The Rogowski Coil Sensor in High Current Application: A Review

Ayob Nazmy Nanyan¹, a, Muzamir Isa¹, b, Haziah Abdul Hamid¹, c, Mohamad Nur Khairul Hafizi Rohani¹, d, Baharuddin Ismail¹, e

¹Centre of Excellence for Renewable Energy (CERE), School of Electrical System Engineering, Universiti Malaysia Perlis (UniMAP), Malaysia

Email: aayob.nazmy@studentmail.unimap.edu.my; bmuzamir@unimap.edu.my; chaziah@unimap.edu.my; dkhairulhafizi89@yahoo.com; ebaha@unimap.edu.my

Abstract. Rogowski coil is used for measuring the alternating current (AC) and high-speed current pulses. However, the technology makes the Rogowski coil (RC) come out with more improvement, modification and until today it's still being studied for the new application. The Rogowski coil has a few advantages compared to the high frequency current transformer (HFCT). A brief review on the basic theory and the application of Rogowski coil as a current sensor measurement that been done by previous researchers are presented and discussed in this paper. Additionally, the review also focused on the capability of Rogowski coil for high current sensor measurement and their application for fault detection, over voltage current sensor, lightning current sensor and high impulse current detection. The experimental set up, techniques and measurement parameters in models also been discussed. Finally, a brief review on the performance analysis of current sensor measurement of Rogowski coil likes sensitivity, the maximum and current detection which could be used as a guideline to another researcher in order to develop an advanced RC as high current sensor in future is presented. This review reveal that the RC has a very good performance in high current sensor detection in term of sensitivity which is up to a few nanosecond, higher bandwidth, excellent in detection of high fault and also could measuring lightning current up to 400kA and has many advantages compare to conventional current transformer(CT).

1. Introduction
Rogowski coil (RC) has been introduced by German physician Walter Rogowski [1] and it was proposed in 1912 [2]. The Rogowski coil is an air core coil that can measure both alternating current and high-speed impulse current based on Ampere's and Faraday's law [1]. However, the application of Rogowski coil is very limited due to the limitation of technology and source on that time. Nowadays, with the technology such as microprocessor –based, modern signal processing technique and others have made an improvement of the Rogowski coil and application of the Rogowski coil has become wider and more suitable for various applications [3]. There are many advantages of Rogowski coil [1] [4][5]; Cause no damage by large load, Capability to measure large currents (ranging from a few milliamperes and up to 1 MA without saturating because of a non-magnetic core, Compact and light...
weight, Wide bandwidth and typically between 0.1 Hz and 1 GHz, Low cost and inexpensive, Safe because there is no direct connection to the main circuit, Excellent transient response, Good linearity due to absence of magnetic material, Isolation and non-intrusive measurement between testing circuit and transducer.

Rogowski coil is commonly used in pulsed applications to make an indirect measurement of very large current [6]. This paper is a review of Rogowski coil as a current sensor by focusing on the over voltage measurement application or high impulse current that commonly occur in high voltage system such as lightning strikes [7], switching operation of circuit breakers [8], gas insulated switchgear switching and electromagnetic pulses. Additionally, Rogowski coil is recognized as primary current sensors and mostly suited to high voltage application [9]. Commonly, there are a few devices that are used for measuring impulse currents such as shunt device, current transformer (CTs) and Rogowski coil[10]. The sections of this paper are as follows. In Section 2, this paper presents the basic of Rogowski coil theory and follows by operating principles in Section 3. Meanwhile, in Section 4 Rogowski coil as high current sensor is reviewed and discussed according to their specific application. The various type of Rogowski coil also been highlight in this section. Finally, Section 5 provides a conclusion of this review paper.

