the mathematical model of Rogowski coils. The experimental setup is described in Section 3, and then, in Section 4, the results are presented and discussed. Section 5 reports the conclusions of this article.

2. Mathematical Model

As previous mentioned, RCs are widely applied in industry to perform current measurements, and their construction is based on a toroidal core wound by wires. According to [14–16] a self-integration Rugoski coil can be developed as presented in Figure 1a. Figure 1b defines the dimensions abbreviations of the toroidal structure, and Figure 1c describes the equivalent circuit for the Rogowski coil.

For this work, the dimensions of the two sensors were chosen to compare two toroid architectures with the same number of turns but with different core materials (Ferrite and Teflon). Table 1 shows the values of measured dimensions of the two types of cores.
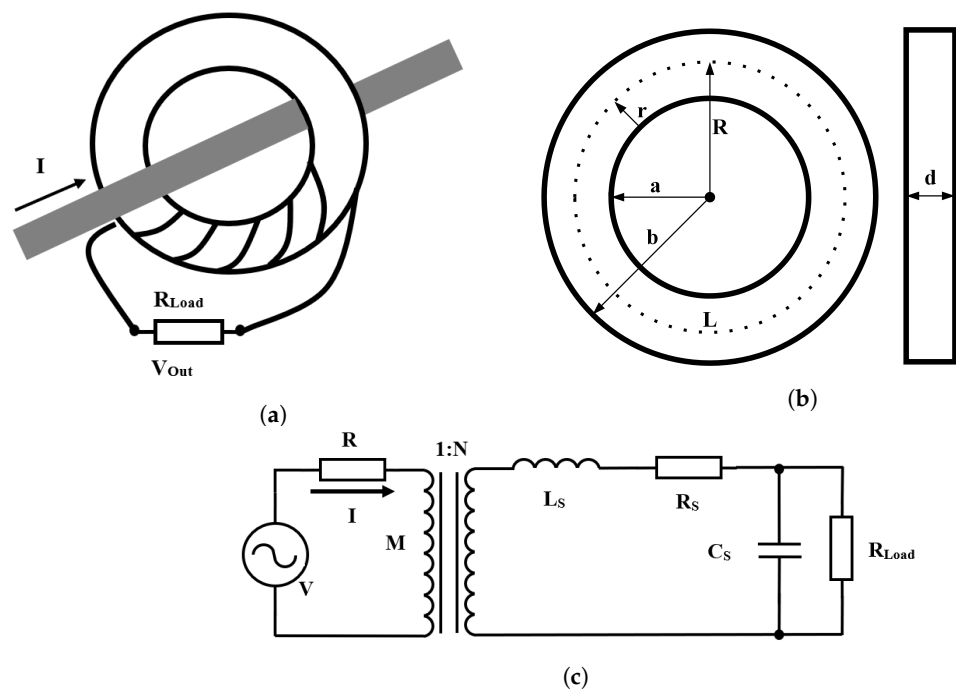

Figure 1. (**a**) Coil architecture, (**b**) Toroid dimensions, and (**c**) Equivalent circuit .

Table 1. Dimension values.

Dimensions	Ferrite	Teflon
Turns (N)	50	50
Toroid average length (L)	78.9 mm	86.2 mm
Toroid thickness (d)	12.46 mm	11.15 mm
Inner radius (a)	18.75 mm	19.33 mm
Outer radius (b)	31.45 mm	35.36 mm
Toroid average radius (R)	25.1 mm	27.35 mm
Toroide average width (r)	6.35 mm	9.02 mm

The electrical parameters seen in Figure 1c can be calculated by [14–16]:

$$L_S = \frac{\mu}{2\pi} \cdot N^2 \cdot d \cdot \log\left(\frac{b}{a}\right) \tag{1}$$

$$M = \frac{\mu}{2\pi} \cdot N \cdot d \cdot \log\left(\frac{b}{a}\right) \tag{2}$$

$$R_S = \rho \cdot \frac{4.L_w}{\pi.D^2} \tag{3}$$

$$C_S = \frac{4.\pi.\epsilon_0.R}{\log\left(\frac{R}{r}\right)} \tag{4}$$

where $\mu = \mu_0 \mu_r$, μ_0 is the air permeability, μ_r is the relative permeability of the material (Teflon = 1, Ferrite = 2500), ϵ_0 is the air dielectric constant, ρ is the copper resistivity, L_w is the wire total length, and D is the wire diameter. Additionally, the output V_{out} across resistor R_{load} can be achieved using:

$$V_{out} = \frac{R_{load}}{L_d} \cdot M \cdot I \tag{5}$$

where L_d is L_s/L_w. Hence, the current I can be measured by reading the voltage V_{out} across the load resistor.

