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Investigation of the Rogowski Coil for Efficiently Monitoring and Locating PD Faults in the High Voltage Apparatus

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***Abstract*-This paper is about analyzing the Rogowski Coil for measuring the partial discharge phenomenon in high voltage apparatus. Designing optimally, we can measure the high frequency and low amplitude currents like PD pulses more efficiently using the mentioned device. Besides, it is possible to find the accurate place of the fault using the signal processing methods. Other advantages include low cost, being non-interfering for the network, ability to send data wirelessly and ability to be used online. Designing approaches for the coil to have a wide band and high gain measuring device are discussed and the equivalent circuit is analyzed theoretically and is simulated for variation of parameters. These results are examined practically by making some special coils and testing under accepted methods for PD measurements.**

I. INTRODUCTION

For protecting high voltage insulation against the partial discharges before they fail, sufficient monitoring systems are needed. The procedure of detection and accepted methods are introduced in the IEC 60270 in more details. After many studies on this subject [1-5], the tendencies are going toward the lower cost, higher performance and more flexible devices that can perform this duty. Rogowski Coil is an air cored transformer that produces a voltage on its output terminal according to the current passing through the measured wire. Some studies were done on the optimal design of this coil for high frequency (HF) measurements like the PDs [6-9]. Beside the detection goals, finding the exact place of the fault is of crucial importance. This aim can be achieved by signal processing methods and finding the correlation between the detected pulses and the saved ones to locate the phenomenon.

There are some problems and challenges in the design and application of the Rogowski Coil for PD detection purposes. For instance, the noises from the environment can make the detection inaccurate and in some cases, the disturbance signals may be considered as PD pulses. Moreover, the PD pulses are so weak that there is a need for a high gain amplifier with a HF bandwidth. Designing of such amplifiers requires special techniques and instruments. For transmitting the output signal of the coil, non interfering equipments are needed such as optical fibers and their electronic converters in order to avoid the effects of the noises.

However, the intention of this paper is to find the optimal design of the Rogowski Coil for having a high gain, low cost and flexible device that can be helpful for PD diagnosis. This includes the calculation and implementation of the characteristics of the coil and showing that the mentioned claim can be achieved with the designed coil.

There are several methods for modeling the coils that has been discussed in the earlier works such as transmission line model, lumped model, hybrid model and detailed model [10-12]. The detailed model is the main idea of the study in this paper and all simulations and mathematical calculations are made according to this model.

II. DISTRIBUTED MODEL OF ROGOWSKI COIL

For a coil that consists of several rings, the characteristics of one ring and its mutual inductance and capacitance with the other rings and ground are the basics of the distributed model. This reconstruction method was widely discussed for the transformers before [13-15]. In these models, the effect of the ferrite core is considered and those are not so relevant to our study, but give guidelines to start with. In other case studies, air-cored transformers were analyzed using the distributed model [16], [17], but the results are not precise enough for our application. Therefore, a combination of these approaches is employed to get a more reliable model for HFs.

The configuration of a simple Rogowski Coil is depicted in Fig. 1. The coil is very sensitive to the noisy conditions and so a shield is necessary to avoid noises. In the present model, the winding is divided into sections and each section consists of one turn. Then, for each turn, there are the electrical components which can be calculated regarding the coil structure. Fig. 2 presents the model for each section including the below parameters:

C_s: Total series capacitance between two adjacent rings
C_{sh}: Capacitance between the ring and shield
R_i: Total series resistance of the ring
L_i: Total self inductance of the ring
L_{ij}: Mutual inductance between i^{th} and j^{th} rings
M: Mutual inductance between the section and the wire carrying the measured current

Putting these sections in serial connection, the complete model can be achieved. The Mentioned parameters are calculated in [18]. For example, the mutual inductance between two rings can be estimated as:

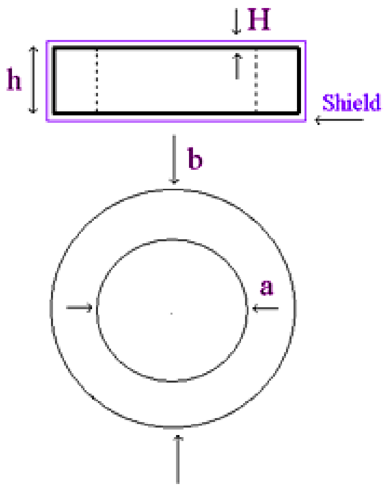


Fig. 1. General structure of the Rogowski Coil

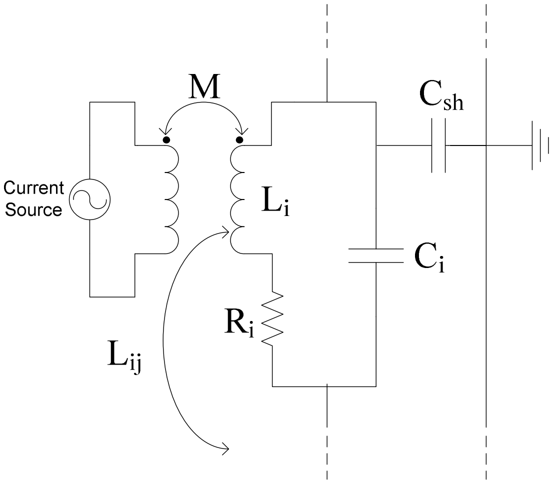


Fig. 2. Electrical model for each section of the coil

$$L_{ij} = \frac{2\mu_0 r}{\sqrt{k'}}\,[K(k') - E(k')]$$

$$\text{Where } k' = \frac{1-\sqrt{1-k^2}}{1+\sqrt{1-k^2}} \text{ and } k = \frac{2r}{\sqrt{r^2+d^2}} \qquad (1)$$

In which r is the radius of the rings and d is the distance between two near rings. $K(k')$ and $E(k')$are the Complete Parabolic Integrals of the first and second orders. For the ring presented in Fig. 3, the self inductance can be determined as:

$$L_i = \mu_0 R(ln\,(\frac{8R}{MGA} - 2)) \qquad (2)$$

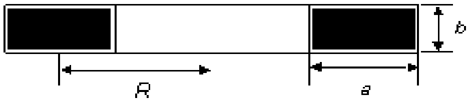


Fig. 3. Dimensions of the ring consisting of one turn of a conductor with rectangular cross section

where MGA is the Mean Geometric Area determined in (3):

$$\ln\left(\frac{MGA}{\sqrt{a^2+b^2}}\right) = \frac{2a}{3b}\tan^{-1}\left(\frac{b}{a}\right) + \frac{2b}{3a}\tan^{-1}\left(\frac{a}{b}\right) - \frac{a^2}{12b^2}\ln\left(\frac{a^2+b^2}{a^2}\right) - \frac{b^2}{12a^2}\ln\left(\frac{a^2+b^2}{b^2}\right) - \frac{25}{12} \qquad (3)$$

The simplest formula for the mutual inductance between the ring and the central wire that carries the measured current is defined in [19] as:

$$M = \frac{\mu_0 r}{\pi}\ln\left(\frac{b}{a}\right) \qquad (4)$$

The steps for finding the resistance of each turn considering the skin and proximity effects was mentioned in [20] and the capacitances were calculated in [21]. Using these equations and putting those together, the final model can be achieved.

For concluding the frequency response of the system, we should first determine the input, output and their relation. The input of this system is a HF current that passes through the measuring wire and the output is a voltage that we obtain from the coil. Therefore, the frequency response of the system is the ratio of V_{out} (ω) to I (ω). Since the induced voltages in the sections are in series, the output voltage is the sum of these voltages. This model can easily be used in the simulating programs. For having a device with the high gain and wide bandwidth, there are two ways. First, after simulating and reaching the desired results, the parameters will be obtained and then the configuration of the coil can be calculated. Second, considering some initial constructing features of the coil regarding to the application criteria, we can find the others by simulating with the existing ones and some assumption of the others. After several repetitions, the best result will be achieved.

III. PRACTICAL AND THEORETICAL RESULTS

Using the network theory for solving the problem, the Transfer Function (TF) of the system can easily be achieved after some matrix calculations. These computations were done in MATLAB using the numerical methods and the results are presented in the following.

Fig. 4 (a) shows the TF of the designed coil characterized in TABLE I. The measured TF of this coil with the Network Analyzer (when the shield is grounded or not) is shown in Fig. 4 (b) and (c). The compatibility between these two figures around the lower frequencies is apparent and approves our claim.