2. Basic and Theory of High Current Rogowski Coil

Rogowski coil current sensors operate on the same principles as conventional iron-core current transformers (CT) and classified as low-power standalone current sensors since their secondary signal is different than the typical CT secondary signal [11]. Basically, the Rogowski coil consists of wire wound on a non-magnetic core [12]. For measuring the current, the Rogowski coil is placed around the conductor. A magnetic field is generated as current flows around the conductor. This field is converted 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 [13]. The Rogowski coil consists of a helical coil of wire with the lead from one end returning through the center of the coil to the other end and making both of terminal are at the same end of the coil. The voltage that is induced in the coil is proportional to the rate of change (derivative) of current in the straight current conductor. The Rogowski coil is connected with integrator circuit (an electronic circuit device) which provides an output signal that is proportional to the output current as shown in

![Figure 1](image)

Figure 1. A measurement current $i(t)$ induces an AC magnetic flux $\phi(t)$, which induces a voltage in the sensing winding of an RC. The voltage induced in the coil is defined[14] by Equation 1:

$$U_i = N_{RC} \frac{d\phi(t)}{dt} \cdot \frac{N_{RC}N_1}{R_m} \cdot \frac{di(t)}{dt} \cdot M \frac{di(t)}{dt}$$

Where $N_{RC}$ is the number of turns of the pick-up winding, $N_1$ is the number of turns passed by the current.

![Figure 1](image)

Figure 1. Rogowski coil with integrator [14]
i(t) and \( R_m \) are the reluctance of toroid with winding \( N_{RC} \) and \( M \) is indicates the mutual inductance between \( N_{RC} \) and \( N_1 \). Normally, one conductor \( (Nl=1) \) will be used when measuring high currents. The time course of the measured current is obtained by integrating the induced voltage according to Equation 2:

\[
i(t) = \frac{1}{M} \int_0^1 u(t) \, dt = \frac{k_i}{M} u_i(t)
\]

where \( U_i \) is the output voltage integrator determine by \( U_i \), and \( k_i \) is the integrator constant. There are harmonic waveform, \( I(\omega t) \) when measuring high current, and the induced voltage can be expressed as in Equation 3:

\[
U_i = j\omega MI
\]

Where \( \omega = 2\pi f \) is the angular frequency of the measured current with frequency, \( f \).

For measuring mains current by using RC with an integrator, the constant of the whole system is given as in Equation 4:

\[
k_s(t) = \frac{u_i}{I}
\]

where the integrator of output voltage is \( U_i \) and the current passing through the central conductor is \( I \).

3. **Types of Rogowski Coil**

In this section, the advantages of Rogowski coil are briefly explained. Nowadays, there are many researchers have come out with the new current sensor technology by using Rogowski coil with various types, shapes and applications such as single- or multi-layer, rigid or flexible, the H-field sensor, Rogowski Coil designed with Discrete Coils made on Printed Circuit Boards (PCB) and others.

i. **Single or multi-layer Rogowski Coil** has coils that have lower values of mutual inductance, series self-inductance, series resistance, and distributed capacitance than multi-layer coils that consist of two windings wound over each other. These parameters should be taken into consideration when performing measurements when high-frequency and low phase-displacement is required. Single- layer-type Rogowski coils typically have several hundred turns to from the practical-sized of \( R_c \). The mutual inductance that is usually obtainable ranges from about 0.1-1 \( \mu \)H [15].

ii. **Rigid Rogowski Coils** are wound over a non-magnetic core usually having a toroidal shape. This core is made of plastic, epoxy, or other insulating material. The main advantage of using non-ferromagnetic material is it can obtain the coil linearity since the non-ferromagnetic material cannot saturate at high currents [15][16][17].

iii. **Flexible Rogowski Coils** may be wound over a silicone rubber core. The wire from the end of the coil winding returns along the length of the coil through a conductor along the axis of the core. Flexible Rogowski coils are convenient for measuring electric current in large or —awkwardly shaped conductors, where space around the conductor is restricted or where only a lightweight transducer can be suspended on the conductor. An Accuracy of flexible coils is not as high (can be improved by proper positioning of the primary conductor)[15].
iv. **H-field current sensor** suitable for applications in 10 kV, 200A. In comparison to classical RC, this discrete coil solution is smaller thus it is suitable for applications with small space available [15].

v. **The Printed Circuit Board Rogowski (PCB) coil** has three type; Rogowski coil designed with Discrete Coils made on Printed Circuit Boards, PCB design technique in a split-core, non-split-core PCB Rogowski coils. The output voltage of PCB Rogowski coils is smaller than the output voltage of Rogowski coils designed with conventional wire wound over an air-core since the core cross-section area is smaller. The use of more PCB coils results in higher accuracy, lower sensitivity to positioning the conductor, and better external field rejection performance. Another advantage of this solution is lower production costs [15] and can be placed on bus bars, bonding wires, and terminals [18].

