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# Development and Performance Analysis of the Rogowski coil sensor for Arcing Fault Measurement

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**Abstract.** Arcing fault is an overvoltage that usually occurs in the power system network, and it is necessary to monitor this phenomenon in electrical equipment. This paper presents the Rogowski coil (RC) as an arcing fault sensor. Finite element method (FEM) software used for analysing the RC magnetic flux density with two types of RC with the different turns and size demonstrated. The sizing of RC based on the 240 mm<sup>2</sup> cross-link polyethylene (XLPE) 11 kV underground cable. The prototypes of the RC sensors were designed using Solidworks software and three-dimensional (3D) printer for fabrication purposes. The main objective of the experiment is to investigate the RC effect with high magnetic flux density by implementing in real measurement. An experimental setup for real arcing fault with various voltages (up to 15 kV) was conducted to verify the RC performance, such as sensitivity and bandwidth range. The result has shown that the bandwidth of RC 1 is higher than RC 2 in all measurement by 22.6%.

## 1. Introduction

Overvoltage phenomenon is the most common problem that always occurs in the power system such as lightning, switching, arc fault or flash and others which can lead to an ignition of the combustible near the failure point and causing a fire or even explosion. Meanwhile, arc fault overvoltage may produce arc flash, which can interrupt the power system network. However, the incipient faults last a few milliseconds and some of the conventional protective schemes cannot detect it and also hard to detect by circuit protection system because this fault current is lower than usual current [1]. Generally, some overvoltage detection sensors have been discussed by other researchers, such as in [2]–[5]. Mostly, overvoltage protection is well developed and applied in commercial and domestic user, but there are not many researchers focusing on the early detection of overvoltage. Theoretically, arc fault overvoltage is the result of the current that flows through the air between conductors in phase-to-phase, single phase-to-ground or multiple phase-to-ground configurations [6][7] and includes both high-frequency components which ranging from several kilohertz up to tens of megahertz (MHz) [8]. Commonly, arc fault caused by insulation ageing, broken or continuous contacting, human error, uncorrected electrical fault, loose jointing at the terminal, moisture present and others [6], [7], [9]. The underground cable widely used in the power system network and always bare to wet conditions and quickly get serious moisture problem which may penetrate the cable's splice and results in a voltage arc. Furthermore, the pre-fault in the cable can't be detected by a human; thus, an early stage monitoring sensor is needed.

In this paper, geometrical analysis of the RC for arcing fault overvoltage detection sensor is presented, which is very helpful especially for the sensor fabrication purposes. The arcing fault experiment was set

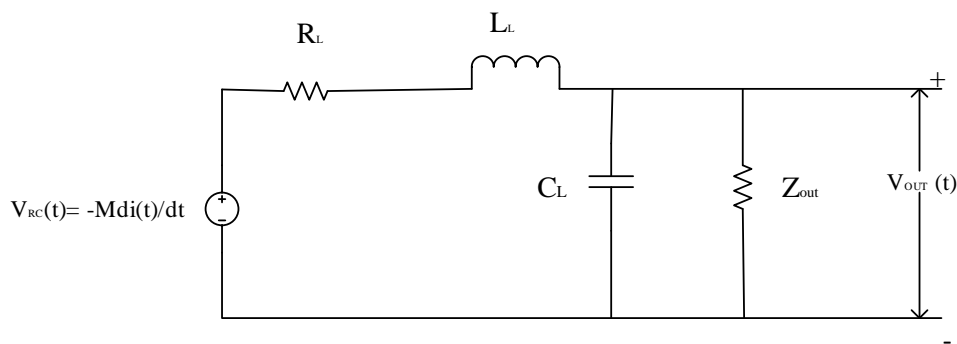


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up to verify the performance of the sensor prototype by injecting voltage range between 3kV to 15kV. Each of the RC geometry has a different characteristic and has been studied in [10]. The advantages of the RC have been discussed in [11]–[13].