TABLE I
Construction features of the proposed Rogowski Coil

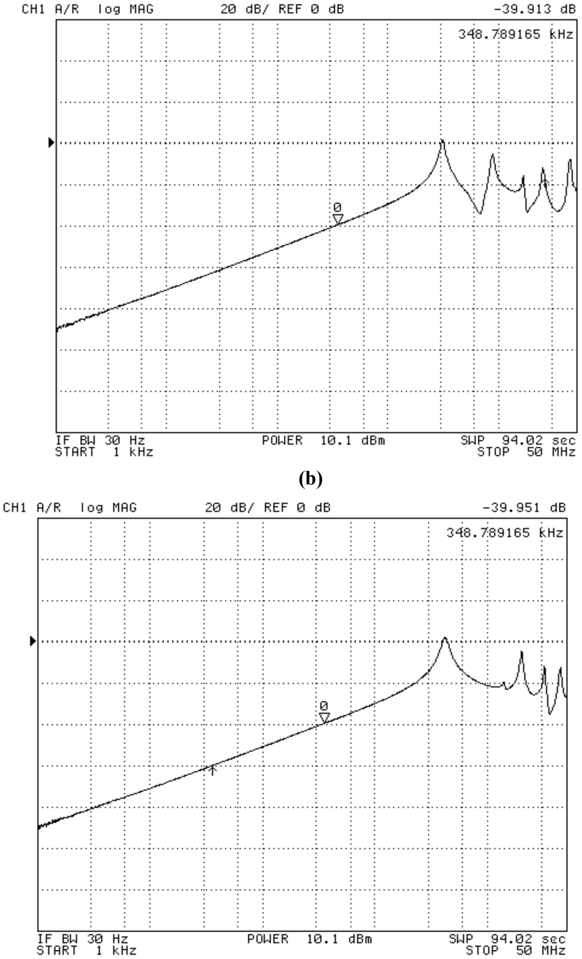
Coil Characteristics	a(cm)	b(cm)	h(cm)	N
Value	2	4	1.5	100

Differences for higher frequencies are originated from the nonequivalent spaces between the turns and the estimations that were done on the spaces between the wires and the grounded shield and under measuring wire. Besides, stray capacitances may disturb our circuit and so change the results. For PD measurements, the bandwidth of the system is more important than the behavior of the system at the higher frequencies. So, the first change in the frequency response is the crucial frequency for our goals (linear region) and this can be known from the proposed model.

When the shield is not grounded, the effect of the noises is yet prevented. As it is obvious from the Fig. 4 (b) and (c), grounding the shield leads to the smooth frequency response at the higher frequencies. In this region, the behavior of the system is not as a differentiator and the calculations based on this concept are not acceptable any more. Furthermore, grounding the shield can expand the bandwidth of the system and so has desirable consequence.

Because the gain of the system is not high enough, we need an extra amplifier to enable us to see the output voltage on the digital oscilloscope. To have a good amplifier, we employed AD818– a video Op-Amp with a high bandwidth. Fig. 6 shows the TF of the system when one dimension of the construction is changed. As we can see, the design procedure is very simple and after some simulations, we can reach the desirable device. For instance, under constant frequency, number of turns and desired inner radius, we can find the optimum outer radius and the height of the coil for having the maximum gain. This approach is presented in Fig. 5. Regarding this figure, it is apparent that the maximum gain can be achieved by the outer radius of about 4cm and the height of 8cm. Although the larger height leads to higher gain, its impact is not very effective.

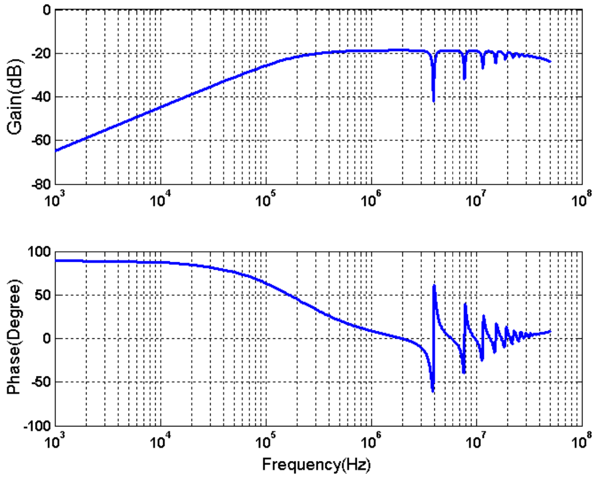
Because of the linearity of the system the calibration using the standard PD calibrator will be valid for every PD measurement. Different kinds of PD can be measured by the coil.



(b)

(c)

Fig. 4 (a)TF of the Coil Characterized in TABLE I. (b) TF of the Coil measured using the Network Analyzer (4395A REV1.04) when the shield is not grounded. (c) TF of the Coil when the shield is grounded.



