Design and applications of Rogowski coil sensors for power system measurements: A Review

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Abstract: The Rogowski coil (RC) is emerging as a robust current measurement solution for various kinds of applications. Due to its endorsed electrical performance and flexible geometrical design, the RC is widely used in a variety of power system measurements. The ability of measuring a wide range of frequencies and signal amplitudes makes the RC a favorable sensor for assessing normal as well as faulty system operations. Researchers dealing with specific measuring or monitoring solutions confine the focus towards a certain design approach for the development of RC sensors. In order to provide a wider perspective, this paper presents a comprehensive overview of RCs considering different perspectives including: design, construction, modelling, and ongoing advances in RC designs and applications. The applications are mainly discussed based on the operation of the power components and characteristics of the measured signals. Further exploration of RC sensors can greatly contribute in increasing the measurement capability and reliability of power grids.

Key words — power system, induction sensor, Rogowski coil, coil parameters, current measurement

1. Introduction

Current measurements are always required in operating electrical circuits. From daily household to industrial and further up to grid systems, current measurement capability has its significance for each application. The purpose of current measurements is to perform mainly two types of analysis. First, keeping the currents of the circuits within the permissible limits for regular operation of the electrical systems. Second, investigating the state of the systems when systems are operating under normal or faulty conditions.

Considering industrial and technological systems, electrical power networks can be considered among the largest interconnected physical systems. Networks are growing, operation of the grid is changing due to integration of distributed energy resources. Bidirectional flow has emerged as a new phenomenon for components and power lines. Inclusion of the high voltage power electronics is increased, and grids are operating both under AC and DC supply conditions. While several further technological advancements under the umbrella of smart grid implementation are on the way, asset optimization, cost-effective operation, self-healing capabilities, and increased reliability are demanding improved monitoring solutions [1]-[3].

In electrical power systems, a variety of components are continuously performing their operations. The electric currents flowing in power system components have a wide range of frequencies and amplitudes that depend on the type of component and their operation. The measurement of electrical current is essential for a number of functions such as metering, monitoring, protection, and control tasks during regular as well as faulty operation [4]-[5]. These goals can be achieved by applying suitable sensors that are efficient in performance, cost effective and flexible in installation.

To evaluate the standing of one current sensor over other alternatives, it is important to consider several factors including simplicity of the design, accuracy of the results, versatility of installation, adaptability with the measurement environment, and economical constraints. Currently, several current measurement techniques are available for power system components. Shunt sensors are resistive in nature and use ohmic voltage drop to measure the current (AC and DC) while current transformers, Rogowski coils (RC), Hall effect sensors, Magneto Impedance sensors (MI), and Giant Magneto Resistive (GMR) techniques use electromagnetic field to measure current (sinusoidal or transients) [6]-[7]. Shunt sensors have the advantage of measuring both AC and DC currents. However, the requirement of galvanic connection, the significance of intrinsic inductance, especially at higher frequencies, and a low temperature coefficient of resistance increases the complexity, cost, and inaccuracies of shunt sensors [6]. The first favorable feature of electromagnetic field-based sensors is their non-intrusiveness. However, because of the general complexity of material technology, signal saturation and cost, the RC offers several advantages over the other types of electromagnetic current transducers. Considering the most important performance parameters of a sensor such as amplitude and frequency response, the RC is capable of measuring high amplitude and large signal bandwidth of currents without saturation. Additionally, the RC has excellent features including reliable response for transient measurement, linearity over measurement ranges, and low output variations under changing temperatures [8]. Similarly, physical geometry, installation possibilities, air-core construction, reduced saturation issues, weight, cost, mechanical design, etc. are a number of features that the RC sensor offers and can demonstrate its qualification to become a preferred sensor for current measurement objectives.

Based on the versatile inherent features of the RC, research has been undertaken on continuous improvements in RC sensors considering various aspects of physical design and operational performance. Ongoing improvements have enabled the use of RC sensors for various power systems and industrial applications to measure the currents over a broad range of amplitudes (mA to several kA) and frequencies (a few Hz to several MHz) [9]-[11]. The performance of the RC has been assessed and acknowledged for a wide variety of component applications such as power lines including cables and overhead lines, substation equipment including power transformers, switchgear, and protection devices, rotating machines, power electronic related infrastructure, and several other components which will be discussed further in the next sections [8], [12]-[13].

There are papers available that are focused on certain operational and design aspects based on the specific applications of RCs. Researchers performing current measurements to carry out monitoring and control of the power grid are focused on the design of the RC for regular operation of the components. When carrying out maintenance, the RC is designed to observe abnormal operation of grid components. In regular grid operations, the amplitude of measured current is higher while the frequency is lower (power frequency). For faulty operation, the amplitude of currents can range from a few mA to several kA depending on the types of faults and characteristics of the signal. Similarly, the bandwidth of the current signals during faulty operation is typically higher (upto several MHz). Similarly, an important consideration for the design of the RC is the type of the component under observation. For example, researchers with expertise in the design and installation of the RC in underground cables may not be completely aware of the application of RC for overhead covered conductors, generators, or switchgear.

This paper aims at providing an in-depth understanding of different aspects of RCs for a wide range of applications that offer researchers an opportunity to compare the variations in RC geometrical designs in relation with the electrical performance of the sensors. The work presented in this paper is based on the review of the present literature and the authors' own work conducted during last several years.

Further in this paper, Section II describes the basic operational principals of a coil transducer. Presenting the construction of the RC from laboratory based raw material, section III discusses the design, modeling, and current measurement process of the RC. Section VI highlights the effect of geometrical parameters on the electrical performance of the RC. Section V provides an overview of the different unconventional design approaches adapted by researchers to improve the measurement performance of the RC. A comprehensive overview of RC sensors for power system applications is presented in Section VI and the paper is concluded in Section VII.