4. Rogowski Coil for Transient, Overvoltage & High Current Sensor

This section discussed the Rogowski coil for high current measurements application focusing on various types of Rogowski coil shapes or types. High-Impulse currents commonly occur in high voltage power systems and may arise from different sources such as lightning strikes, switching operations of circuit breakers, switching manoeuvres in gas-insulated switchgear, and electromagnetic pulses [19]. High-impulse current and voltage measurements were originally associated almost entirely with short-circuit and insulation testing of high-voltage ac bulk power system equipment and with the recording of actual or simulated power system switching and lightning surges [20]. Additionally, the over voltages may go as high as six (6) times normal power frequency voltage [21].

In September 2010, a new standard IEC 62475 has been introduced as a horizontal standard to cover high current measurement techniques in general [22]. Basically, Rogowski coil can be considered as special current transformer [23]. The Rogowski coil can be used instead of CTs for fault detection in the transmission line and electrical machine as well [24]. The advanced Rogowski coil is made or designed by using printed circuit board PCB, Rogowski Coil. Rogowski coil based on the technology of PCB has high accuracy in design and manufacture, and is flexible in wiring way and is easily mass produced [25]. Furthermore, PCB has high-temperature stability which is important for industrial applications [23]. The Rogowski coil also can be placed around high-voltage bushings, for on-line monitoring [26].

4.1. Rogowski coil Application for Fault Current & High Current Sensor

Fault current magnitude is determined by the source inductance which in effect, limits the maximum rate of change of the current [9]. The Rogowski coil has a high reliability as a current sensor for protection and monitoring the power system and is the best choice for high current measurement in high-power laboratories [27]. The research of PCB with high-precision Rogowski coils has been carried out by L.Jubomir A. Kojovic which the applications are for protection, control, and metering in electric power systems and applied Rogowski coils as current sensors. The function of this sensor is to detect the fault current in different protection system for power transformers, power cables, and capacitor banks and connected with a relay. The relays communicate over fibre-optic cables connected to Ethernet [28]. The designed sensor has the capability with the following [29]; 1) Linearity, no saturation provides excellent protection security even at high fault currents exceeding 100 kA, 2) Light weight and compact size and 3) Increased personnel safety since opened secondary.

Figure 2 illustrates the Rogowski coils that are designed using two PCBs sandwiched together as a multi-layer PCB design and it provides high accuracy of the coils. Figure 3 presents the application of designed Rogowski coil as a current sensor for integrated protection system in power system which
the sensor's installed for high-voltage power cable protection, capacitor bank protection, and power transformer protection.

Figure 2. The PCB Rogowski coil Design [29]

Figure 3. The Integrated Protection, Control, and Metering Functions[29]

The Rogowski coil sensor has a high possibility operating in secondary circuits fed by conventional current transformers (CTs). Hence, the Rogowski coil had been implemented inside the protective relays to replace the CTs with the same function but more reliable [9]. The Rogowski coil sensor worked very well which can detects current up to 2kA rms as well as operating from a 5A auxiliary CT secondary. The high sensitivity current sensor is needed to protect the transmission line system such as detection of the faulty current and normally the conventional CTs are often employed. The PCB Rogowski coil with high precision was designed to overcome this matter [26]. The sensor response time for impulse signals testing is less than 50ns, less transmission delay and fits to apply in traveling wave based faults detection and location [26]. Meanwhile, a hybrid current sensor for metering and protective relaying also been developed [30] which was a combination of Rogowski coil with a passive integrator and integrated-optic Pockels cell (IOPC). The sensor's had to be a highly linear and exceeding 0.2% linear standards and capable detect the current between 30 Ampere to 30 kA.

