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Suitability of Rogowski Coil for DC Shipboard Protection

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Abstract—The achievements made in the field of DC shipboard power systems over the past decade have been impressive. However, the widespread acceptance of DC shipboard power systems is still hindered by the difficulty in ensuring protection of the system. One of the challenges in designing the protection systems is the selection of current sensors. This paper aims to study the suitability of Rogowski coil for use in DC shipboard power system protection relays. This paper describes the design and implementation issues of the Rogowski coil. It is shown that the geometrical orientation of the Rogowski coil has a major impact on the measurement sensitivity of fault currents.

Index Terms—DC Faults, DC Shipboard Power System, DC Bus bar, Rogowski Coil.

I. INTRODUCTION

DC power systems offer numerous advantages when applied to shipboard integrated power and propulsion. Some of the advantages are improved fuel efficiency, easier integration of emerging generation sources and no requirement of phase and frequency synchronisation of generators. However, the DC power system in shipboard system faces challenges with regards to protection. Without effective and stable measures to detect and counter the electrical faults in the system, the ship may be unable to carry out its intended mission and may jeopardize the safety of vessel and crew. To maintain the stability of the system and to safeguard the DC shipboard power system from high fault currents, we are in need to design the protection devices like relays, circuit breakers with protection algorithms. Research has been going on to study the fault response of LVDC/MVDC distribution system [1]–[4] and devising suitable protection philosophies. One of the important aspects of the protection system is the selection of current sensors which are required to measure the fault current as required for fault detection. A variety of different current sensors are available for the detection of fault currents. These include shunt resistors, current transformers (CT's), hall effect sensors and Rogowski coils [5]. The Rogowski coil is used to measure high alternating and pulsed currents without saturation. The flexible nature and capability to endure large current overloads with excellent transient response makes the Rogowski coil highly popular [5].

This paper aims to study the characteristic of the Rogowski coil and to infer whether this could be used for DC shipboard protection systems. Lumped model approach has been used to model the Rogowski coil to study the electrical characteristics.

The variation of the geometrical parameters on its performance (such as sensitivity) is also analysed. The paper is divided into six sections. Section II describes the state of the art of the Rogowski coil, its underlying principle of operation, types of Rogowski coil along with its construction and application. Section III deals with the modeling and design of the Rogowski coil. Section IV covers the DC shipboard power system under study along with the geometrical and electrical parameters of the bus bars where the Rogowski coil would be integrated. The performance of the Rogowski coil under DC faults is studied in Section V and subsequently the paper is concluded in Section VI.

II. ROGOWSKI COIL: STATE OF ART

A. Operating Principle

One of the distinguishing feature of the Rogowski coil is the sensor coil which is flexible and wound with uniform cross section on non-ferrous core. On account of the air core, the coil does not saturate. The toroidal structure of Rogowski coil encircles the current carrying conductor. According to Ampere's law, the current flowing through a conductor passing through the aperture of Rogowski coil gives rise to a magnetic field [6] surrounding this conductor where:

$$I(t) = \frac{1}{\mu_o} \oint \vec{B}(t) \cdot d\vec{s}. \quad (1)$$

According to Faraday's law [6]:

$$u(t) = \frac{d\phi}{dt} = \int B(t) \cdot dA = \frac{A}{s} \mu_o I(t) \quad (2)$$

where μ_o is the permeability of free space, $u(t)$ is the induced voltage in the coil terminals, B is the magnetic field, I is the current and A is the cross-section of the coil and s is the number of turns per length unit. The voltage measured across the coil would be proportional to the rate of change of magnetic field which is directly proportional to the rate of change of primary current.

B. Advantages of Rogowski Coil

The Rogowski coil is generally used to measure alternating currents and high speed impulse currents without saturation. The coil is used to detect the fault current in transmission lines and electrical machines. Electronic integrators are used to integrate the voltage signals from the coil to reproduce the fault current. The electrical characteristics of the Rogowski coil are studied with the help of lumped or distributed models

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with integrators designed for different frequency ranges [7]. The properties such as non-intrusive nature, low cost, high flexibility and non-saturation make the Rogowski coil popular for current sensing. Some of the noted advantages of the Rogowski coil are [8]:

- 1) *Linear Characteristics*: Compared with other devices for current measurement, Rogowski coil has linear characteristic. When the current to be measured goes high, the voltage in the Rogowski coil does not have saturation problem. Thus it will not induce voltage that is high enough to damage the circuit. This characteristic is shown in Figure 1(a).