2. Principle of Voltage Induction in a Rogowski Coil

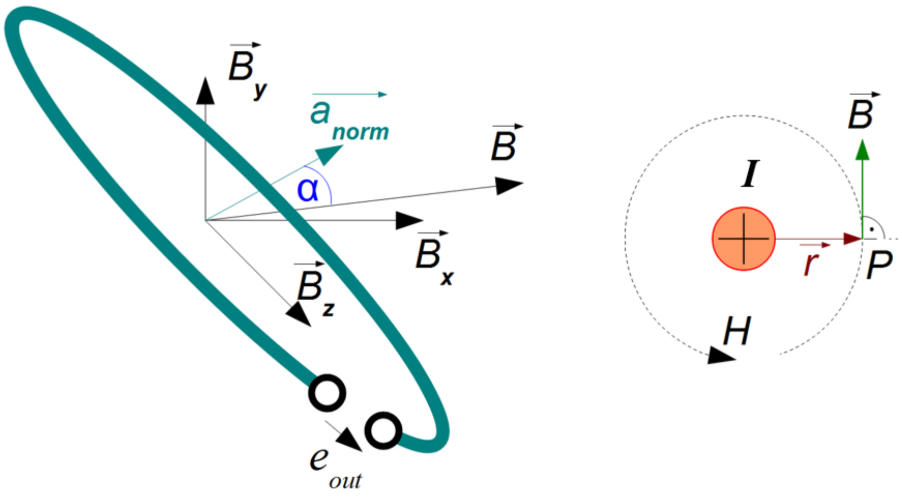
The RC is an electromagnetic induction sensor that works on the principle of Faraday's law [14]. When a time varying magnetic flux (Φ) is linked up with a coil winding, the relationship between the magnetic flux and electromotive force (emf e) induced in a loop can be described by Faraday's law as:

$$e = -\frac{d\Phi}{dt} \tag{1}$$

As shown in Fig. 1, the magnetic flux can be expressed as:

$$\Phi = \int_A B\cos \propto da \tag{2}$$

where B is the magnitude of the magnetic flux density, a is the loop area, da is an element of loop area a and α is the angle between the area normal vector a_{norm} and magnetic flux density vector B. When α is zero, magnetic flux is maximum.



(a) (b)

Fig. 1. (a) Magnetic flux for a loop, and (b) Magnetic flux around a current-carrying wire.

At a point P near the conductor such that the conductor appears as a near infinite conductor, the magnetic flux is perpendicular to the radius vector r. The magnetic field intensity H and the magnetic flux density B at point P is expressed as:

$$B = \mu_o . H = \frac{\mu_o . I}{2\pi . r} \quad (3)$$

where μ_o is the absolute magnetic permeability of the medium (for air $\mu_o = 4\pi \times 10^{-7}$ H/m) and I is the conductor current. For N identical loops placed at the same distance from the wire i.e., in a perpendicular position to the radius vector (α = 90º), the total magnetic flux can be found by (4):

$$\Phi_{tot} = \int_A B\cos \propto da = N \int_A \mu_o H \, da = \frac{N \, \mu_o I}{2\pi} \int_A \frac{1}{r} da \quad (4)$$

and the generated emf can be found by (5):

$$e = -\frac{d\Phi_{tot}}{dt} = -\frac{N \ \mu_o \ I}{2\pi} \int_A \frac{1}{r} \ da = -\frac{di}{dt} \frac{N \ \mu_o}{2\pi} \int_A \frac{1}{r} da \quad (5)$$

Consider that the geometrical parameters do not change with time. This separates eq. (5) into the time-differential of current (*di*/*dt*) and time-invariant quantities, constants, and geometrical parameters as

$$e(t) = -M \frac{di_p(t)}{dt} \quad (6)$$

where M is the mutual inductance of the coil, expressed as:

$$M = \frac{N \ \mu_o}{2\pi} \int_A \frac{1}{r} \ da \quad (7)$$

M is the ability of the RC to induce the output voltage $e(t)$ due to rate of change of primary current $i_p(t)$ and determines the sensitivity (in V/A) and amplitude response of the sensor for a specific range of frequencies.

3. Development of Rogowski Coil

Based on the current measurement, installation, and application requirements, the process of developing the RC is initiated from its geometrical design. The geometrical design determines the electrical model which derives the behavior of the coil's electrical components towards the sensed signals. The obtained signal is processed using additional components to carry out damping and integration functions. Further, the processed signal is calibrated to obtain the original signal considering key features such as amplitude and waveshape. Finally, a data acquisition system is interfaced as part of the sensor itself or as an external device, to record or display the obtained signal. The overall process of development of the RC sensor is highlighted in Fig. 2 and will be discussed in detail further in this paper.

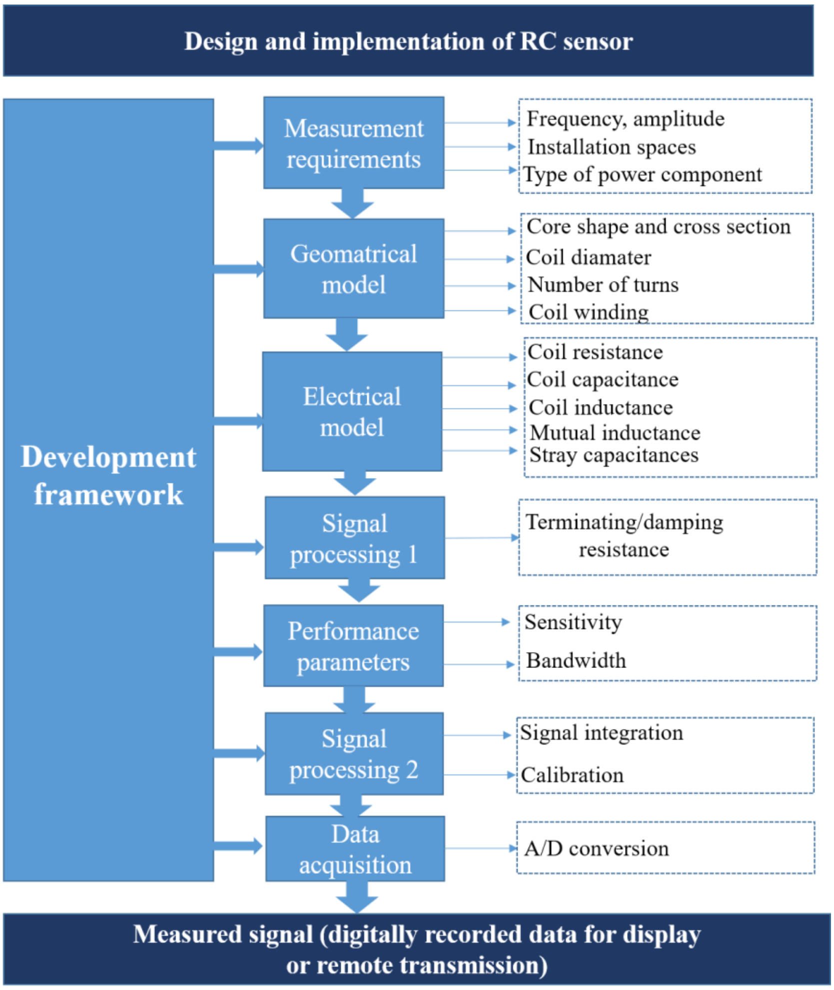


Fig. 2. RC development framework.