## 2. Rogowski Coil As Arcing Fault Sensor

Generally, the RC is a family of an inductive coil group which was introduced by Walter Rogowski in 1912. The RC consists of wire wound on a non-magnetic core and the required current to be measured will flow through the conductor or cable conductor and for measuring current purposes, the RC will be placed around the cable or conductor. Theoretically, a current-carrying wire produces the magnetic field around it and measured in Weber. This field will convert into a signal according to Faraday's induction law, which is proportional to the current or proportional to the rate of change of the current flowing in the conductor [14][15]. The RC detection method based on the high-frequency current pulse that passes through the conductor such as during arcing fault. The RC equivalent circuit and also known as lumped parameter circuit is shown in figure 1 which consists of lumped inductance,  $L_L$ , lumped resistance,  $R_L$ , lumped capacitance,  $C_L$  and terminating impedance,  $Z_o$ .



**Figure 1.** The equivalent of RC Sensor (Lumped parameter model).

## 3. Rogowski Coil Design

In this work, the finite element method (FEM) was used for analysing the magnetic flux density,  $B$  of the sensor. Theoretically, magnetic flux,  $\Phi$  defined as the group of magnetic field lines emitted outward from the north pole of a magnet, and generally, a current-carrying wire produces the magnetic field around it, and it measured in Weber. The magnetic field intensity,  $H$  and the magnetic flux density,  $B$  at some defined point are in a reciprocal relation to the distance from the wire and the related between magnetic field intensity and magnetic flux density as expressed in Equation 1. The  $\mu_o$  is the absolute permeability of the medium and the value is  $4\pi \times 10^{-7}$  H/m.

$$B = \mu_o \cdot H = \frac{\mu_o \cdot I}{2 \cdot r} \quad (1)$$

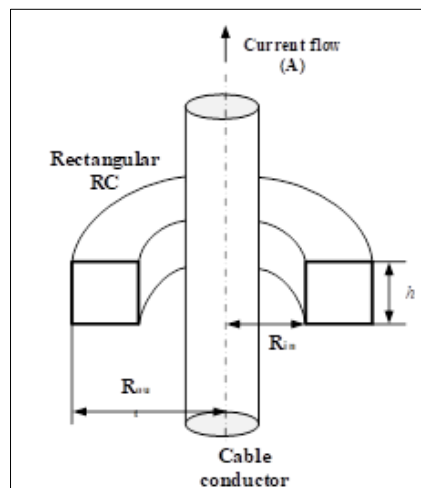
Another parameter to be considered when designing the RC sensor is mutual inductance,  $M$  and it is determined by mathematical calculation. Mutual inductance calculation is a conventional method to determine the sensitivity of the coil sensor. The values of the parameter of RC ( $R_c$ ,  $C_c$  and  $L_c$ ) are slightly different among others and depend on the coil geometry [10]. The mathematical formula of mutual inductance is widely discussed in [15][16]. The calculation of mutual inductance for rectangular cross-section is expressed in Equation 2. From equation 2,  $N$  is representing the number of turns,  $h$  is the height of core and  $\mu_o$  is equal to  $4\pi \times 10^{-7}$ . Based on the previous researchers reviewed and discussion

[16], the rectangular cross-section had high sensitivity; thus, this cross-section was selected for arcing fault RC sensor development.

$$M = \frac{\mu_0}{2\pi} N h \ln \left( \frac{R_{out}}{R_{in}} \right) \quad (2)$$

### 1.1. RC Sensor Geometry

Firstly, two (2) types of the rectangular cross-section; RC 1 and RC 2 were designed and simulated using FEM software. The FEM analysis was applied for the electromagnetic flux density, B analysis of RC before fabrication is made (the lowest B is the best for manufacture). The geometrical sizing of the RC sensor is based on three cores 240 mm<sup>2</sup> cross-link polyethylene (XLPE) 11 kV unarmoured underground cable. The basic rectangular cross-section design and calibration of the Rogowski coil have widely discussed by [17]. Figure 2 shows the RC cross-section, which is consist of height, h, inner radius, R<sub>in</sub> and outer radius, R<sub>out</sub>. The constructed parameters of the RC 1 and RC 2 is shown in table 1.