The value chosen for R_{load} was 50Ω. Also, the wire diameter (D) is 0.40386 mm and the wire length (L_w) is 2 m for both coils. Finally, using the previous information, the values of the electrical parameters were calculated (Table 2).

Table 2. Dimension values.

Parameter	Teflon	Ferrite
L_s	1.4 uH	3.65 mH
M	28 nH	73.1 uH
R_s	0.268 Ω	0.268 Ω
C_s	4.68 pF	6.32 pF

3. Materials and Methods

In order to assess the sensitivity of the Rogowski coils to FD detection, several tests were carried out in a power transformer (30 kVA, 13.8 k/220V). An electrode with a 5 mm gap was immersed in the transformer oil (Figure 2a) to generate FDs. A high voltage source was applied to the electrode and it was observed that FD activity started at 3.5 kV.

The supply cables were involved by the two coils (Figure 2b) and an oscilloscope was used to acquire the voltage across the resistor R_{load} (50 ohms). The sampling frequency was set to 50 MS/s. The signals were processed by Matlab®software using the Short-time Fourier Transform and the Power Spectrum Density function. Both of these techniques were successfully applied to fault detection in electrical machines in previous works [2,17].
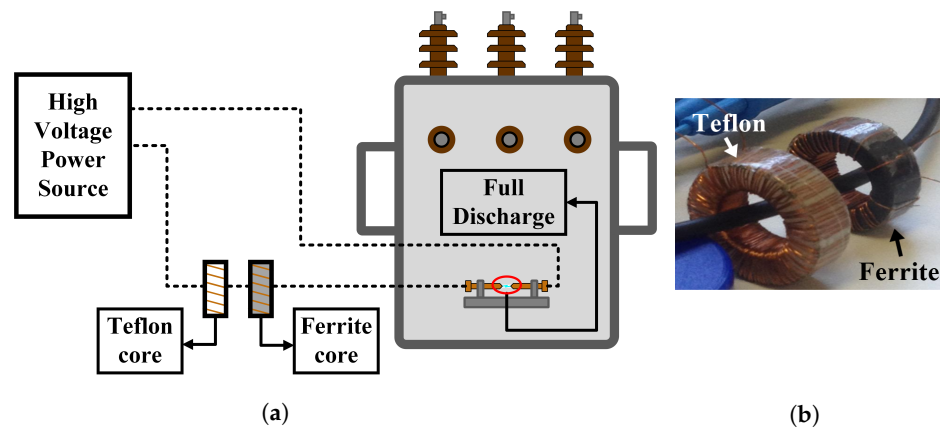
(**a**)　　　　　　　　　　　　　　　　　　　　　　　　(**b**)

Figure 2. Test bench for PD generation (**a**), and Rogowski Coils (**b**).

4. Results and Discussion

The full discharge current signals provided by Teflon and Ferrire coils are presented in Figure 3. Since the measures were taken simultaneously, five full discharges peaks can be observed for both core materials. However, by comparing Figures 3a,b, it is clear that each coil type presents different frequency and time responses.
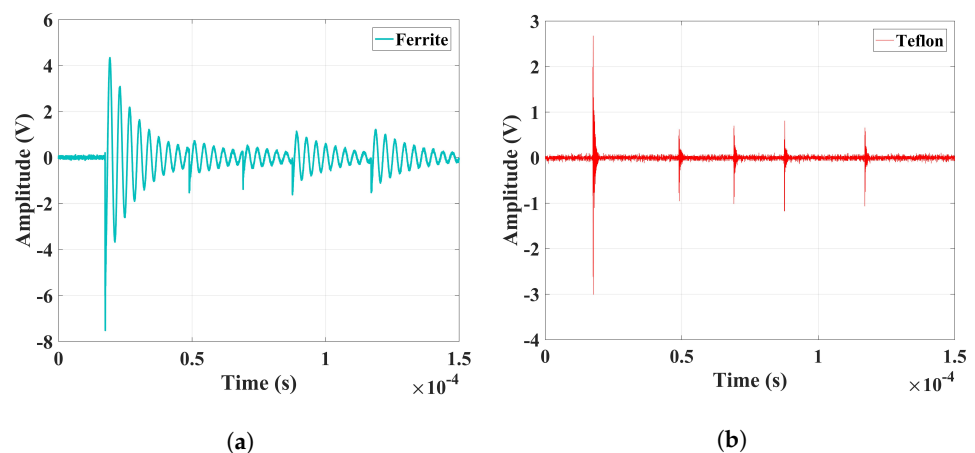

(**a**)　　　　　　　　　　　　　　　　　　　　　　　　(**b**)

Figure 3. PD signals in time domain for Ferrite (**a**), and Teflon (**b**) cores.