In power system, the bus bar protection system is one of the most important element and the sensor with high reliability, high speed, and stability are required. An overcurrent may damage or interrupt the whole system. With the CTs saturation problem, it may provide the abnormal situation to the CTs which errors happen due to the mismatch of CT turns ration and magnetization current resulting the CTs could not operate as required. Thus, the Rogowski coil was introduced to replace the CTs and as protection to the bus bar and combined with fuzzy reasoning system [31]. The advantage of this sensor is when fault is detected, the sensor will response very fast to clear the fault. The other test conducted shows that the Rogowski coil with the integrator performed the current measurement was up to 25kA at 50Hz frequencies [14]. Due to the limitation of CTs, if fault current occur to capacitor bank, high current flows which results in unbalance of CTs (may explode the CTs) and significantly damage the
capacitor bank. Hence, to overcome this problem, the Rogowski coil current sensor has been introduced for capacitor bank protection system [28]. The indicated result shows that the installed Rogowski coils have performed very well and the circuit and equipment test set up as shown in Figure 4. Similarly, Relays is used to communicate over fiber-optic cables connected to an Ethernet switch [28] [29][11]. Meanwhile, the reliability of Rogowski coil for fault current detection was investigated by A.Dos Santos,et.al [11]. The low power stand-alone current sensor based on Rogowski coil was developed and this sensor had the capability of detecting high fault current up to 60kA.

4.2. Rogowski Coil Application for Another High Impulse Current Sensor

An accurate measurement for high-impulse current at ns/kA range is important [30][6]. In order to test different impulse current waveforms, a new design of a side-looking ‘‘flat spiral’’ self-integrating Rogowski coil that is wound by twin coaxial cable with individual sheath was designed by I.A.Metwally [32]. The improvement had been done to this sensor is it is designed without magnetic core and it gives high self-inductance and low self-resistance because of its winding structure. The advantages of the design are it gives higher bandwidth and lower plateau low corner frequency compared to the other designed coils, possesses a wide range of sensitivity, less susceptibility to measure other currents and stray magnetic fields in close proximity, and can be used in some applications when the conventional toroidal air-cored or PCB Rogowski coils are not suitable [32]. The measured results indicate that achieved bandwidth and sensitivity are up to 7.854 MHz and 3.623 V/kA, respectively. Additionally, sensitivities for the designed coil deviate from the corresponding measured ones by relative errors percentage within ±0.15 %. Figure 5 presents a new design of a side-looking “flat spiral” self-integrating Rogowski coil.

The development of Rogowski coil for impulse current measurements also has been carried out by Peerawut Yutthagowith and this sensor is very convenience in current measurements for the high-voltage test and based on the clamp on device type [33]. One of the characteristics of high impulse current is it has a fast rise time in a range of a few microseconds and a good sensor must be designed
4.3. Rogowski Coil Application for Lightning Current Detection Sensor

This section is specific to lightning current sensor application. Measuring lightning current is the most important criteria to study the lightning behaviour. Lightning current has a high amplitude and its rising time is short enough to cause over voltage in the power system. Lightning tests are necessary to measure the current flow along critical parts of the structure under test and Rogowski coils have been found very useful [38]. Thus, a good high current sensor is needed for this purpose. The Rogowski coil was tested for measuring the lightning current especially to the telecommunication tower [39] and wind turbine [40]. A shunt lightning current measuring system was introduced for measuring lightning current by using Rogowski coil [40]. The sensor consists of the integration circuit with a
low-frequency amplifier, and low pass filter were designed and has a good accuracy for integration in the range of 100 Hz–1 MHz [40]. The range of measuring current was up to 1 kA and confirmed that the Rogowski coil could be used for measurement up to 2.4 MHz, which is higher than the maximum frequency of 1 MHz [40]. Lightning current contains high frequency, thus the B-Dot sensor was proposed in conjunction with Rogowski coil [39].

