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Combined rogowski coil for the detection of partial discharge

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Abstract

The design and optimization of Combined Rogowski coil (CBRC) for the Partial discharge (PD) detection is proposed. The designed CBRC have shown to resolve the limitation of traditional Rogowski coil and Printed circuit board Rogowski coil (PCBRC). The electrical parameters that affected the performance of coil were controlled by the geometric variables and optimized by multi-objective genetic algorithm to achieve the optimum design of coil. The CBRC has upper frequency (f_h) of 219.67 MHz and mutual inductance (M) of 96.747 nH, while PCBRC has f_h of 200.63 MHz and M of 29.215 nH. The experimental results showed that the CBRC was able to measure the simulated of PD signal which is in nanosecond and current magnitude range of milli ampere. Its output signal has achieved better signal integrity and was able to eliminate the oscillation of detected signal output.

Keywords: Partial discharge, Rogowski coil, Printed circuit Board, Optimization

1. Introduction

PD is a fatal phenomenon for the insulation of high voltage equipment. PD causes the insulator degradation gradually and eventually the insulator will completely breakdown. Based on the electromagnetic coupling methods of PD detection, RC is a simple current transducer and has many advantages [1]. Manufacturing process of traditional RC, the winding is mostly wounded by hand that may result to the non-uniform winding which can cause an error to the output of the coil [2]. This problem can be remedied by design PCBRC with CAD software [3] which can precisely place the winding properly. But, PCBRC has a narrow working bandwidth and low sensitivity because of its structure. It means that PCBRC is not suitable for the detection of low amplitude and wideband signal such as PD.

This paper present a CBRC based on PCB which combines both look of traditional RC and PCBRC. The designed coil is also optimized by multi-objective genetic algorithm to achieve the proper dimension of coil for high frequency application.

2. Rogowski coil principle

RC was developed by Rogowski and Steinhas in 1912. The coil operation is based on the theory of electromagnetic coupling, Ampere's Law and Faraday's Law to provide the relationship between current in the conductor, $i_p(t)$ and output of the coil, $V_c(t)$ as

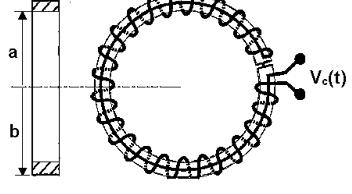
$$V_c(t) = -M\frac{di_p(t)}{dt} \tag{1}$$

where

$$M = \frac{\mu_0 N h}{2\pi}\ln\frac{b}{a} \tag{2}$$

M is the mutual inductance between conductor and RC, μ_0 is the magnetic permeability of air, a is inner radius, b is outer radius, h is height of core and N is number of turns. The winding must be formed by returning the wire through the center of winding for cancelling the external fields [4]. Figure 1 shows the dimension of RC and lumped parameter model [5].

(a)



(b)

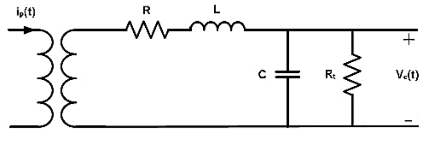


Figure 1 (a) Dimension of RC. (b) Lumped parameter model

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Where R, L, C, are the resistance, inductance and capacitance of coil, ρ is electrical resistivity, l is length of wire or imprint on PCB, d is wire diameter, ε_0 is the electric permittivity of air, k is relative permittivity and R_t is damping resistance. From the lumped parameter model, the transfer function $H(s)$ is given by

$$H(s) = \frac{V_{out}(s)}{I_p(s)} = \frac{\frac{M}{LC}s}{s^2+\left(\frac{L+RR_tC}{R_tLC}\right)s+\left(\frac{R+R_t}{R_tLC}\right)} \quad (3)$$

3. Proposed approach

3.1 CBRC

PD initiate from the weak point of the insulating material such as void, crack or irregularity. When PD is initiated, a very small pulsating current with high frequency will appear [6-7]. Therefore RC for the PD detection should have a high sensitivity and high upper frequency capability.

The CBRC uses copper wire as a half loop and imprint on PCB as a half loop for completing the coil instead using only imprint as whole loop like PCBRC. From this method, the capacitance of coil is decreased because of using air as a core material which has a lower value of permittivity than PCB material. As a result, the upper frequency of coil would be improved [8]. Copper wire made coil's cross-section larger than PCBRC, mutual inductance that directly linked to the sensitivity of coil also improved.

