ENHANCING THE FREQUENCY RESPONSE OF ROGOWSKI COIL USING FEEDBACK PID COMPENSATOR WITH INTEGRATOR CIRCUIT

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ABSTRACT
Rogowski coil is considered an electrical device used for the measurement of Alternating Current (AC) or high-speed current pulses from other devices. It has gone through many stages of development towards improving its performance and applications. It has been a challenging task to develop a Rogowski coil model that maximizes the sensitivity and bandwidth of the coil simultaneously for current measurement based on the arbitrary selection of the geometric factors. To address this challenge, an adaptive compensator for Rogowski coil performance improvement using Proportional Integral and Derivative (PID) technique has been presented. The mathematical models of Rogowski coil circuit have been developed, an integrator designed and a PID compensator was developed. Then MATLAB/Simulink models including MATLAB programme were developed for Rogowski coils whose output responses were improved with the addition of the PID controller. In the first analysis, the Rogowski coils were evaluated in their conventional state and the frequency domain analysis revealed that the first model has a gain of 13.3 dB at a frequency of 144 MHz and the second model has a gain of 38 dB at a frequency of 27.4 MHz. Their phase margins (errors) were 103^o and 90.7^o respectively. Thus, these results showed that the Rogowski coils band of frequencies from lower and upper limits were in the tens of MHz. An integrator was added to the Rogowski coils and the simulation results indicated that the frequencies of the coils were enhanced such that a frequency of 50/60 Hz can be measured or detected together with frequencies in tens of MHz (up to 7 decades and more). Furthermore, the PID compensator was designed and integrated with the individual Rogowski coils plus the integrator. The results revealed that the frequency limits of the coils were further improved such that it is possible to measure and detect current for fast switching transient and at the same time, retain the capacity to accurately measure currents of 50/60 Hz given that the lower limit of the frequency band is 0.1 Hz. Generally, two Rogowski coil models were simulated with the developed PID compensator and the results showed that the PID compensator provided similar results in the frequency domain for both coils, which validates its adaptability to parameter variation.

Keywords: Rogowski coil, Frequency, PID compensator, Integrator

1. INTRODUCTION
Rogowski coil as a device has gone through many stages of development towards improving its performance and applications. A lot of work has been done on the design and analysis of Rogowski coils and still various aspects need to be explored further to improve performance (Samimi *et al*., 2015). The design of suitable geometrical parameters has been identified as an important aspect regarding the proper operation and installation of the coil around the power component being tested (Shafiq *et al*., 2014; Liu *et al*., 2011). These parameters determine the electrical properties and significantly affect the measuring performance of the coil in terms of its sensitivity and bandwidth.

Higher sensitivity and wider bandwidth are generally desired in the design of the Rogowski coil sensor. However, changing one geometrical parameter may negatively affect the sensitivity and bandwidth and vice versa (Shafiq *et al.*, 2014). Consequently, it has been a challenging task to develop a Rogowski coil model that maximizes the sensitivity and bandwidth of the coil simultaneously for current measurement based on the arbitrary selection of the geometric factors. The problem of selecting the parameters of the coil for proper function and improved performance of the system has been identified as the major design challenge limiting

the performance of the Rogowski coil. Secondly, there is a lack of feedback mechanisms and adequate damping measures for proper optimization of the performance and stability of the system. This makes it difficult to achieve the desired improvement in the performance and stability of the system.
Rogowski coil has been considered as one of the vital components in the instrumentation industries and other manufacturing industries due to its ability to measure a wide range of current, easy way of usage, low cost, and wide applications. Despite its average performance and wide applications, it is gathering increasing research interest. This is because some of the Rogowski coil performance challenges have affected its functional behaviours and any performance improvement achieved will be very significant in achieving improved measurements and sensing capability.