**Figure 2.** The rectangular cross-section of RC

**Table 1:** The parameters of constructed RC.

Coil Parameters	RC1	RC 2
Inner radius, R <sub>in</sub> (mm)	44	44
Outer radius, R <sub>out</sub> (mm)	54	54
D <sub>rc</sub> (R <sub>out</sub> – R <sub>in</sub> )	10	10
Height of core, h	20	20
Number of turns, N	30	50
Mutual inductance, M (μH)	24.58	40.96
Magnetic Flux Density, B (mTesla)	1.47	3.68
Coil Inductance, L <sub>c</sub> (μH)	4.21	5.76
Coil Capacitance, C <sub>c</sub> (pF)	104.72	172.27
Coil Resistance, R <sub>c</sub> (Ω)	0.17	0.26

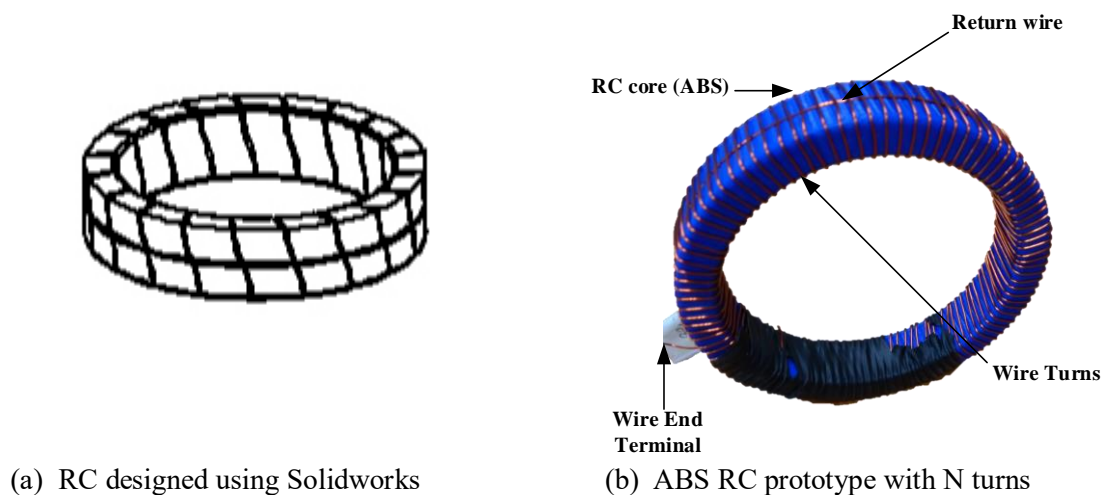
For fabrication purposes, the RC was designed by using 3D Solidworks tool software which is compatible with 3D printer function. A filament material, Acrylonitrile Butadiene Styrene (ABS) was used as the casing of prototype and this material was proposed in [18]. The ABS is categorised as a non-conducting attribute and has low conductivity and classified as an insulator[19]. The advantages of ABS are widely discussed in [20]–[22].

### 1.2. RC Design Considerations

Rogowski coil consists of a copper helical coil wire that has two winding techniques; return loop and return wire. The purpose of these techniques is to cancel the electromagnetic field from outside the coil. In this work, the RC was designed by wounding the copper wire with a diameter of 0.7 mm around the ABS rectangular shape and loop back through the centre of the coil to the end as a return wire to give less affected to the electromagnetic field.

The number of turns will give the effect to the coil sensitivity and the coil inductance,  $L_c$ . The  $L_c$  increased when the core height increased or adding a higher number of turn (the copper wire becomes more longer in this case). The value of inductance should be applicable to result in elevated sensitivity while preserving the high-frequency band sensitivity. Meanwhile, by increasing the capacitance value, it will result in reducing the reaction of the upper frequency while maintaining the sensitivity. The capacitance must be held as low as possible to prevent high-frequency fall.