3.2 Optimization

As mentioned above, the property of sensor that significant for PD detection are sensitivity and upper limitation frequency. According to the equation (3) and proper damping resistor [9], upper frequency limitation can be found as

$$f_h = \frac{\left(L+\frac{R}{2}\sqrt{LC}\right)+\sqrt{2L^2++3RL\sqrt{LC}+\frac{1}{4}R^2LC}}{2\pi L\sqrt{LC}} \quad (4)$$

Improving the sensitivity by increasing h or N. Nevertheless, increasing inappropriate of these parameters also decrease the sensitivity [10]. So that, the multi-objective function genetics algorithm was used [11]. These R, L, C parameters are written as a function of geometric parameters [12] and the constraints are shown in Table1.

Table 1 Constraint parameters

Parameters of the coil	Constraints
Inner radius $a(m)$	0.035 - 0.04
Outer radius $b(m)$	0.08 - 0.137
Height of core $h(m)$	0.01 - 0.05
Number of turns $N(turns)$	50 - 66

The simulation was performed by using Matlab with *gaoptimset* toolbox. Parameters setting of populationSize 100, CrossoverFraction 0.8, and 0.5 of ParetoFraction. The set of pareto optimal solutions are shown in Figure 2.

The selected parameters of constructed coils are a = 0.0394 m, b = 0.0804 m, h = 0.0106 m and N = 64 turns. The electrical parameters are shown in Table2. The goal of constructing PCBRC with the same size is for comparison of the measured results from the CBRC. The photo of two coils and the bode plot are shown in Figure 3 and Figure 4, respectively.

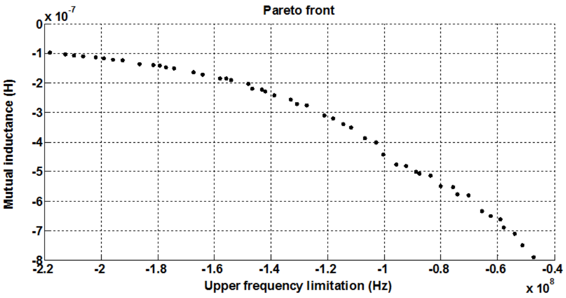

Figure 2 Pareto front

Table 2 Electrical parameters

Parameters of constructed coil	CBRC	PCBRC
Resistance (Ohm)	0.5696	1.0279
Inductance (uH)	6.1935	1.8697
Capacitance (pF)	19.527	78.107
Damping resistor (Ohm)	280	72
Mutual inductance (nH)	96.774	29.215
Upper frequency limitation (MHz)	219.67	200.63

(a) (b) (c)

Figure 3 (a) PCBRC. (b) CBRC. (c) Side view of CBRC

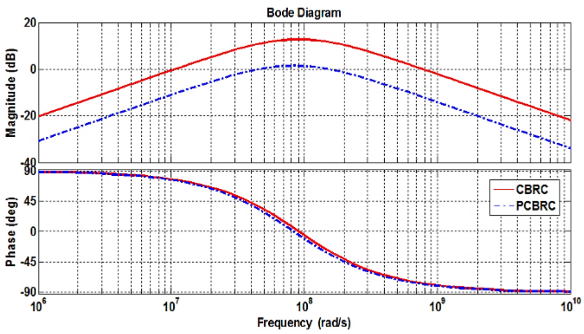

Figure 4 Bode plot of constructed coils

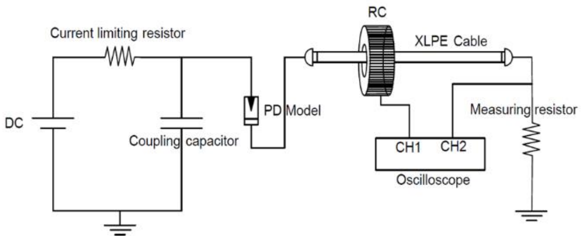

Figure 5 Experiment circuit diagram

4. Experimental measurement and results

The experimental setup was based on the circuits for measuring PD shown in Figure 5. The measuring of PD was made by using 4 Rogowski coils. These coils were clamped