In this study, to address the issue of manually selecting the geometrical parameters of the coil for the system performance optimization, a feedback mechanism based on the Proportional-Integral-Derivative (PID) method was applied for the development of a compensating element or subunit. The subunit model can be designed by selecting the gains of the compensating element to improve the performance and stability of the device. The method involves measuring the output of the coil and feeding it back to the system for comparison with the reference input to generate an error signal which is compensated or cancelled by the developed compensating element. This technique which is carried out in MATLAB application software provides a means of automatically selecting the gains of the compensating element to compensate the error signal for the improvement of the coil performance. It will help to achieve simultaneous improvement in the performance and stability of the system since the design of the compensating element is based on the reduction of error which will help to achieve an output closely similar to the reference input or desired output.

2. REVIEW OF RELATED WORKS ON ROGOWSKI COIL

The frequency response characteristics of a Rogowski coil for measuring lightning were carried out using an active integrator (Paophan*et al*., 2020). The study revealed that the Rogowski coil with the active integrator frequency bandwidth was suitable for proper measurement of lightning current. For measuring partial discharge pulses, a Rogowski coil was modelled using a simplified model based on lump parameters and simulated in Simulink in Rojas-Moreno *et al*. (2017). It was shown that the electrical model can be used in analysing the time and frequency responses of Rogowski coils with different numbers of turns and dimensions to determine a configuration that suits the required type of pulses to be measured. Geometric characteristics maximization of bandwidth gain product using particle swarm optimization (PSO) and coil adaptation to specific application requirements was used to design a Rogowski coil (Robles *et al*., 2018). A mathematical model for the determination of electromotive force (EMF) of measuring current transformer secondary winding using a Rogowski coil was developed by Oganyan *et al.* (2019). The magnetic flux passing through the Rogowski coil was determined using regression models obtained to find the EMF in the secondary winding using a statistical program. The results of the study revealed the essence of considering the primary bus position with respect to the Rogowski coil. Iloh *et al.* (2014) presented an overview of Rogowski coil current sensing technology while highlighting its basic concept and application in the automation of power systems. Improvised Rogowski coils were constructed using coaxial cables and laminated copper wires. The characteristics of three Rogowski coils were experimentally determined and compared with standard Rogowski coils. In addition, the sensitivities of the coils for application in automation system design for a substation were determined. Designed technique and designed metric of multi-layer printed circuit board (PCB) Rogowski coil with good-high frequency performance, strong anti-interference ability, and sufficient sensitivity was presented by Jiao *et al*. (2020). The results from the Pspice simulation and the experiment revealed that the sensor sensitivity was 40mV/A, the current measurement capacity was 0-375 A, and the bandwidth was above 3 MHz. To improve the immunity of the Rogowski coil from electromagnetic interference, the effect of the structure and parameter variations of the double-layer PCB Rogowski coil on the measurement accuracy of mutual inductance was studied (Yue *et al.*, 2023). The frequency response curves of four directly connected double-layer PCB coils indicated that coils with return loops and a symmetrical structure can minimize the effect of magnetic field interference on the accuracy of the mutual inductance

coefficient measurements. Model optimization and simulation method was used to develop the Rogowski coil for energy metering and billing systems. The simulation model was designed using Proteus Isis 8.0, which served as the testing tool to evaluate the Rogowski coil response (Iloh and Odigbo, 2018). Proportional integral and derivative (PID) controller and an attenuation coefficient were used to improve the performance of Al-Alaoui integrator to change its DC response and get an ideal frequency response in Luo *et al.* (2014).
Regarding the application of control strategies, it was observed that few study interests have been reported in the literature. Hence, in this paper, the study by Rojas-Moreno *et al.* (2017) and Robles *et al.* (2018) where the Rogowski coil models were designed and evaluated without the use of an integrator are further examined. Thus, an attempt was made in this paper to apply integrator and PID controller to improve the frequency characteristics of the models.