Figure 1. (a) Rogowski coil characteristic and (b) bandwidth of LEM Flex II sensor [8].

- 2) *Ease of Use*: The components of Rogowski Coil are robust, light in weight and easy to manipulate.
- 3) *Non-intrusive Nature*: The Rogowski coil acts as an independent measuring tool which needs to be placed around the current carrying conductor.
- 4) *Wide-Bandwidth*: The Rogowski coil has larger bandwidth as compared to other current sensors such as LEM Flex II current probe [8] as shown in Figure 1(b). This large current bandwidth ensures that there will be no “blind zone” for metering application in normal situations. For Rogowski coil, the measurable frequency range is typically from 0.1 Hz to 1 GHz.
- 5) *Excellent Transient Response*: The response time of the Rogowski Coil is very fast which is helpful particularly for the DC shipboard power system.
- 6) *Safety*: The Rogowski coil is external current measurement device where the current path and measurement path are electrically isolated, hence it provides electrical safety to the operating personnel.

A comparative study on current measuring techniques is listed in Table I and it is noted that the Rogowski coil is preferable to other current measurement methods in various respects [5].

However, the major drawback of the Rogowski coil is the need of an integrator circuit to translate the output voltage of the coil into current waveform. The integrator circuit needs an independent power source for operation. RC based integration is used for high frequencies (> 100 MHz) whereas the opamp based integration method is useful for low frequency (< 100 MHz) measurements. The microprocessor based algorithms are developed for precise waveform reconstruction which is useful for mid-frequency ranges [9], [10]. The coil sensitivity is an important performance parameter of the Rogowski coil. Increasing the number of turns increases the sensitivity of the coil.

TABLE I
COMPARISON OF DIFFERENT CURRENT MEASURING TOOLS

Current Sensing Technology	Low Resistance Current Shunt	Current Transformer	Hall Effect Sensor	Rogowski Coil
Cost	Very Low	Medium	High	Low
Linearity over measurement range	Very Good	Fair	Poor	Very Good
High Current measuring capability	Very Poor	Good	Good	Very Good
Power Consumption	High	Low	Medium	Low
DC/high current saturation problem	No	Yes	Yes	No
Output Variation with Temperature	Medium	Low	High	Very Low
DC offset problem	Yes	No	Yes	No
Saturation and Hysteresis Problem	No	Yes	Yes	No

C. Types of Rogowski Coil

The different types of Rogowski Coil are [11]:

- 1) *Traditional Rogowski Coil*: This is the most commonly used coil which is easy to make using varnished wire or cable core to a circular plastic ring.
- 2) *PCB Rogowski Coil*: Different designs of PCB Rogowski coil are available where the printed circuit boards are used. The baseboard is the coil's core and insulation between the conductors. The usage of very thin baseboard has low self-inductance and large distributed capacitance.
- 3) *Hybrid PCB Rogowski Coil*: The hybrid PCB coil is similar to the typical PCB coil but the difference is that the hybrid coil combines the copper wire and printed conductor as the winding.

D. Construction of Rogowski Coil

As discussed, Rogowski coil is built on a non-magnetic material, making the coil to be an air core. Starting from one end of the core, the coil has N number of turns which proceeds through the other end of the coil and after the final turn it passes through the centre of the core to the starting of the core [12]. Rogowski coils are designed with two wire loops connected in electrically opposite directions. This cancels electromagnetic fields coming from outside the coil loop. For accuracy of the measurement, the Rogowski coil should be mounted in such a way that the current carrying wires passes through the centre of the sensor. This way the turns are located perpendicular to the current to be measured.

E. Applications of Rogowski Coil

The Rogowski coil finds application in monitoring of current in precision welding systems. The Rogowski coil is also often used for current measurement in arc melting furnaces. It finds application in monitoring electrical plant for protection purposes requiring accurate detection of fault current. It is also useful to monitor the signalling currents in railway lines and the applications where the primary current conductor has poor geometric structure.