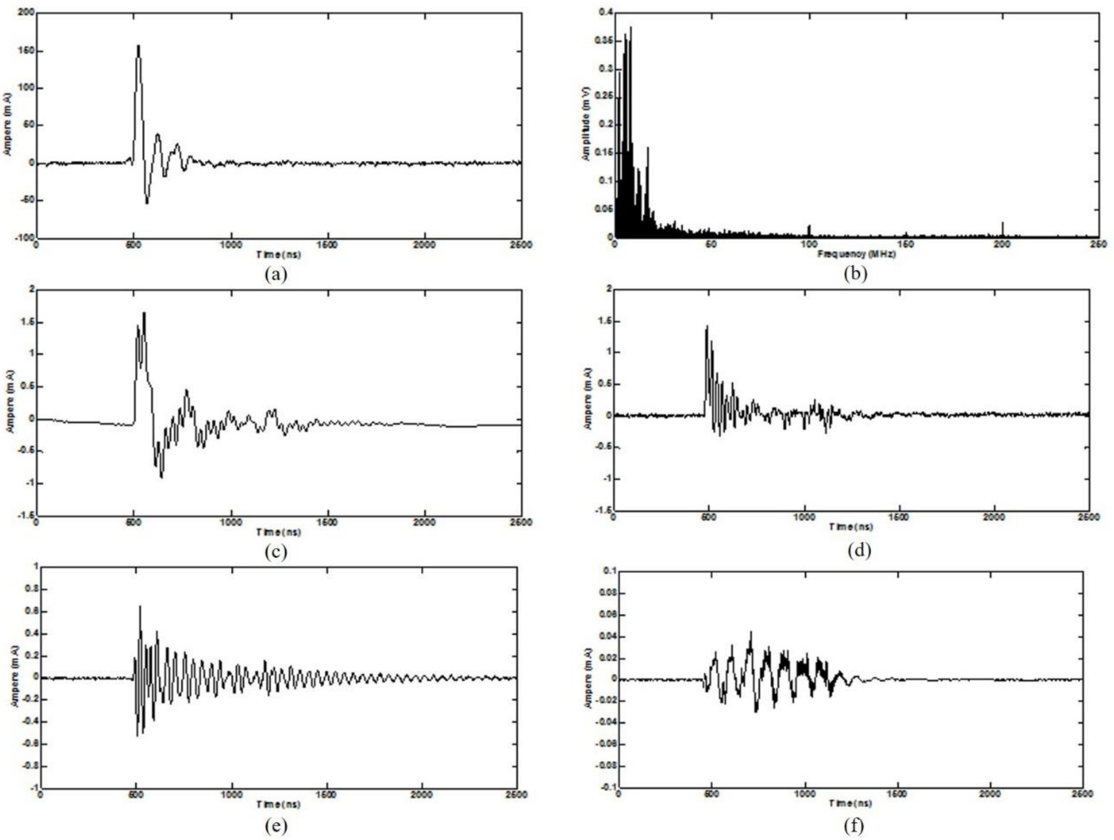

Figure 6 Measured waveform. (a) PD pulse. (b) FFT of PD. (c) Integrating result of CBRC. (d) Integrating result of PCBRC. (e) Integrating result of non-uniform RC. (f) Integrating result of Fluike i6000s

on XLPE cable which was injected with the pulse by PD generator. The generation of PD is via the use of needle-plate electrode configuration [13]. The output of each coils were recorded by Tektronix TDS 1001B oscilloscope. Figure 6 shows the PD waveform and the integration results of each coils output by using the method of trapezoidal rule [14].

The comparison of the reconstructed current waveforms measured by these coils have shown that the waveform obtained from CBRC closely match with the PD pulse and higher amplitude than that of the other coils. This is due to the CBRC has higher sensitivity, while the waveform obtained from Fluike i6000s has lowest amplitude because it wasn't designed for a small signal. Waveform from both RC that based on PCB also have a small oscillation than the waveform from non-uniform RC.

5. Conclusions

Due to the limitation of PCBRC on narrow band and low sensitivity which is not suitable for the measurement of PD pulse. This paper present a new type of RC that can overcome these drawbacks of PCBRC. In the design process, electrical parameters that affected the sensitivity and frequency response of coil were discussed and optimized by multi-objective genetic algorithm in order to achieve the best optimum permissible value. The CBRC has many advantages on a small signal detection due to low value of capacitance that will improve the upper frequency limitation, more cross-section area leads to higher sensitivity and uniform winding to diminish the signal oscillation. From the experimental, CBRC was able to measure a simulated of PD signal that has broad spectrum under 30 MHz and with the capability of current detection in the range of milli ampere. The reconstructed waveform from CBRC is perfectly matched with the original pulse, so that it can guaranteed the signal integrity performance.

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