3. SYSTEM MODEL

The proposed model for improving the performance and stability of Rogowski coil is shown in Figure 1. The model is a block diagram description of the Rogowski coil in which the electrical behaviour of the coil is improved by integrating a feedback PID compensator with an integrator circuit at the forward path. This enhances the sensitivity of the coil by increasing the magnitude of the output of the device.

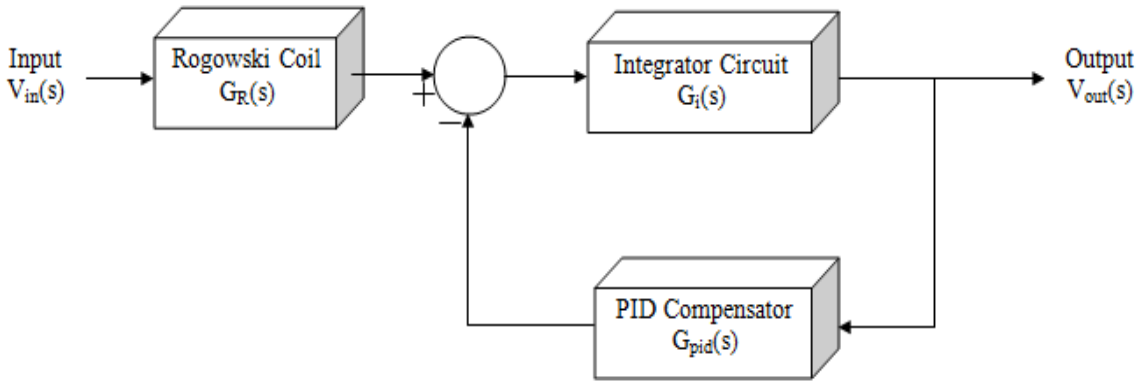
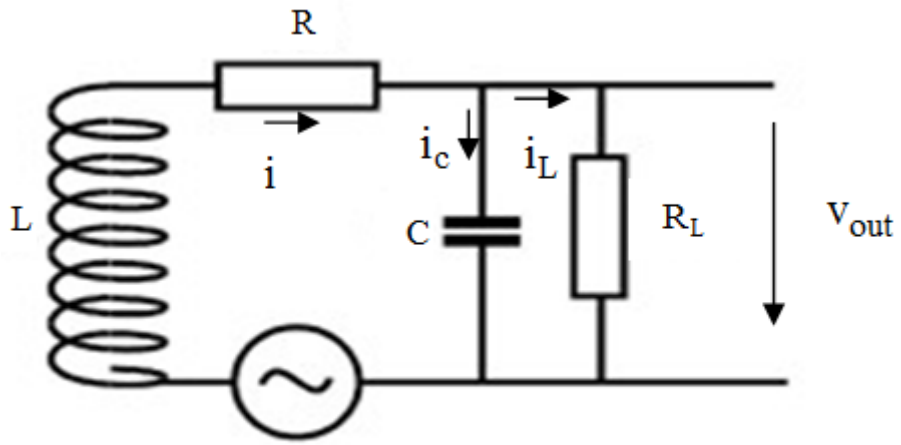


Figure 1. Block diagram of the proposed Rogowski coil model

As shown in Figure 1, the proposed structure consists of basically three essential components, which are represented in terms of their dynamic characteristics using transfer functions. Thus the subsequent subsections are devoted to developing the mathematical equations representing the various components that make up the system. In the block diagram, $G_R(s)$ is the transfer function of the Rogowski coil, $G_i(s)$ is the transfer function of the low pass filter integrator, $G_{pid}(s)$ is the PID compensator transfer function, $V_{in}(s)$ and $V_{out}(s)$ are the applied voltage and output (or measured) voltage of the system.