3(a). Design and modeling

Considering the construction, the RC transducer consists of a toroidal wound coil with a circular non-magnetic air-core (a plastic gas-pipe with rough surface). Starting from End A (terminal T_1) of the conductor, the coil winding progresses along with the core towards End *B* with N number of turns, as shown in Fig. 3. Onward from the last turn at End B, the winding conductor takes the return path through the center of the core and reaches back to the starting point (End A) of the core as terminal T_2. Considering typical geometrical construction of RC, two important features are:

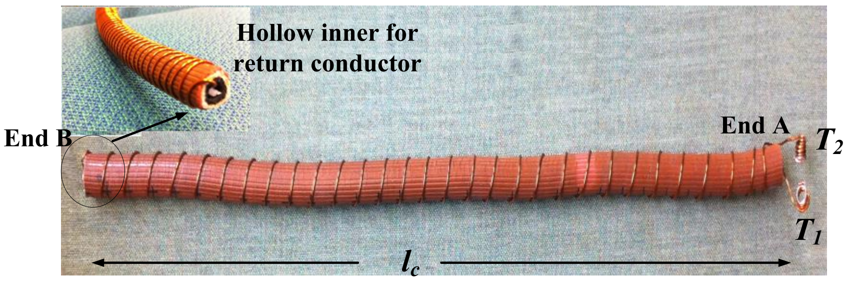


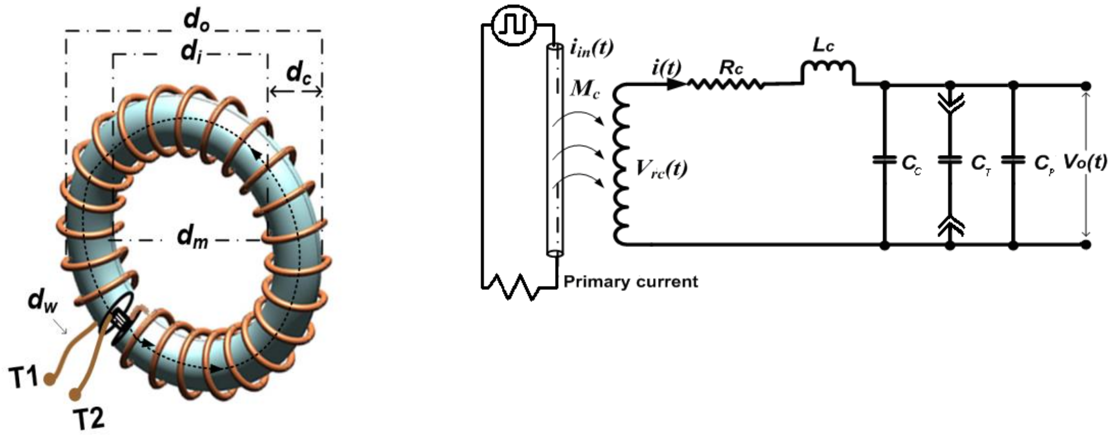
Fig. 3. Manual construction of RC in the laboratory.

- Availability of both winding terminals (T_1 and T_2) at the same core ends, results in a flexibly openable coil or core ends that enable a non-intrusive installation around any primary

conductor.
- The return conductor serves to cancel out the effect of the external electromagnetic disturbances [8].

The feature of flexibility of installation without interrupting the power line has also been obtained in the modern current transformers (CTs) by introducing split core construction. In doing so, the airgap between the split magnetic cores is minimized and mechanical robustness is ensured against vibrations and shocks. The return conductor in RC can help in cancellation of external of electromagnetic disturbances emerged due to current flowing through the conductors in the vicinity such as the adjacent phases in case of three phase power systems.

The outer diameter of the coil d_o, inner diameter d_i, core diameter d_c, and wire diameter d_w are the major parameters to describe the geometry of the coil, as shown in Fig. 4(a). Having fulfilled the physical requirements related to installation as the first priority, variations in the geometry can be performed when required. The number of turns of the coil winding has a significant impact on the operational requirements and electrical performance of the sensor, which also will be discussed later in this paper. The key geometrical and electrical parameter equivalent models are listed in Table 1.



(a) (b)

Fig. 4. Modeling of RC sensor, (a) geometrical model, and (b) lumped electrical model.

While conventional construction of RC is shown in Fig. 4(a), different researchers have adopted different approaches considering shape, electrical modelling, and processing of the sensed primary signals. The electrical parameters (Fig. 4(b)) of the coil are derived from the geometrical parameters. The accuracy of the measurement and interpretation of the results depend on the accuracy of the electrical model. Calculation of electrical parameters, damping of oscillations caused by coil parameters, and integration of the measured voltage, can be considered as major focus of the design (see Fig. 2).

The major electrical parameters of RC are mutual inductance, self-inductance, self-capacitance, self-resistance, and the voltage induced across the coil winding. The development of coil model can be adopted based on the frequency of interest and the coil's electrical length. Most of the researchers have used lumped parameters model [15]-[16] as shown in Fig. 4(b); presenting the electrical parameters of the coil as single elements irrespective of the electrical length of the coil winding. Distributed parameters model is presented in [17]-[18] where the electrical length of the coil winding is divided into n sections. Each section represents a per unit series self-inductance, self-capacitance, self-resistance, and the voltage source (induced voltage), modelling the front and backward travelling wave based on transmission line theory. Performance comparison of the both types of models (lumped and distributed) is provided in [19]-[20]. Considering parameter calculation, use of mathematical expressions to determine the electrical parameters of the RC has gained increased interest of the researchers as presented in [21]-[22]. However, for accuracy of the design and true interpretation of the measured signals, more effective approach of experimental methods can be useful (discussed further in this paper) especially for high frequency operation. Damping component or terminating resistance plays an important part in processing of the measured signals. The work presented in [23] proposes the methodology of self-integration using terminating resistance for both, damping and integration. The other approach is the use of terminating resistance for damping the oscillations and the integration operation is performed by adding electronic (active/passive) or digital integrator [24]-[25]. In order to demonstrate the systematic modeling and analysis, lumped parameter based electrical modelling, along with terminating resistance and digital integrator is considered further in this work.