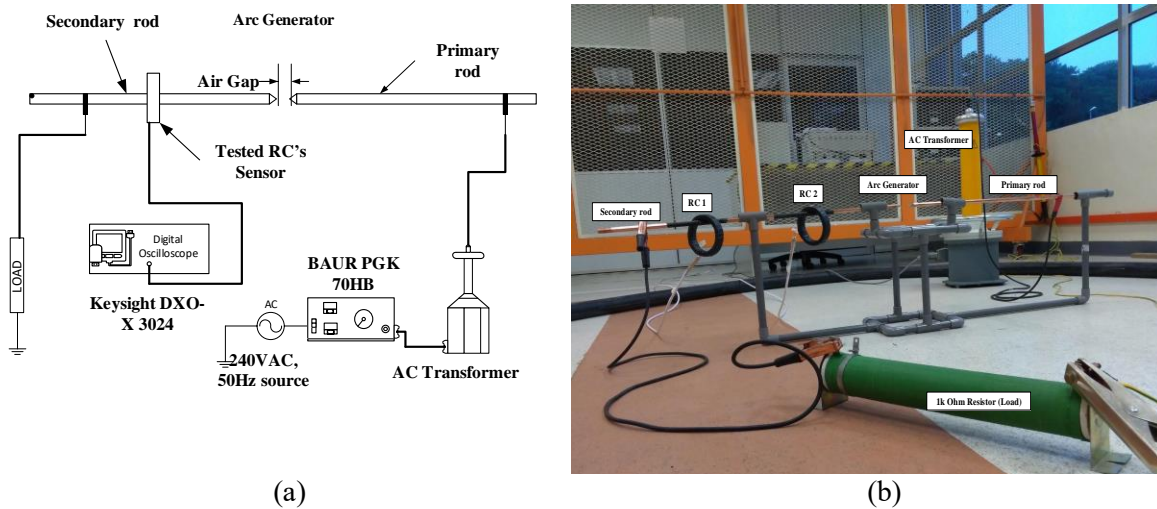
Therefore, the prototype of the RC's was built using Solidworks and 3D printer based on the design consideration and feature above. Figure 3(a) and (b) show the prototype of RC's that fabricated in the lab. The coil resistance,  $R_c$  and coil inductance,  $L_c$  were measured using Agilent U1731C Handheld LCR Meter, and 1kHz frequency was selected.



**Figure 3.** The prototype of RC's sensor (rectangular cross-section).

## 4. Experimental Setup

The experiment set up of the arcing fault signal was conducted in high voltage lab. An arc fault forms when the air becomes conductive due to a high electrical potential between two conductors (above the breakdown voltage). Theoretically, the average breakdown voltage ranges from 25 kV / cm to 30 kV /cm and depends on the insulating material, the shape of the tip of the conductor, and the gap between the two conductors [23]. However, it is found that the temperature also influenced the breakdown voltage. Arc generator model was set up by using two (2) copper rods; primary and secondary with 1.0-meter length each. These copper rods represent as the power cable which arcing fault signal travels until the end. The RC sensors are clamped and placed at secondary copper and measuring the travel signal. Figure 4 shows the arcing fault measurement setup which consists of the BAUR PGK 70HB (for high voltage injection signal) and 1 k $\Omega$  resistor as load. The digital oscilloscope, Keysight DSO-X 3024A was used to detect the output signal that captured from the RC.



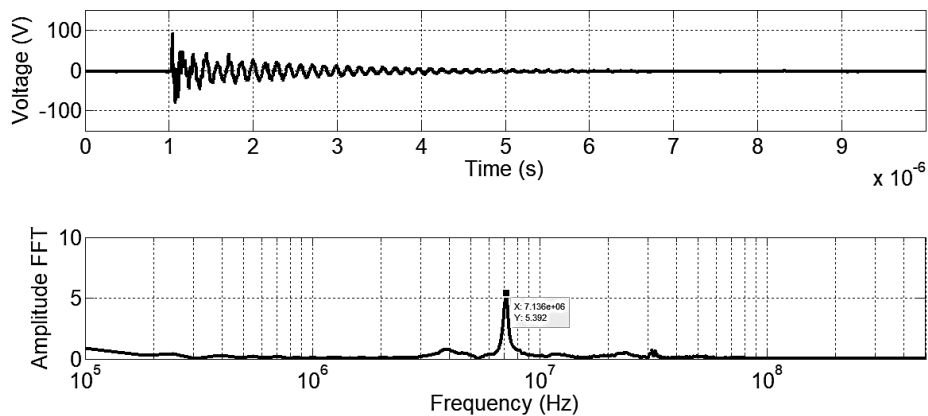
**Figure 4.** Experimental setup for Arcing Fault measurement (a) Schematic diagram for experimental setup, (b) Laboratory experimental setup.