III. MODELING OF ROGOWSKI COIL

The electrical parameters of the coil depends upon its geometrical structure [12]. The prime attributes dealt with the Rogowski coil are resistance (R_l), self-inductance (L_l), capacitance (C_l) and mutual resistance (M_l) [6], [12]:

$$R_l = \rho_c \frac{l_w}{\pi d^2} \quad (3)$$

$$L_l = \frac{\mu_o N^2 d_{rc} b}{2\pi} \ln \frac{b}{a} \quad (4)$$

$$C_l = \frac{4\pi^2 \epsilon_o (b+a)}{\log(\frac{b+a}{b-a})} \quad (5)$$

$$M_l = \mu_o N \frac{r_m - \sqrt{r_m^2 - r_{rc}^2}}{4\pi} \quad (6)$$

where ρ_c is the electrical resistivity of the coil wire, μ_o is the permeability of free space, l_w is the length of coil wire, d is the radius of the wire, d_{rc} is the diameter of the loop of the coil, r_{rc} is the radius of each loop in the coil, r_m is the mean radius of the Rogowski coil, N is the number of turns and a, b are the internal and external radius of the Rogowski coil. Lumped model is utilized for the low-frequency analysis [6] which includes lumped inductor, resistor and capacitor as shown in Figure 2. The transfer function of the lumped model can be

Figure 2. Lumped model of Rogowski Coil.

given as [6]:

$$H(s) = \frac{V(s)}{I(s)} = \frac{s.M}{L_l C_l s^2 + (R_l C_l + \frac{L_l}{Z}).s + 1 + \frac{R_l}{Z}} \quad (7)$$

Since the resistance of the coil is negligible, the transfer function is reduced to:

$$H(s) = \frac{V(s)}{I(s)} = \frac{s.M}{L_l C_l s^2 + (R_l C_l + \frac{L_l}{Z}).s + 1} \quad (8)$$

The accurate value of terminating resistor can be calculated using root locus analysis or bode plot, but for not so precise measurement the terminating resistor can be given by Eq. 8:

$$R_d = Z = \frac{1}{2\zeta} \sqrt{\frac{L_l}{C_l}} \quad (9)$$

The terminating resistor is a determining factor of the coil output quality [6]. The coil has better performance for low values and the combined effect of small reflections and ohmic damping results in poor response with the higher termination resistance. $\zeta = 1$ is good value for terminating resistor for critical damping.

IV. TARGET DC SHIPBOARD POWER SYSTEM

The Rogowski coil is modeled and integrated with the target DC shipboard power system under study to capture the profile of fault current. In the proposed DC distribution system, the generators are connected with the loads using DC common bus. Two level voltage source converter (2L-VSC) is used in the system for rectification and inversion purpose. The generation source comprises of 4 x 2048 kVA synchronous generator which is interfaced with the 2L-VSC. The propulsion load comprise of 2 x 883 kW tunnel thruster (TT-1 & TT-2), 2 x 2500 kW propulsion systems (MP-1 & MP-2) and 1 x 883 kW rudder thruster (RT). The rating of houseload is

300 kVA (Houseload 1-4). The short circuit fault (F) between positive rail and negative rail of the DC bus is intended to be detected by the Rogowski coil (A). The schematic of the target DC shipboard power system is shown in Figure 3(a). DC bus bar is designed to carry the full load current throughout its cross section. No provision is made for current tapering towards the ends of the electrical cabinet. The DC bus voltage is 1500 V which also accounts for 15% design margin above the rated current. The bus bar design parameters are based on the copper development association [13] and are shown in Table II. Since the Rogowski coil is intended to measure the

TABLE II

BUS BAR PARAMETERS

Design Specifications	Parameters
Generation Capacity	8.192 MW
Bus Bar Voltage Level	1500 V
Bus Bar Current	5460 A
Conductivity of Copper	5.85×10^7 Siemens/m
Dielectric Constant	2
Generation Capacity	8 MW
Number of Conductors (N)	3
Length	18 m
Width	0.2032 m
Conductor Thickness	0.0127 m
Thickness of di-electric	2

fault current on the DC bus, the coil parameters are based on Table II. From Table II and Figure 4, the perimeter of the bus-bar cross section is $0.2032 \times 2 + 0.0127 \times 3 \times 2 = 0.4826$ m. Hence, the Rogowski coil of 0.5 m length is chosen for the given bus-bar. The parameters are:

- $\mu_o = 1.26 \times 10^{-6}$ H/m
- $\epsilon_o = 8.854 \times 10^{-12}$ F/m
- Length of the coil is taken as $l_{min} = 0.5$ m
- Diameter of each loop of the coil, $h = 0.002$ m
- The inner diameter, $d = 0.078$ m
- The outer diameter, $D = 0.080$ m
- Number of turns, $N = 150$

The value of resistance is very small hence can be neglected. From Eq. 4, Eq. 5 and Eq. 6 the self-inductance (L_l), capacitance (C_l) and mutual inductance (M_l) of the lumped parameter is calculated. The damping resistance (R_d) is calculated from Eq. 9. However, if the number of turns in the coil (N) changes then the parameters of the coil L_l , M_l also changes. This variation is shown in Table III.

V. FAULT DETECTION USING ROGOWSKI COIL

The Rogowski coil discussed in the previous sections is intended to be used for fault detection in DC shipboard power system. Lumped model of the Rogowski coil is used in this paper for fault detection. The Rogowski coil is installed at point 'A' to detect the current flow during rail-rail fault ('F') as shown in Figure 3(a). The current at point 'A' and the Rogowski coil output is shown in Figure 3(b). The Rogowski coil primarily measures the rate of change of fault current. It can be observed that the output of the coil varies instantaneously when the fault occurs. However, the ease of fault detection by the coil depends on the geometric configuration. One of the prime factors being the number of turns of the coil. The number of turns ' N ' of the coil are varied and the parameters of the coil are calculated as per Section III-A. The results are presented in Table III. The bolted short

Figure 3. (a) Single line diagram of target DC shipboard power system indicating the Rogowski coil at point 'A', fault at point 'F' & the cross-section area of the bus-bar and (b) comparison of the Rogowski coil output and fault current for bolted short circuit.

TABLE III
LUMPED MODEL PARAMETERS

Case	Number of Turns (N)	Length of Coil (l) (m)	Radius of the Coil (r) (m)	Diameter of each loop (h) (m)	Inner Diameter (d) (m)	Outer Diameter (D) (m)	$L_1(\mu\text{H})$	$C_1(\text{pF})$	$R_d(\Omega)$	$M_1(\mu\text{H})$
1	60	0.5	0.079	0.002	0.078	0.080	1.251	29	49	0.436
2	90	0.5	0.079	0.002	0.078	0.080	2.814	29	49	0.654
3	120	0.5	0.079	0.002	0.078	0.080	5.003	29	49	0.873
4	150	0.5	0.079	0.002	0.078	0.080	7.817	29	49	1.0914

circuit is applied at point 'F' and the response of all the different Rogowski coil cases of Table III are presented in Figure 4(a). It can be seen that the sensitivity of the Rogowski

Figure 4. Comparison of Rogowski coil output for (a) bolted short circuit for different cases and (b) for different fault scenarios with case-4.

coil is highest for Case-4 which comprises of highest number of turns ' $N = 150$ '. The major factor behind this increased sensitivity is the increased mutual inductance between the coil and current carrying conductor. Six different scenarios with Case-4 Rogowski coil have been implemented at point 'A'. The bolted short circuit (0Ω), low resistance fault (0.001Ω), high resistance fault (0.01Ω), very high pulsed load (0.1Ω), high load (1Ω) and low load (10Ω) is implemented at point A and the Rogowski coil's output is shown in Figure 4(b). It can be seen that output of the coil decreases from very high load onwards and it cannot detect the change in current for low load. However, it can easily detect the bolted short circuit faults, low impedance fault and high impedance fault. The output voltage of the Rogowski coil can be divided into 'Trip Region' and 'No-Trip Region' as shown in Figure 4(b) which can be used as a parameter for devising the protection logic.

VI. CONCLUSION

This paper studies the Rogowski coil and its use in fault current detection within DC shipboard power systems. The operation and modeling of Rogowski coil is presented where it is seen that increase in number of turns of the coil results in

better sensitivity owing to increased mutual inductance. It is also seen that the coil is able to sense the current changes for bolted short circuit, low impedance fault and high impedance fault which could be useful for devising suitable protection philosophy for DC shipboard power system. Although it can detect the very high load, suitable thresholds can be set to differentiate between the trip and no-trip region.

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