3.1 Mathematical Description of Rogowski Coil

The Rogowski coil can be modelled in terms of resistance R, self-inductance L, and capacitance C between the winding and the returning conductor that forms an RLC circuit as shown in Figure 2.



$$v_{in} = M\frac{di}{dt}$$

Figure 2. Equivalent RLC circuit of Rogowski coil

Generally, Rogowski coil is represented by RLC circuit components shown in Figure 2 which are the electrical parameters that determine the sensitivity and bandwidth of the coil (Robles *et al.*, 2018). The mutual inductance between the primary conductor and coil is represented by M.

In the circuit, a voltage source proportional to current variation in the measured conductor $V_{in} = M\,di/dt$ is applied, which makes it operate like resonant RLC circuit. Thus, a critical property of the Rogowski coil (circuit) is the ability to resonate at a given frequency called the resonance frequency, which is given by:

$$\omega_0 = 2\pi f_0 \tag{1}$$

where ω_0 is the resonant angular frequency in rad/s, and f_0 is the resonant frequency in hertz.

Looking at the circuit diagram shown in Figure 2, the current in the circuit i is determined in terms of Kirchhoff current law (KCL) and it is given by:

$$i = i_C + i_L = C\frac{dv_{out}}{dt} + \frac{v_{out}}{R_L} \tag{2}$$

Where i_C and i_L are the capacitive current and the load current respectively.

The voltage drop in the circuit is determined using the Kirchhoff voltage law (KVL) and it is given by:

$$v_{in} = L\frac{di}{dt} + Ri + v_{out} \tag{3}$$

Hence, substituting the values for the input voltage and the current in Equation (2) into Equation (3) gives:

$$v_{out} = M\frac{di}{dt} - LC\frac{d^2v_{out}}{dt^2} - \frac{L}{R_L}\frac{dv_{out}}{dt} - RC\frac{dv_{out}}{dt} - \frac{R}{R_L}v_{out} \tag{4}$$

Taking the Laplace transform of Equation (3.4) and assuming all initial condition to be zero, Equation (5) is realized given by:

$$V_{out}(s) = MsI(s) - LCs^2V_{out}(s) - \frac{L}{R_L}sV_{out}(s) - RCsV_{out}(s) - \frac{R}{R_L}V_{out}(s) \tag{5}$$

Rearranging Equation (5) gives:

$$\begin{aligned} &V_{out}(s) + LCs^2V_{out}(s) + \frac{L}{R_L}sV_{out}(s) + RCsV_{out}(s) - \frac{R}{R_L}V_{out}(s) = MsI(s) \\ &V_{out}(s)\left(1 + LCs^2 + \frac{L}{R_L}s + RCs + \frac{R}{R_L}\right) = MsI(s) \end{aligned} \tag{6}$$

The transfer function of the Rogowski coil can be defined by:

$$V_{out}(s) = \frac{MsI(s)}{LCs^2 + \frac{L}{R_L}s + RCs + \frac{R}{R_L} + 1} \quad (7)$$

But $G_R(s) = V_{out}(s)/I(s)$, thus Equation (7) can be expressed as shown:

$$G_R(s) = \frac{Ms}{LCs^2 + \frac{L}{R_L}s + RCs + \frac{R}{R_L} + 1} \quad (8)$$

Further simplification of Equation (8) gives:

$$G_R(s) = \frac{R_L Ms}{LR_L Cs^2 + (L + RR_L C)s + R + R_L} \quad (9)$$

From Equation (9), substituting the Rogowski parameters in Table 1 with respect to those of Rojas-Moreno *et al.* (2017) (tagged first model) and Robles *et al.* (2018) (tagged second model) gives Equations (10) and (11) respectively:

$$G_{R1}(s) = \frac{4.04e-05s}{6.165e-17s^2 + 8.745e-07s + 50.6} \quad (10)$$

$$G_{R2}(s) = \frac{9.51e-05s}{3.42e-16s^2 + 1.2e-06s + 10.1} \quad (11)$$

If the expression $1/(R + R_L)$ is used to multiply Equation (9), the following expression is obtained:

$$G_R(s) = \frac{Ms\left(\frac{R_L}{R + R_L}\right)}{\left(\frac{R_L LC}{R + R_L}\right)s^2 + \left(\frac{L}{R + R_L} + \frac{RR_L C}{R + R_L}\right)s + \left(\frac{R + R_L}{R + R_L}\right)} \quad (12)$$