### 5. Simulation And Experimental Result For Arcing Fault Measurement

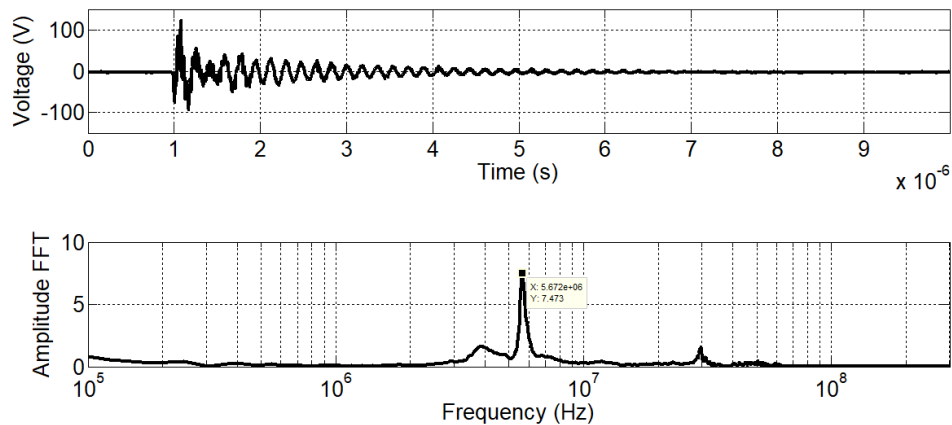
In this measurement, RC 1 and RC 2 were clamped on the secondary copper rode, and the voltage from 3 kV to 15 kV was injected at primary copper which results in voltage breakdown at air gap rod area (arc spark). The Fast Fourier Transform (FFT) analysis was carried out by importing the oscilloscope captured data signal and analysed by using MATLAB. Table 2 presents the arc fault measurement result of the RC 1 and RC 2. Figure 5 and figure 6 show the measurement waveform result of RC1 and RC 2, which was analysed using MATLAB at 3 kV. As can be seen, the amplitude of arc fault signal at 3 kV captured by RC 1 and RC 2 are 92.5 V and 123.0 V respectively. Similar trends have been observed in frequency resonance of RC 1 and RC 2, which are 7.14 MHz and 5.51 MHz. It shows that the RC with a more significant turn area has a significantly lower bandwidth. As seen in table 1, the more substantial number of turns gradually increased coil inductance. Thus, this observation indicates that the sensitivity of the RC 2 sensor decreased as it has a higher inductance than RC 1. In this case, RC 2 coil wire became longer (having 30 turns extra) than RC 1. Given the results obtained, the percentage difference of frequency resonance between RC 1 and RC 2 is 22.96%.

**Table 2.** The Arc Fault Measurement Result of RC 1 and RC 2 at 3 kV and 15 Kv.

Sensor ID	Injected voltage (kV)	Resonance frequency (MHz)	Amplitude (V)
RC 1	3	7.14	92.5
RC 2	3	5.51	123.0
RC 1	15	7.03	250.0
RC 2	15	5.47	260.0