The resistance of the coil is due to the resistance of the cross-section area A_w of wire and the length of wire l_w, used to develop the winding. Depending on the electrical resistivity ρ, the self-resistance of the coil can be determined as:

$$R_c = \frac{\rho l_w}{A_w} = \frac{\rho N\sqrt{(\pi d_c)^2 + p_w}}{A_w} \tag{8}$$

where p_w is the pitch of the coil winding which is defined as the distance between the starts of two consecutive turns and is presumed uniform for the whole winding of the coil. The parameters p_w, d_c, and N determine the l_w and thus the resistance of the coil. L_C mainly depends on the loop dimension and the number of loops. The L_C of coil with the circular core is calculated as [15],

$$L_c = \frac{\mu_o N^2}{2}\left[\left(\frac{d_i + d_o}{2}\right) - \left(\sqrt{d_i d_o}\right)\right] \tag{9}$$

The self-capacitance C_c of the RC is mainly the capacitance between the coil winding (turns) and the return wire in the center of the winding which is determined as [15],

$$C_c = \frac{4\pi^2 \varepsilon (d_o + d_i)}{\log(d_o + d_i)/(d_o - d_i)} \tag{10}$$

Table 1. Design parameters of the RC

Geometrical parameters		Electrical parameters	
Name of Parameter	**Symbol**	**Name of Parameter**	**Symbol**
Outer diameter	d_o	Self-inductance	L_c
Inner diameter	d_i	Self- Capacitance	C_c
Coil/mean diameter	d_m	Self-resistance	R_c
Core diameter	d_c	Mutual inductance	M_c
Wire diameter	d_w	Terminating resistance	R_T
Number of turns	N	Resonance frequency	f_{rc}
		Bandwidth	BW
		Sensitivity	S
		Stray capacitances	C_s

where ε_o is the dielectric permittivity of air equal to 8.85 x 10^{-12} farad per meter (F/m). In the operation of the RC, the contribution of the self-resistance R_c is not significant. However, the inductance and capacitance play an important role in its operation.

The electrical model is an essential part of developing an accurate design of the RC sensor to obtain reliable measurements. A conventional approach is to apply mathematical expressions to determine the electrical parameters of the RC [26]-[28]. The mathematical expression may provide an approximation of the RLC parameter values to have an understanding of the expected electrical performance of the coil. This approach may not present a significant difference between approximate and real response of the coil for low frequency operation. However, when dealing with high frequency operation where 'unseen' or parasitic behavior of the conductive elements of the transducer contributes to the RLC parameters, these mathematical expressions do not provide accurate values of the RLC components. Non-uniformity of winding density, deformation of the core shape, deviation of the return loop from the central position, etc. are some of the factors that can produce errors in the calculated values. The connection points and the wires may cause the same effects. Due to skin and proximity effects at higher frequencies, non-uniform distribution of current within the wires can also develop parasitic inductance and capacitance. There is a lack of mathematical models (expressions) that take into account these factors. In-depth studies addressing these aspects are discussed in [29]-[31].

The resonant frequency of an induction coil is a clear reflection of its electromagnetic parameters [32]. Considering the possible miscalculations due to the factors highlighted above, the work presented in [33] determines the electrical parameters based on the study of the resonant frequency with a simple experimental technique. The true values of L_c and C_c are found by comparative variation in the resonant frequency of the coil as a result of additional known capacitance in parallel to the RC. The resonance frequency f_{rc} of the coil is determined from the measured response. Mathematically, f_{rc} is given as:

$$f_{rc} = \frac{1}{2\pi\sqrt{L_c C_c}} \tag{11}$$

To determine two values of L_c and C_c, two mathematical equations must be available relating L_c and C_c. Keeping the self-inductance unchanged, additional fixed known capacitors C_{T1}, C_{T2}, and C_p are added in parallel that result in the equations below (derived from (10)):

$$\frac{f_{rc11}}{f_{rc12}} = \frac{\sqrt{C_c+C_p+C_{T1}}}{\sqrt{C_c+C_p+C_{T2}}} \tag{12}$$

This finally results in:

$$L_{11} = \frac{1}{2\pi\,(C_c+C_p+C_{T1}){f^2}_{rc11}}, L_{12} = \frac{1}{2\pi\,(C_c+C_p+C_{T2}){f^2}_{rc12}} \tag{13}$$

As inductance is kept unchanged during both cases (C_{T1} and C_{T2}), therefore calculated value of L_{11} and L_{12} are equal. In addition to L_c and C_c of the coil, the stray capacitance C_c emerges because of the cables (connection wires) between the coil terminals and the data acquisition unit to measure the signal output. The stray capacitances can be determined using the experimental technique discussed above.

3(b). Current measurement process

The measurement process from the initial sensing of the primary current to its final display is depicted in Fig. 5. Stage 1 is the induction of the voltage $V_{rc}(t)$ across the coil, due to primary current in the conductor whose location should be held ideally in the center of the coil, and is expressed as:

$$V_{rc}(t) = -\mu_a A_c N \frac{di_p(t)}{dt} \quad (14)$$

Considering the Biot-Savart-Laplace law, the mutual inductance varies if the location of the conductor carrying primary current is off-centered that has been studied in detail by re-locating the current carrying conductor at seven different off-centered positions [34].

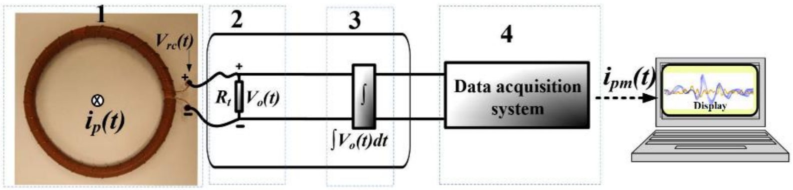


Fig. 5. Design stage; primary conductor to measurement display.