Similarly, the Rogowski coil has been tested for measuring lightning current up to several kilo Ampere (kA). This sensor was developed in order to measure and locate the lightning current on the transmission line based on the designed Rogowski coil with an external integrator and detected the lightning current up to 400 kA [40]. However, there is unwanted electromagnetic interference that will affect the performance of the sensor. Hence, an electrostatic shield which is made of copper or aluminium is added and it is often wrapped around the coil. Furthermore, to prevent the eddy current that induced by the magnetic flux, a slot along the inner circumference should be made to ensure the shielding box is not completely closed [41]. From their measurement result, this sensor has the capability of measuring lightning current in power grid up to 400 kA and the sensitivity is 0.1144 V/kA for output voltage below 50 V. The sensitivity of the coil linearly increases with the increase number of turns and sectional area. The sensitivity of the coil decreases exponentially with the increases of the effective magnetic path, integral resistance or capacitance [41]. Furthermore, the reliability PCB Rogowski to measure high amplitude of lightning current has been proved by integrating with passive external circuit which does not require the power [42]. The designed sensor has a good bandwidth and it measures the lightning current correctly.

5. Conclusion

In this paper, a high current sensor based on Rogowski coil with various types and applications were presented. The PCB Rogowski coil is a transformation of conventional Rogowski coil and it has very useful, high technology and has many advantages especially for high current measurement. From this review, it could say that Rogowski coils are widely used for protection, measuring and metering in power system and its performance is better than conventional CTs. It is proved that the Rogowski coil has a high capability for high current measuring or sensor such as fault current detection, high impulse current detection, and lightning current. Furthermore, Rogowski coil is very suitable to replace the CTs because it has more advantages such as it will not damage when a large load applied, no saturation has a wide bandwidth, able to measure large current, low cost (inexpensive), good transient response and much more. Additionally, all the high current test and measurement technique must follow the standard IEC 62475. However, the wireless Rogowski coil for high current measurement has not been developed yet, thus if this technology is applied to the Rogowski coil and it is believed that it will be more interesting.