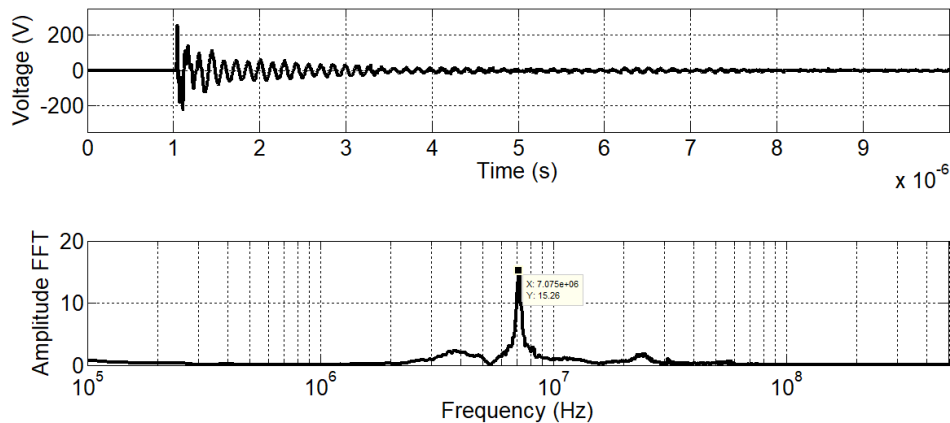


**Figure 5.** Arc Fault Detected by RC 1 at 3 kV breakdown voltage.

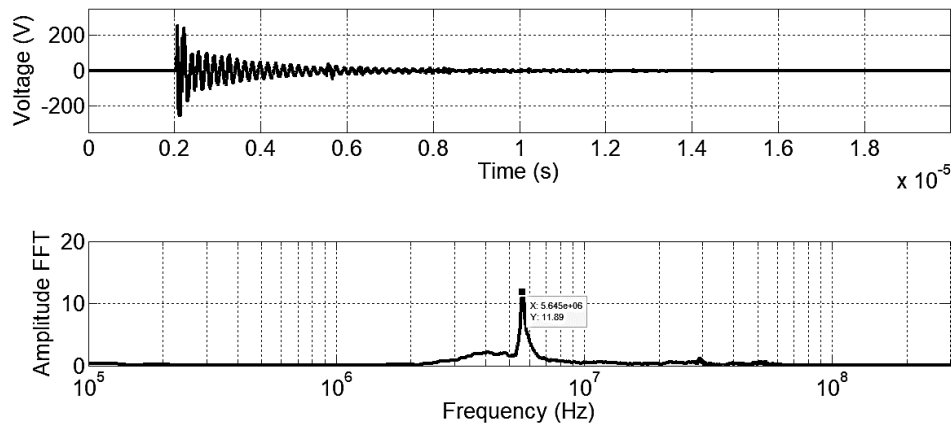


**Figure 6.** Arc Fault Detected by RC 2 at 3 kV breakdown voltage.

The measurement of sensor performance was verified on a 15 kV breakdown voltage as well, and the results are shown in figure 7 and figure 8. In this voltage level, the resonance frequency of RC 1 was 7.03 MHz while 5.47 MHz was captured by RC 2. It can be seen that, at this voltage, small changes of the resonance frequency has been measured and similar to 3kV measurement signal. Similarly, the voltage amplitude increased when the arc fault signal increased. However, the amplitude of RC 1 was 250 V and 260 V captured by RC 2. As can be seen, the result indicates that the RC with a lower number of turns has better resonance frequency compared to the higher number of turns.



**Figure 7.** Arc Fault Detected by RC 1 at 15kV breakdown voltage.



**Figure 8.** Arc Fault Detected by RC 2 at 15kV breakdown voltage.

## 6. Conclusion

In this paper, the measurement of arcing fault signal using RC as a sensor was successfully done. The performance in terms of sensitivity of each RCs design has been discussed. This real measurement has proved that the higher magnetic flux density and mutual inductance does not produce a high-frequency response. At 3kV and 15kV, the lower number of turns results in better resonance frequency at 7.14 MHz and 7.03 MHz for arcing fault detection. Also, the RC with low coil capacitance value has improved the upper-frequency limitation. The proposed ABS as sensor material is suitable and successfully measured the high voltage arcing fault.

## References

- [1] F. Naseri, T. Ghanbari, and E. Farjah 2015 Incipient fault monitoring of medium voltage UD-EPR power cable using Rogowski coil *International Congress on Electric Industry Automation* , pp. 33–36.
- [2] R. Han, Q. Yang, W. Sima, T. Yuan, H. Dong, and S. Sun 2014 A non-contact electro-optic sensor for lightning overvoltage measurement *International Conference on Lightning Protection (ICLP)*, pp. 1147–1150.
- [3] T. Wang, Z. Wang, Q. Zhang, and L. Li 2013 Measurement method of transient overvoltage distribution in transformer windings *Annual Report Conference on Electrical Insulation and*