The voltage $V_{rc}(t)$ induced in the coil acts as an emf source for the coil's circuit while the voltage output $V_o(t)$ across the terminal (stage 2) of the RC under zero initial condition can be expressed in s-domain as [35],

$$V_o(s) = \frac{\frac{1}{L_C C}}{s^2 + \frac{1}{L_C C}\left(\frac{L_C}{R_T} + R_C C\right)s + \frac{1}{L_C C}\left(\frac{R_C}{R_T} + 1\right)} V_{RC}(s)s \quad (15)$$

The zero initial conditions imply that for coil's RLC circuit (Fig. 4b), the capacitor voltage $V_o(0^+)$ and inductor current $i_{LC}(0^+)$ cannot be changed abruptly. The solution of this expression can be expressed as:

$$V_o(t) = V_{RC}(t) + V_{RC}(t).e^{-\zeta\omega_n} sin\left(\omega_n\sqrt{1-\zeta^2}\right)t \quad (16)$$

where ζ is the damping coefficient which depends on the L_c, C_c, R_c, and R_t. The sinusoidal oscillations of natural (resonance) frequency ω_n are introduced in the output due to the LC response of the 2nd circuit of the coil. These oscillations can be eliminated by a suitable value of the terminating or damping impedance/resistance R_T, given through:

$$R_T = \frac{L_C}{2\zeta\omega_n L_C C - R_C C} \quad (17)$$

The terminating resistance can play a vital role to damp the unwanted oscillations. In order to find the appropriate value of R_T, the criterion is to have the most optimum behavior of the coil oscillation (critically damped). The value of R_T can be detrmined as:

$$R_T = \frac{1}{2C\omega_n} = \frac{Z_C}{2} \quad (18)$$

where Z_c is the characteristic impedance of the coil which mainly depends on L_c and C_c. For this value of R_T the coil circuit behaves as an RL-series circuit with real poles and the output voltage $V_o(t)$ is obtained without oscillations. This output of the RC is the derivative of the primary current. Therefore, integration is required to obtain the original current which is stage 3 of the current measurement process and numerically can be expressed as:

$$i_{in}(t) = \int V_o(t)dt \tag{19}$$

It has been observed that $V_o(t)$ is based on the time derivative of the primary current. For sinusoidal signals, integration of the output provides the correct phase angle. However, for transient signals, integration provides the original wave shape of the signal, which is critically essential to observe signal characteristics such as rise time, fall time, and pulse width. Various techniques of integration are discussed in section V.

The voltage $V_{rc}(t)$ is induced across the coil due to mutual inductance M_c between the coil and the primary current $i_p(t)$ [34]. Therefore, M_c can be considered as the compensation or calibration factor during stage 4 which is the reconstruction of the original signals i.e., $i_o(t)= i_{in}(t)\ M_c$. The magnitude of the calibration factor can be determined as [33],

$$M_c = \frac{ip(t)}{i_{in}(t)} \tag{20}$$

where $i_{in}(t)$ is obtained from the integration as above while $i_p(t)$ is measured with a standard current sensor.

4. Effects of Geometry on Coil's Performance

The geometry of the RC plays a predominant role in establishing the sensor's measurement capability in terms of both physical installation and electrical performance [28], [36]-[38]. Installation space, weight, size, sensitivity, bandwidth, core of material, and cost are the major factors that determine the parameters of the shape of the coil transducer. In Table 2, three sub-tables (a), (b), and (c) present geometrical, electrical, and performance parameters of the RC respectively, developed and tested in a laboratory. The change in any of the geometrical parameters (listed in Table 1) affects the operational performance of the coil. However, d_{rc}, d_m, and N are practically more dominant parameters in the construction of the coils and have a decisive impact [39], discussed further in this section.

Table 2. Parameters of the Rogowski coil

	(a) Geometrical parameter					
RC	d_o (mm)	d_i (mm)	d_{rc} (mm)	d_m (mm)	d_w (mm)	N
A	155.0	131.0	12.0	143.0	0.85	30

	(b) Electrical parameter			(c) Performance parameter	
RC	C_c (pF)	L_c (µH)	M_c (nH)	F_r (MHz)	S (mV/A)
A	5.7	1.20	9.51	1.20	9.51

In order to observe the effect of the geometrical parameters (d_{rc}, d_m, and N) of the coil, changes in the values these parameters can be made so that one parameter is changed at a time while the other parameters remain fixed. The changes are made selectively to evaluate a corresponding effect. Table 3 presents the results of the variations where A is the reference RC while B, C, and D are the coils with a change in d_{rc}, d_m, and N, one at a time respectively. A larger d_{rc} increases the cross-section A_c of the core and thus a higher mutual inductance value is obtained. This results in lower bandwidth and higher sensitivity. However, an increase in d_{rc} beyond a certain limit causes an undesirable bend of the core and can de-shape the coil winding during installation. De-shaping of the core can cause deformation and non-uniform spacing of the coil winding which can produce an error in the calculated and actual electrical parameters which consequently causes error in the calculated and actual performance parameters [38]. The experimental study demonstrates that for an increase in the turn area by 30%, the sensitivity increases approximately twice and would lead to a decrease in the resonant frequency by 16% [39].

The inner diameter of the coil (d_i) is selected to have a suitable installation around the primary conductor. Due to smaller distance between the winding and the primary conductor, a smaller inner diameter can increase the sensitivity. However, the insulation level between the primary line and the coil winding should be observed, especially in the case of high voltage power lines. Insulation layers of suitable thickness can be used to cover the coil winding. It is observed that reducing d_m by 50% of the original diameter, results in an increase of sensitivity by two times, with a slight (6-7%) increase in the resonant frequency [39].

Table 3. Variation of the geometrical parameters and performance comparison

(a). Different core diameters (d_{rc})				(b). Different coil diameter (d_m)				(c). Different number of turns(N)			
RC	d_{rc} (mm)	F_r (MHz)	S (mV/A)	**RC**	d_m (mm)	F_r (MHz)	S (mV/A)	**RC**	N	F_r (MHz)	S (mV/A)
A	12	60.7	9.51	**A**	143	60.7	9.51	**A**	30	60.7	9.51
B	17	50.8	19.1	**C**	95.6	64.1	14.3	**D**	60	36.4	19.0

The sensitivity of the coil is directly proportional to the number of turns while bandwidth has an inverse relationship. Adding turns to the coil increases the value of mutual and self-inductances. Mutual inductance is more related to sensitivity whereas self-inductance has a significant impact on the frequency response [40]. Increasing the number of turns by two, the sensitivity increases by two and the resonant frequency is decreased by approximately 33% [39].