References

[1] M. H. Samimi, A. Mahari, M. A. Farahnakian, and H. Mohseni, “The Rogowski Coil Principles and Applications: A Review,” *IEEE Sens. J.*, vol. 15, no. 2, pp. 651–658, Feb. 2015.
[2] Yi Li, Yunchen Guo, Yi Long, Chengu Yao, Yan Mi, and Junfeng Wu, “Novel lightning current sensor based on Printed Circuit Board Rogowski coil,” in *2012 International Conference on High Voltage Engineering and Application*, 2012, pp. 334–338.
[3] C. C. Yii, M. N. K. H. Rohani, M. Isa, and S. I. S. Hassan, “Multi-end PD location algorithm using segmented correlation and trimmed mean data filtering techniques for MV Underground Cable,” *IEEE Trans. Dielectr. Electr. Insul.*, vol. 24, no. 1, pp. 92–98, Feb. 2017.
[4] Chucheng Xiao, Lingyin Zhao, T. Asada, W. G. Odendaal, and J. D. van Wyk, “An overview of integratable current sensor technologies,” in *38th IAS Annual Meeting on Conference Record of the Industry Applications Conference*, 2003., vol. 2, pp. 1251–1258.
[5] I. A. Metwally, “Self-Integrating Rogowski Coil for High-Impulse Current Measurement,” *IEEE Trans. Instrum. Meas.*, vol. 59, no. 2, pp. 353–360, Feb. 2010.
[6] J. Douglass, J. Greenly, D. Hammer, B. Kusse, R. McBride, and S. Pikuz, “Design and use of Small Rogowski Coils for use with Large, Fast Current Pulses,” in *2005 IEEE Pulsed Power Conference*, 2005, pp. 717–720.
[7] I. A. Metwally, W. J. Zischank, and F. H. Heidler, “Measurement of Magnetic Fields Inside Single- and Double-Layer Reinforced Concrete Buildings During Simulated Lightning Currents,” *IEEE Trans. Electromagn. Compat.*, vol. 46, no. 2, pp. 208–221, May 2004.
[8] A. Haddad *et al.* , “Direct voltage and trapped charge effects on the protective characteristic of ZnO surge arresters,” *IEEE Proc. - Sci. Meas. Technol.*, vol. 142, no. 6, pp. 442–448, Nov. 1995.
[9] V. Skendzic and B. Hughes, “Using Rogowski coils inside protective relays,” in *2013 66th Annual Conference for Protective Relay Engineers*, 2013, pp. 1–10.
[10] “4-2013 IEEE Standard for HV Testing Techniques.”
[11] A. dos Santos, J. F. Martins, P. Monteiro, L. J. A. Kojovic, M. T. Bishop, and T. R. Day, “Line differential protection systems based on low power stand alone current sensors,” in *10th IET International Conference on Developments in Power System Protection (DPSP 2010). Managing the Change*, 2010, pp. 121–121.
[12] L. A. Kojovic, “Comparative Performance Characteristics of Current Transformers and Rogowski Coils used for Protective Relaying Purposes,” in *2007 IEEE Power Engineering Society General Meeting*, 2007, pp. 1–6.
[13] N. Karrer and P. Hofer-Noser, “PCB Rogowski coils for high di/dt current measurement,” in *2000 IEEE 31st Annual Power Electronics Specialists Conference. Conference Proceedings (Cat. No.00CH37018)*, vol. 3, pp. 1296–1301.
[14] K. Draxler and R. Styblikova, “Calibration of Rogowski coils at high currents,” in *CEP 2010*, 2010, pp. 537–538.
[15] L. a. Kojovic and R. Beresh, “Practical Aspects of Rogowski Coil Applications to Relaying,” *IEEE PSRC Spec. Rep.*, no. September, pp. 1–72, 2010.
[16] M. N. K. H. Rohani *et al.*, “Evaluation of Rogowski coil sensor performance using EMTP-ATP software,” in *2016 3rd International Conference on Electronic Design (ICED)*, 2016, pp. 446–451.
[17] M. N. K. H. Rohani *et al.*, “Geometrical Shapes Impact on the Performance of ABS-Based Coreless Inductive Sensors for PD Measurement in HV Power Cables,” *IEEE Sensors Journal*, vol. 16, no. 17, pp. 6625–6632, 2016.
[18] M. Tsukuda, M. Koga, K. Nakashima, and I. Omura, “Micro PCB Rogowski coil for current monitoring and protection of high voltage power modules,” *Microelectron. Reliab.*, vol. 64, pp. 479–483, 2016.
[19] I. A. Metwally, “Self-Integrating Rogowski Coil for High-Impulse Current Measurement,” *IEEE Trans. Instrum. Meas.*, vol. 59, no. 2, pp. 353–360, Feb. 2010.
[20] R. J. Thomas, “High-Impulse Current and Voltage Measurement,” *IEEE Trans. Instrum. Meas.*, vol. 19, no. 2, pp. 102–117, 1970.
[21] MS Naidu & V.Kamaraju, “Overvoltage Phenomenon & Insulation Coordination in Electric Power System,” in *High Voltage Engineering*, Third Edit., Singapore: McGraw-Hill Education Publishing Company Limited, 2004, pp. 285–356.
[22] C.-H. Stuckenholz and M. Gamlin, “Overview of impulse current test standards and the impact on test equipment,” in *2012 International Conference on Lightning Protection (ICLP)*, 2012, pp. 1–6.
[23] J. P. Dupraz, A. Fanget, W. Grieshaber, and G. F. Montillet, “Rogowski Coil: Exceptional Current Measurement Tool For Almost Any Application,” in *2007 IEEE Power Engineering Society General Meeting*, 2007, pp. 1–8.
[24] O. Poncelas, J. A. Rosero, J. Cusido, J. A. Ortega, and L. Romeral, “Motor Fault Detection Using a Rogowski Sensor Without an Integrator,” *IEEE Trans. Ind. Electron.*, vol. 56, no. 10,
[25] Z. hua Li, S. hong Yan, W. zhong Hu, Z. xing Li, and Y. chun Xu, “High Accuracy On-Line Calibration System for Current Transformers Based on Clamp-Shape Rogowski Coil and Improved Digital Integrator,” *Mapan - J. Metrol. Soc. India*, vol. 31, no. 2, pp. 119–127, Jun. 2016.