Therefore, the Fourier Transform was applied to the discharge signals to achieve the PSD for both sensors (Figure 4). Also, considering the full discharges as impulsive current signals in the time domain, these results describe the frequency response of the sensors. The result reveals that the Ferrite coil has a higher power density in the 0–1 MHz range. On the other hand, the Teflon coil presented a higher power density between 5–10 MHz.

To further investigate the application of the sensors for full discharge detection, the STFT was applied to the current signals (Figure 5). This technique allowed the analysis of the frequency pattern of the currents over the entire acquisition period. In Figure 5a, all five discharges peaks could be identified by high power values using the Ferrite coil. In the same way, the faults were also detected by using the Teflon coil in Figure 5b. Although the power spectrum density can characterize the occurrence of FD, this technique cannot assess the recurrence of the failure like STFT.

The previous results indicate that both sensors are capable of assessing the full discharges in power transformers. However, the Teflon coil can be pointed out as a better alternative for fault detection for two reasons:

1.　In industrial scenarios, electromagnetic noise is generally restricted to a maximum of hundreds of kilohertz. However, the frequency response of the Teflon coil is limited to 5–10 MHz. Therefore, this device avoids measurement errors due to high noise

industrial scenarios. On the other hand, the Ferrite coil proved to be more sensitive to these noises since it presented a high PSD for lower frequencies.

2. The production cost of the Teflon coil is financially advantageous compared to the Ferrite coil due to the composition of the core.
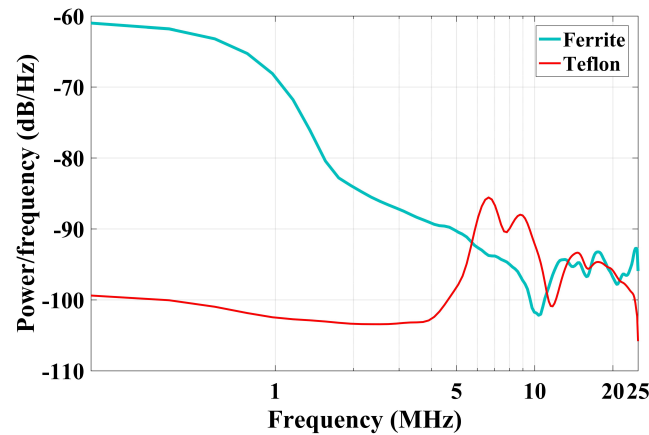

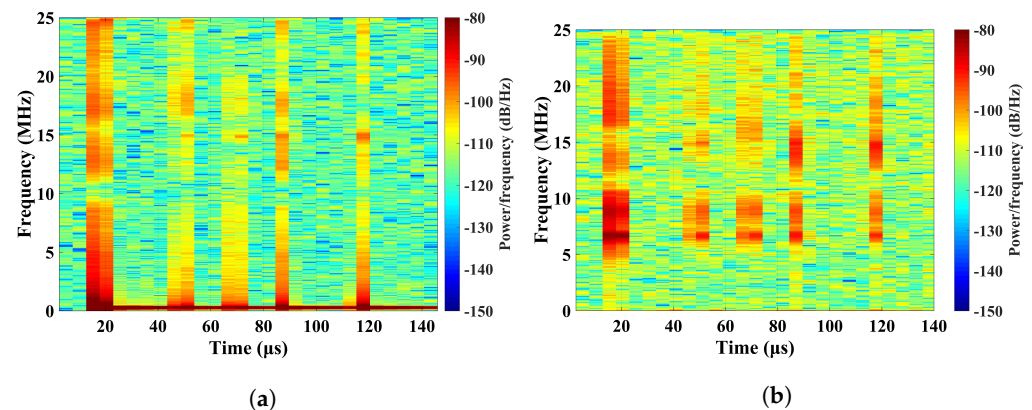**Figure 4.** Power Spectrum Density for Rogowski coils based on Ferrite and Teflon.

(**a**)   (**b**)

Figure 5. STFT for (**a**) Ferrite and (**b**) Teflon cores.

5. Conclusions

Full discharge detection is crucial to power transforms maintenance plans. Hence, this article presents a comparison between two topologies of Rogowski coils for discharge identification. The mathematical model of the sensor was presented, and the sensitivity of Ferrite and Teflon coils was assessed by PSD and STFT. Results indicate that although the two topologies provided promising results for fault evaluation, it can be concluded that the Teflon coil has more advantageous features and better noise immunity for industrial applications due to its narrow response band. Besides, Teflon has a low cost in relation to Ferrite, being an alternative to expand nondestructive testings in power transformers. Future works can evaluate other topologies and the capability of these sensors to perform separation of discharge types.

Institutional Review Board Statement:

Informed Consent Statement:

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