Simplifying Equation (12) gives:

$$G_R(s) = \frac{Ms\left(\frac{R_L}{R + R_L}\right)}{\left(\frac{1}{\omega_n}\right)s^2 + \left(\frac{L + RR_L C}{R + R_L}\right)s + 1} \quad (13)$$

where ω_n is the natural frequency of the Rogowski coil and is given by:

$$\omega_n = \sqrt{\frac{R + R_L}{R_L LC}} \quad (14)$$

The next subsection will present the integrator circuit.

3.2 Mathematical Description of Integrator Circuit

The circuit diagram of a simple low pass filter, which is an RC circuit that acts as an integrator is shown in Figure 3.

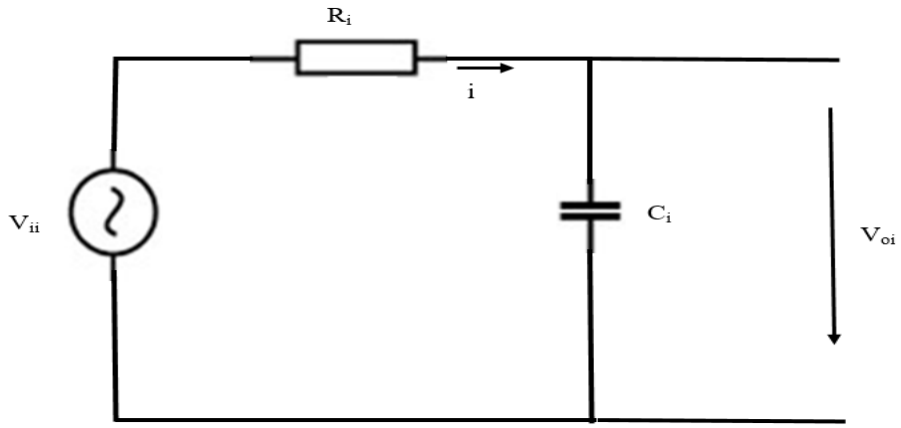


Figure 3. Circuit of simple RC passive integrator

The sum of the voltage drop and the current in the circuit are given by:

$$v_{oi} = v_{ii} - R_i i \tag{15}$$

$$i = C_i \frac{dv_{oi}}{dt} \tag{16}$$

Thus, substituting Equation (16) into Equation (15) gives:

$$v_{oi} = v_{ii} - R_i C_i \frac{dv_{oi}}{dt} \tag{17}$$

Taking the Laplace transform of Equation (17) and assuming zero initial condition gives:

$$V_{oi}(s) = V_{ii}(s) - R_i C_i s V_{oi}(s)$$

or

$$V_{oi}(s)\left(1 + R_i C_i s\right) = V_{ii}(s) \tag{18}$$

But $G_i(s) = V_{oi}(s)/V_{ii}(s)$, therefore the transfer function of the integrator is given by:

$$G_i(s) = \frac{1}{\left(1 + R_i C_i s\right)} \tag{19}$$

Substituting the integrator parameters in Table 2 gives:

$$G_i(s) = \frac{1}{0.9918s + 1} \tag{20}$$

The time constant of the circuit is given by:

$$\tau = R_i C_i \tag{21}$$

The overall transfer function for the Rogowski coil with the integrator is given by:

$$G_{Ri}(s) = G_R(s) \times G_i(s) \tag{22}$$

Substituting Equation (9) and Equation (19) in to Equation (22) results in:

$$G_{Ri}(s) = \left(\frac{R_L M s}{LR_L C s^2 + (L + RR_L C)s + R + R_L} \right) \times \frac{1}{\left(1 + R_i C_i s\right)} \tag{23}$$