An optimized sensor design can ensure reliable measurement and true interpretation of the state of the equipment under study. Here the optimized design refers to the most optimum selection of the geometrical parameters that fulfil the measurement requirements in terms of installation and performance parameters. A suitable combination of changing one or more parameters is required to obtain the most optimized design of the coil based on intended coil performance [41]. The performance evaluation presented above provides a quantified operational response of the coil to its mechanical design. This understanding is vital in developing a suitable design of the RC for its intended measurement requirements.

5. Design Consideration

Previous sections have discussed the RC from the perspective of its conventional formation. While the RC has remained a sensor of increasing interest for various applications, a number of evolutionary design alterations have been analyzed by different researchers to obtain improved performance of RC sensors. In this section, some important design alterations are reviewed.

The circular cross-section of the core represents the conventional shape of the coil. However, with time, as the RC has been explored gradually for more applications, other shapes have also been investigated [28], [42] to develop more efficient RC sensor. The cylindrical shape of the coil is presented in [43]. Considering cylindrical structures, the cross-section area of the core can be changed by changing only the height of the cylindrical core if it requires to fit-in certain installation spaces. Further, the sensitivity of the coil can be increased without increasing the number of turns of the coil winding. A rectangular RC is developed by combining 4 straight coils of circular cross-section [44]. This structure can be useful in the case a larger cross section (d_c) of the core and smaller mean diameter (d_m) of the coil is required. One advantage of this geometry can be its capability to install around conductors with smaller clearance space in the vicinity where a circular coil is not able to be installed due to inability of bending the core below its minimum bending radius. This is because a conventional circular coil experiences a deformation in the core's circular shape and possible displacement of the coil turns when the coil is over-bent considering permissible bending radius. Associated with the sensitivity of the coil, mutual inductance is a key parameter. Keeping the circular cross section as reference, a detailed study is carried out in [38]-[39], [45] to evaluate mutual inductance of the rectangular and oval cross section of the coils. These studies demonstrated that considering equivalent dimensions of the coil cross section, the sensitivity of the rectangular coil is comparatively higher.

As compared to manual or machinable manufacturing of the coil, a printed circuit board RC (PCBRC) is developed to reduce the measurement error up to 0.1 percent [46]. The imperfection of the coil winding, turn spacing, location of the return loop, and possible deviation during use of the sensor can reduce the accuracy, which can be avoided by using CAD based layout and advanced PCB manufacturing technology. In relation to the dimensions of a conventional RC, the above referred work presents a PCBRC prototype as a toroidal core form of 3 mm thickness having radial copper tracks as coil turns where two vias are placed at the ends of each track. Similarly, a variety of shapes and designs can be adopted to alter the geometrical and electrical configuration of the coil to develop a tailor-made design of RC sensor [47].

The return loop of the coil winding passes through the central position of the turns, which is the typical practice for the construction of the conventional RC. A new approach of reverse or return winding has been investigated [39], [48]. The forward and return windings must be identical regarding the number of turns, turn spacing, and uniformity. This modification not only provides the return loop but also provides the possibility of having a greater (two times) number of turns on the same core dimensions wound in opposite directions. However, though it was shown that the return winding construction as a two-layer winding provides the same sensitivity as obtained from the single-layer winding (with N=60 in both cases) the bandwidth is reduced by 26% [39]. Therefore, from an optimized design point of view, the foreseen mechanical advantages of return winding constructions are not expected to provide improved electrical performance.

The terminating resistance eliminates the unwanted oscillations introduced by the sensors' electrical parameters (capacitance and inductance). The integrator converts the derivated signal back to its original form (waveshape) by applying the integration operation. For PD studies, an RC sensor can be used for the detection and location of the faults without terminating resistance and integrator [49]. Detection of PDs can be observed from the appearance of PD pulses within certain phase angles of an AC operational voltage [50]. To determine the location of the defects, the starting or peak time of the PD pulses can be used for calculation of the PD defect that do not necessarily require an accurate waveshape of the PD signals. Determination of the types of insulation defects insulation defects is directly related to the amount of the electrical charge released during PD events which can be accurately determined from the true waveshape of the PD signals [27], [49]. Therefore, for quantification of the actual waveshape the complete processing of the measured signal using terminating resistance and integrator are essential.

The performance, complexity of the design, and cost of the coil sensor are significantly dependent on the approach adopted for the design of the integrator. Active, passive, and numerical (digital) integration techniques have been used by researchers. An active integrator is based on an operational amplifier along with a resistance capacitance network. This technique is suitable for signals from low frequency up to a few kHz [51]. To develop passive integrators, mainly the RC-network and *L/R* (self-integration) are used. This type of integrator is more suitable for higher frequencies in ranges

>100 kHz [52]. Active and passive integrators consist of analog electronics which make the circuit design complex and expensive. When aiming at high precision effects on instrumentation circuits bias current, voltage input offset, and thermal drift become much more critical. Similarly, long-term stability, sensibility to environmental conditions, possible electromagnetic disturbances due to high voltage and current, and expensive periodic calibration are problem associated with analogue electronics [53]. Moreover, the limited range of amplitude, frequency, and waveshape of the primary signals is also a concern when adopting electronic integrators [51]. In [33], digital integration is implemented in the data acquisition unit by using numerical algorithms to compute the definite integral of the digitized measured signal. Digital integration is based on a successive process of integral evaluation for *n* number of samples obtained at a suitable sampling frequency. The trapezoidal integration rule provides faster convergence for better performance even in case of rougher signals as compared to other commonly used digital integration methods such as rectangular integration and Simpson's rule [54].

During construction, particular attention is paid to geometry, orientation, and positioning of the primary conductor in order to minimize the uncertainties associated with the RC based measurements. Considering modern tools, additive manufacturing is gaining increasing interest for development of RC. To cope with the above mentioned issues, additive manufacturing (3D printing) offers excellent capability of maintaining the geometric structuring such as core shape, symmetry of the winding, central position of the primary conductor, and its orthogonal position to the surface defined by the coil itself [55]-[56]. In addition, before the real construction using 3D manufacturing begins, the simulation and design tools such as Finite element method (FEM) and solid works are also being used to analyze the electromagnetic and geometrical properties of the coil [57].