[26] C. Xianghu, Z. Xiangjun, D. Feng, and L. Ling, “Novel PCB sensor based on Rogowski coil for transmission lines fault detection,” in *2009 IEEE Power & Energy Society General Meeting*, 2009, pp. 1–4.

[27] E.-P. Suomalainen and J. Hallstrom, “On-site calibration of a current transformer using a Rogowski coil,” in *2008 Conference on Precision Electromagnetic Measurements Digest*, 2008, pp. 468–469.

[28] A. dos Santos, J. Lourenco, J. F. Martins, P. Monteiro, and L. A. Kojovic, “Current sensors for improved capacitor bank protection,” in *11th IET International Conference on Developments in Power Systems Protection (DPSP 2012)*, 2012, pp. 153–153.

[29] L. A. Kojovic, “New Protection Schemes Based on Novel Current Sensors for Up-To-Date Grid,” *IEEE Trans. Power Deliv.*, vol. 20, no. 1, pp. 32–38, Jan. 2005.

[30] A. H. Abdulwahid and Shaorong Wang, “A busbar differential protection based on fuzzy reasoning system and Rogowski-coil current sensor for microgrid,” in *2016 IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEC)*, 2016, pp. 194–199.

[31] I. A. Metwally, “New Side-Looking Rogowski Coil Sensor for Measuring Large-Magnitude Fast Impulse Currents,” *Sens. Imaging*, vol. 16, no. 1, p. 100, Dec. 2015.

[32] Y. Yuthagowith, “Rogowski coil with a non-inverting integrator used for impulse current measurement in high-voltage tests,” *Electr. Power Syst. Res.*, vol. 139, pp. 101–108, 2016.

[33] I. A. Metwally, “Performance Improvement of Slow-Wave Rogowski Coils for High Impulse Current Measurement,” *IEEE Sens. J.*, vol. 13, no. 2, pp. 538–547, Feb. 2013.

[34] Y. Zhang, J. Liu, G. Bai, and J. Feng, “Analysis of damping resistor’s effects on pulse response of self-integrating Rogowski coil with magnetic core,” *Measurement*, vol. 45, no. 5, pp. 1277–1285, 2012.

[35] T. Orosz, Z. A. Tamus, and I. Vajda, “Modeling the high frequency behavior of the Rogowski-coil passive L/r integrator current transducer with analytical and finite element method,” in *2014 49th International Universities Power Engineering Conference (UPEC)*, 2014, pp. 1–4.

[36] W. F. Ray, C. R. Hewson, and J. M. Metcalfe, “High frequency effects in current measurement using Rogowski coils,” in *2005 European Conference on Power Electronics and Applications*, 2005, p. 9 pp.-pp.P.9.

[37] D. A. Ward and J. L. T. Exon, “Using Rogowski coils for transient current measurements,” *Eng. Sci. Educ. J.*, vol. 2, no. 3, p. 105, 1993.

[38] C. Romero et al., “Measurement of lightning currents using a combination of Rogowski coils and B-dot sensors,” in *2010 30th International Conference on Lightning Protection (ICLP)*, 2010, pp. 1–5.

[39] T. Kawabata, S. Yanagawa, H. Takahashi, and K. Yamamoto, “Development of a shunt lightning current measuring system using a Rogowski coil,” *IEEE Trans. Power Syst.*, vol. 118, pp. 110–113, 2015.

[40] Z. Li, Q. Zhang, L. Zhang, F. Liu, and X. Tan, “Design of Rogowski Coil with external integrator for measurement of lightning current up to 400kA,” *PRZEGŁAD ELEKTROTECHNICZNY (Electrical Rev.)*, vol. 87, no. 7, pp. 33–2907, 2011.

[41] Y. Li, Yunchen Guo, Yi Long, Chenguo Yao, Yan Mi, and Junfeng Wu, “Novel lightning current sensor based on Printed Circuit Board Rogowski coil,” in *2012 International Conference on High Voltage Engineering and Application*, 2012, pp. 334–338.