The equivalent transfer function models for Rogowski coil plus integrator with respect to Equation (23) are given by:

$$G_{R1}(s) \times G_i(s) = T(s) = \frac{4.04e-06s}{6.115e-17s^3 + 8.674e-07s^2 + 50.19s + 50.6} \tag{24}$$

$$G_{R2}(s) \times G_i(s) = L(s) = \frac{9.51e-05s}{3.392e-16s^3 + 1.19e-06s^2 + 10.02s + 10.1} \tag{25}$$

Equations (24) and (25) are the Rogowski coil with integrator corresponding to first model and second model.

Having determined the mathematical expression for integrator, the next section will consider the design of PID controller.

3.3 Design of PID Compensator

The block diagram of PID compensator is shown in Figure 4.

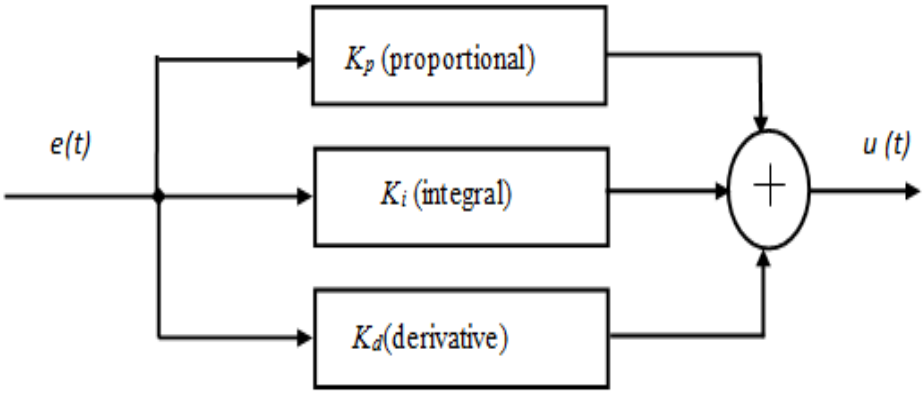


Figure 4 Block diagram of PID compensator

The PID control action is defined according this conventional formula:

$$u(t) = K_p \left[e(t) + \frac{1}{T_i} \int e(t)dt + T_d \frac{de(t)}{dt} \right] \quad (26)$$

where,

K_p is the proportional gain,

$e(t) = r(t) - y(t)$ is the error signal (as in Figure 4),

T_i and T_d are the integral time constant and derivative time constant respectively,

r(t) is the reference input, and

y(t) is the actual output.

A transfer function in s-domain can be derived for Equation (26) by applying Laplace transform and assuming zero initial conditions as follows:

$$G_{pid}(s) = \frac{U(s)}{E(s)} = K_p \left[+ \frac{1}{T_i s} + T_d s \right] \quad (27)$$

where $U(s)/E(s)$ is the ratio of the control action to the error input and represents the PID compensator $G_{pid}(s)$. The integral gain, K_i and derivative gain, K_d can be defined by:

$$K_i = \frac{K_p}{T_i} \quad (28)$$

$$K_d = K_p T_d \quad (29)$$

The PID controller in Laplace transform is defined by:

$$G_{pid}(s) = K_p + \frac{K_i}{s} + K_d s \quad (30)$$

The resulting PID parameters are K_p = 1.92, K_i = 2.51, K_d = 0.14, T_f = 0.282. The designed PID has a low pass filter added to the derivative component. Hence, substituting the values of the designed PID controller into Equation (30) gives:

$$G_{pid}(s) = 1.92 + \frac{2.51}{s} + \frac{0.14s}{0.282s + 1} \quad (31)$$

The Simulink models of the systems are shown in Figures 6 and 7 for the two Rogowski coil with integrator and PID controller.