(a)

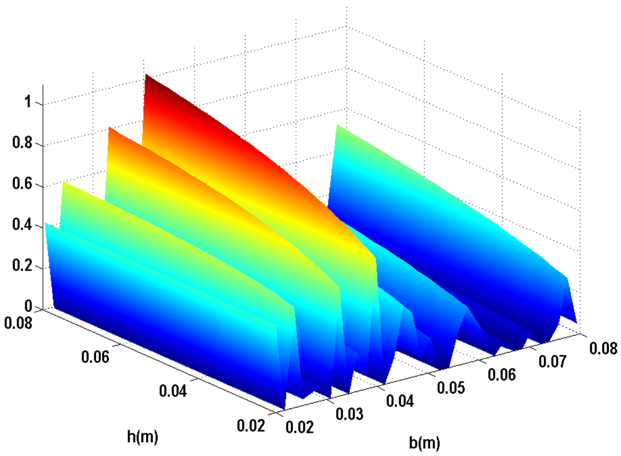


Fig. 5 Gain of the Coil when its outer radius and height vary. Maximum gain is obtained at b = 4cm and h = 8cm.

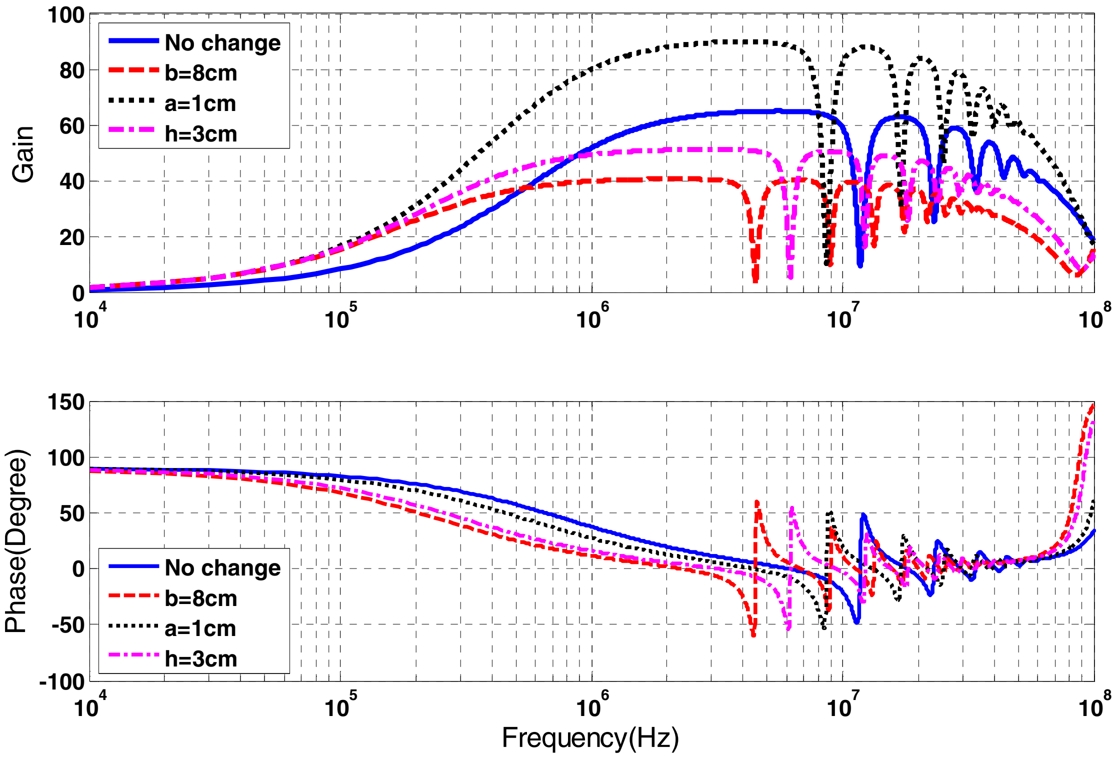


Fig. 6. TF of the Coil when only one parameter is changed. Other parameters are as TABLE I.

For analyzing these data to find the exact place of the discharge, signal processing methods can be employed [22], [23]. The benefit of the detailed model for all electrical coils is here for finding the place of the fault. In the simulation, we can make the faults in different places and save the results. Next, the location can be found by correlating the monitored PD pulses with the Rogowski Coil and comparing it with the existing ones.

IV. CONCLUSION

The Rogowski Coil that was introduced is a low cost, high gain and flexible device for partial discharge measurements. Design procedure of the coil for high frequency measurements such as PD detection was discussed and the theoretical calculations and results were reported. Results for a true specimen were compared with the theoretical results of the model. The results are acceptable and this approach is assumed to be applicable.

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