In addition to design ties between sensor and measurement signals, the operational voltages are critical to consider for the safety of the measurement system [58]. For medium and high voltage applications, a safe insulation level must be ensured based on the distance between the measurement conductor and coil winding.

6. Applications of Rogowski Coil in Power Systems

An overview of the RC's versatility of current measurements is presented in Fig. 6. A variety of advantages of an RC over the other current measurement solutions, enable the RC to be used for the functions of metering, monitoring, protection, and control. Due to stable operation over a wide range of signal amplitude, frequency, and ability to measure steady state and transient signals, the RC is becoming popular in several applications of electrical installation, namely: rotating plant, static power system components, rectifier monitoring, relays, substation equipment, transmission system components, overhead and underground power lines, railway systems, and many more. The bandwidth and amplitude of the current signals are considered as the key specifications of a measuring sensor. Different ranges of the bandwidth can be described as; low frequency (up to 10s of Hz), medium frequency (up to100s of KHz), high frequency (up to 100s of MHz), and ultra-high frequency (up to 100s of GHz) [59].

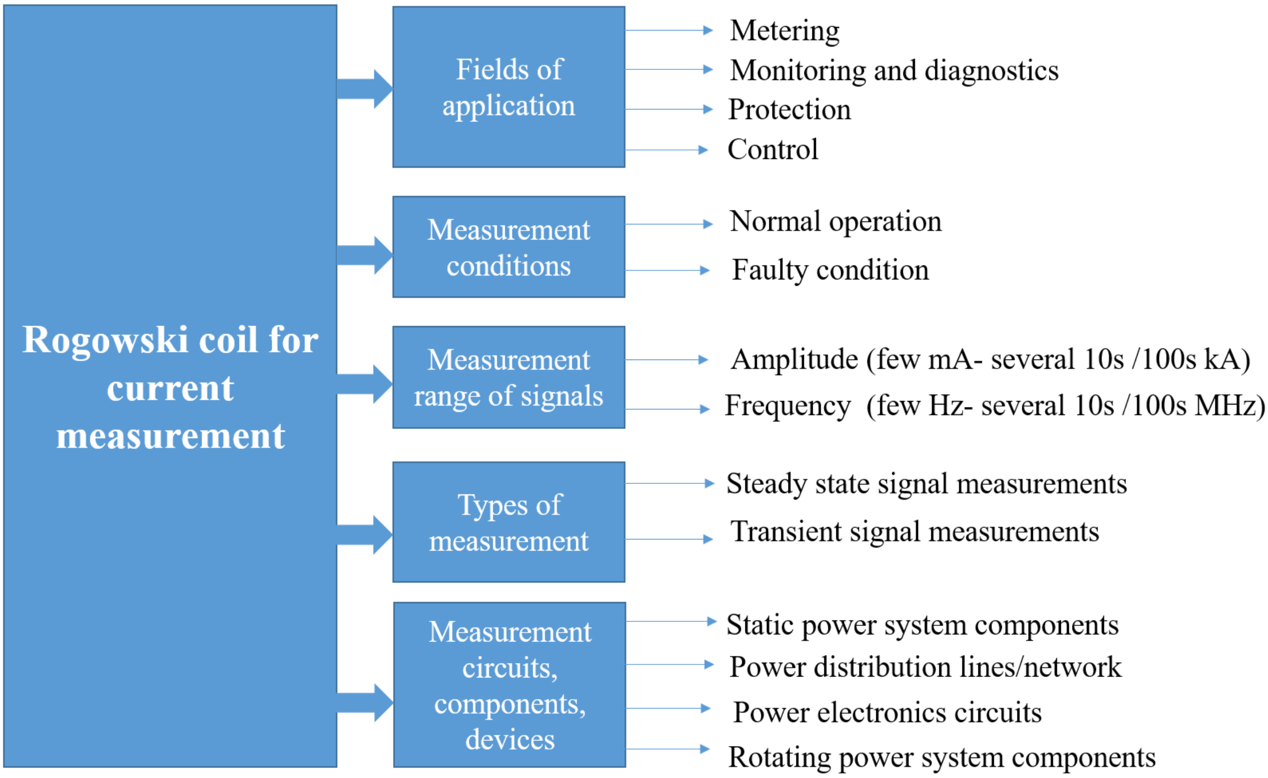


Fig. 6. Overview of Rogowski coil's application in power systems.

During regular operation, the frequency of the measuring signal can be observed directly from the cycles per second of the sinusoidal signal. For the non-sinusoidal signals, the frequency contents of the signal can be determined using suitable tools based on Fourier transform. Similarly, the range of currents in power components can be from a few mA to hundreds of kA considering the application. Further in this section, the applications of RCs are described considering measurement requirements in terms of characteristics of the signals and related equipment. The respective designs of RCs are reviewed which not only illustrate the coil designs for specific applications but also provide a primary comparison between these designs.

In power systems, regular operation is observed for medium and high voltage equipment with measured current signals up to tens of kA at 50/60 Hz sinusoidal supply. Power system components mainly include power transformers, cables, switchgear, and insulators. CT sensors have been widely used in power system applications. However, for higher currents and frequencies, the performance of CT becomes a concern because of linearity and saturation issues which depend on the type of the core material [60]. Various design aspects, measurement capabilities, and applications of CTs are presented in details in IEC 61869-10. Considering the construction of both devices i.e., CTs and Rogowski coil, core material stands as an important difference of construction and measurement performance. Ferromagnetic material for cores is well-known for its improved linearity and saturation in CTs while Rogowski coil sensors can be considered as 'air-core CTs'. Implementing smart devices considering energy meters and network analyzers, traditionally used CTs are being replaced by the Rogowski coils for power quality monitoring. [61]. For example, to develop the network analyzer for improved monitoring of power quality in the grid, the Rogowski coil is preferred for current measurement (with a sensitivity 100 mV/1000 A at 50 Hz) [62]. In [63], the performance of a CT and an RC is evaluated for measurement of 450 A current at power frequency. Measurements obtained from the CT exhibit deformation of the signals at 400 A that appeared as the third harmonics while the RC has shown stable measurements. The linearity and saturation issues in CTs can cause serious harmonics for the operation of protection relays that can be avoided by using an RC. In order to measure a current range of up to 1200 A, the RC was designed with the dimensions; internal diameter as 105 mm, external diameter as 135 mm, while the number of turns was 1470 [64]. It can be noticed that the number of turns for the RC in Section IV is significantly smaller. It should be recognized that the output of the RC is proportional to the rate of change of current. Therefore, considering the primary signal of power frequency, a greater number of turns is required to obtain a suitable sensitivity [65].