- Dielectric Phenomena*, pp. 1093–1096.
- [4] D. Chatrefou, M. Pristchepa, and D. Uhde 2000 Application of optical sensors for measurement of high frequency overvoltages in power transformers *Power Engineering Society Winter Meeting IEEE*, **vol. 3**, pp. 2257–2268
- [5] S. Wenrong 2011 Study on a new method for overvoltage measurement using CVT *East*, **No. 9**, pp. 321–324.
- [6] R. Mandler, R. Hasan, J. B. Trolle, and N. L. Mina 2014 Hazardous Rated Electrical Equipment and the Arc Flash Hazard *IEEE Petroleum and Chemical Industry Technical Conference (PCIC)*, pp. 45–51.
- [7] T. B. Dugan 2007 Reducing the flash hazard *IEEE Ind. Appl. Mag.*, **vol. 13**, no. 3, pp. 51–58.
- [8] S. Chen, L. Zhu, S. Ji, and X. Liu 2017 Detection of series DC arc fault using rogowski coil *IEEE Conference on Electrical Insulation and Dielectric Phenomenon (CEIDP)*, pp. 401–404.
- [9] Yuan Wu, Zhengxiang Song, and Xue Li 2013 A method for arc fault detection based on the analysis of signal's characteristic frequency band with wavelet transform *2nd International Conference on Electric Power Equipment - Switching Technology (ICEPE-ST)*, pp. 1–4.
- [10] M. Shafiq, G. A. Hussain, L. Kütt, and M. Lehtonen 2014 Effect of geometrical parameters on high frequency performance of Rogowski coil for partial discharge measurements *Meas. J.*, **vol. 49**, pp. 126–137, Mar..
- [11] M. H. Samimi, A. Mahari, M. A. Farahnakian, and H. Mohseni 2015 The Rogowski Coil Principles and Applications: A Review *IEEE Sens. J.*, **vol. 15**, no. 2, pp. 651–658
- [12] A. H. Abdulwahid and Shaorong Wang 2016 A busbar differential protection based on fuzzy reasoning system and Rogowski-coil current sensor for microgrid *IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC)*, pp. 194–199.
- [13] I. A. Metwally 2013 Performance Improvement of Slow-Wave Rogowski Coils for High Impulse Current Measurement *IEEE Sens. J.*, **vol. 13**, no. 2, pp. 538–547.
- [14] L. A. Kojovic 2007 Comparative Performance Characteristics of Current Transformers and Rogowski Coils used for Protective Relaying Purposes *IEEE Power Engineering Society General Meeting*, pp. 1–6.
- [15] A. N. Nanyan, M. Isa, H. A. Hamid, M. N. K. Hafizi Rohani, and B. Ismail 2018 The Rogowski Coil Sensor in High Current Application: A Review *IOP Conf. Ser. Mater. Sci. Eng.*, **vol. 318**, no. 1, p. 012054.
- [16] M. N. K. H. Rohani *et al* 2016 Evaluation of Rogowski coil sensor performance using EMTP-ATP software *3rd International Conference on Electronic Design (ICED)*, pp. 446–451.
- [17] R. Styblíková and K. Draxler 2011 Design and Calibration of Rogowski Coils *Power Energy Work.*, p. 100000,.
- [18] M. N. K. H. Rohani *et al* 2016 Geometrical Shapes Impact on the Performance of ABS-Based Coreless Inductive Sensors for PD Measurement in HV Power Cables *IEEE Sens. J.*, **vol. 16**, no. 17, pp. 6625–6632,.
- [19] S. Mohd Alauddin, I. Ismail, F. Shafiq Zaili, N. Farahanis Ilias, and N. Fadhilah Kamalul Aripin 2018 Electrical and Mechanical Properties of Acrylonitrile Butadiene Styrene/Graphene Platelet Nanocomposite *Mater. Today Proc.*, **vol. 5**, pp. S125–S129.
- [20] Manish, D. Gurjar, S. Sharma, and Akash 2018 A Review on testing methods of recycled Acrylonitrile Butadiene-Styrene *Mater. Today Proc.*, **vol. 5**, no. 14, pp. 28296–28304.
- [21] Y. Li *et al* 2017 Reparation of recycled acrylonitrile- butadiene-styrene by pyromellitic dianhydride: Reparation performance evaluation and property analysis *Polymer (Guildf)*, **vol. 124**, pp. 41–47.
- [22] R. Goutham, T. R. Veena, Babagowda, and K. R. S. Prasad, 2018 Study on mechanical properties of recycled Acrylonitrile Butadiene Styrene (ABS) blended with virgin Acrylonitrile Butadiene Styrene (ABS) using Taguchi method *Mater. Today Proc.*, **vol. 5**, no. 11, pp. 24836–24845.
- [23] J. C. Kim, D. O. Neacsu, B. Lehman, and R. Ball 2019 Series AC Arc Fault Detection Using Only Voltage Waveforms *IEEE Applied Power Electronics Conference and Exposition (APEC)*, pp. 2385–2389.

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