High current pulse measurements in several critical applications such as excitation current for electrodynamic accelerators, devices powered by fast current pulses, dynamic loads in power networks, lightning current, high-power converters, medical equipment, and the food industry [66]-[67]. The amplitude of these current pulses can be from kA to even MA with the current rising rate of changes in the order of kA/μs. During the testing of transient voltage surge suppressors of 2.5 kV rating in a medium voltage grid, its pulse current withstanding capability is measured as 30 kA peak current with a rate of current 40 kA/μs [68] A discharge current of 200 kA with initial rising rate of 58 kA/μs was measured during switching of high-power thyristor [69]. In addition to high current applications at power frequency, the use of RC for high current high frequency measurements is also a favorable choice. In [66] a detailed study has been carried out to compare the performance of current shunts and Rogowski coil for high current pulses. Lightning is a common phenomenon of transient pulses of high impact. Statistics indicate that 50% of lightning discharges can produce a discharge current up to 30 kA while 1% of lightning discharges are of 800 kA [70]. Focusing on the lightning current in the range of 100 kA, the work done in [71] create different designs of coils having an outer diameter of 200 mm. In this work, it can be seen that when the internal diameter is increased from 10 mm to 50 mm, the number of turns is decreased from 604 to 19. The coil design is focused on achieving a sensitivity of 0.1 mv/A with maximum output of 10 V for the current range of 100 kA. In addition to conventional power system equipment, the RC also offers an efficient solution for measuring lightning current flows inside and outside a wind turbine generator system [72].

A protection device based on electromechanical equipment requires a high-power output from current measurement devices to relay in the power network for which a CT has remained a capable sensor. With the development of microprocessor-based protection relays, a lower voltage level for output is required from the sensor to an analog-to-digital (A/D) converter which is a challenging for a CT [73]. As reported in the C37.235-2007 - IEEE Guide, the saturation of a CT starts near 20 times rated current and rated burden which is one of the major drawbacks for a CT sensor while RCs have linear response. This makes the RC sensors an efficient sensor for microprocessor-based protection and relaying systems [74]-[75].

While high current signals with low and high frequencies are important applications for monitoring and protection in power systems (presented above), the design of sensors for accurate measurement of low amplitude currents with high frequency is challenging. This regime of signals can be associated with pre-fault conditions in the power system components. Emerged from weakening insulation issues, these signals can be termed as partial discharges or electrical discharges. The final stage of these pre-fault discharges can lead to short circuit conditions and failure of affected components [40]. The measurement of these discharging signals requires sensors with a wider bandwidth and higher sensitivity. These discharges produce current transients of smaller magnitude up to a few mA while the pulse width or rise time of these pulses be less than 100 ns. Due to preferred performance for linearity and saturation at higher frequencies, the RC has gained significant attention for these signals. Depending on the insulation system (solid, liquid, and gas) and the type of discharge (such as arcing, corona, surface, and internal), the characteristics of these signals can vary. RCs have been used in these applications for proactive diagnostics, i.e., detection, location, and quantification of insulation faults, in a number of grid components [12]. Considering design aspects for low amplitude high frequency signal, a greater number of turns increases the self-inductance and self-capacitance of the coil which causes a reduction in the coil's bandwidth. However, on the other hand, a lower number of turns reduces the sensitivity, which is undesirable. Due to the lower amplitude of PD signals, coil sensitivity needs to be higher. The trade-off of the core dimensions and number of turns is adjusted to achieve a higher bandwidth and greater sensitivity [38]-[39]. As an example, for PD, the coil can be designed with an outer diameter as 50 mm, internal diameter as 13 mm, thickness as 50 mm, and the number of turns as 12, to achieve a frequency band between 1.0 and 770 MHz [27]. The high frequency RC designed in [45] is developed for PD measurements with the outer diameter as 160 mm, internal diameter as 141 mm, core diameter as 19.6 mm, and having a number of turns as 30. The measurement bandwidth of this coil was centered at 37.6 MHz. In this design of RC, an optimum measurement bandwidth can be obtained on the basis of suitable choice of terminating resistance.

The use of RCs in power transformers and switchgear is common for the detection of faults; however, its use for power cables and overhead covered conductor is most favorable for location and quantification tasks as well [76]-[78]. This is because of the structure and compact size of transformers and switchgear which make them more suitable to be measured with acoustic sensors. Due to clear traces of current pulses propagating along the power cables, an RC sensor provides improved accuracy for the location of insulation defects. In addition to static power network components, the use of an RC is also increasing in rotating plant (generator and motors) for incipient fault monitoring [79]-[80].

7. Conclusion

Measurement of electrical current is required for ensuring the reliable operation of electric components and related processes. Measurement performance, degree of non-intrusiveness, and compatibility with wide range of equipment and their operation can be considered as the key features in evaluating the suitability of a sensor. In this paper, the RC sensor is comprehensively reviewed considering its design, modelling, operation, and applications for power system components. Based on the literature review, important aspects are discussed to highlight a practical insight of the coil's design, current measurement process, and behavior of the coil due to variations in its geometrical design. The applications of RCs are presented based on the range of the current (amplitude and frequency) signal, signal waveshape, and the design related to particular application. The paper is aimed to provide a deeper understanding of the competencies of RCs for new and existing researchers in the field of current measurement. While continuous progress has been observed in the use of RC sensors in past decade, this paper emphasizes the need to explore the RC further as an efficient sensor to enhance the current measurement performance for power components.

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CRediT authorship contribution statement

Muhammad Shafiq: conceptualization, methodology, formal analysis, investigation, writing – original draft, Brian Stewart: visualization, writing – review & editing, Amjad Hussain: conceptualization, resources, funding acquisition, review & editing, Waqar Hassan: methodology, review & editing, Maninder Choudhary: Writing – review & editing, and Ivo Palo: visualization, resources, review & editing.

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