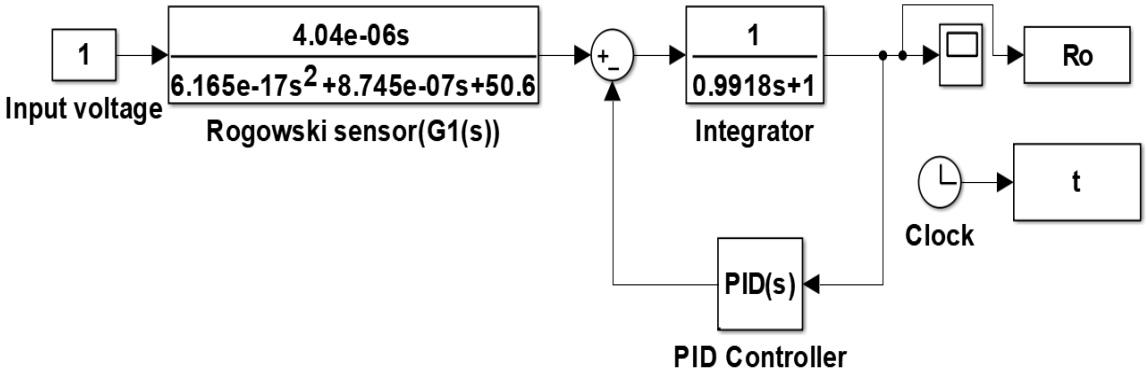


Figure 6 Simulink model of Rogowski coil with PID controller (first model)

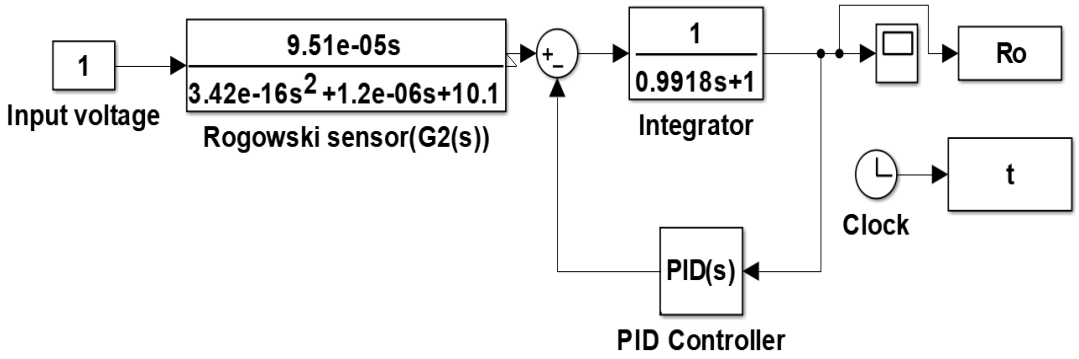


Figure 7 Simulink model of Rogowski coil with PID controller (second model)

3.4 Simulation Parameters

Simulations were carried out using the parameters of Rogowski coils presented in Rojas-Moreno *et al*. (2017) and Robles *et al*. (2018) respectively. This is to improve the transient and steady-state performance of the coils. The simulations were also used to validate the robustness and effectiveness of the proposed method. The simulation parameters are shown in Tables 1 and 2 for the electrical quantities of the Rogowski coils and the passive integrator.

Table 1: Electrical parameters of Rogowski coils

Definition	**Symbol**	**Rojas-Moreno *et al.* (2017)**	**Robles *et al.* (2018)**
Mutual inductance	M	80.8 nH	9.51 µH
Inductance	L	874.5 nH	1.2 µH
Capacitance	C	1.41 pF	5.7 pF
Resistance	R	0.6 Ω	0.1 Ω
Terminal impedance or resistance of coil	R_L	50 Ω	10 Ω

Table 2: Electrical parameters of integrator

Definition	**Symbol**	**Value**
Capacitance	C_i	8.7 µF
Resistance	R_i	114×10^3 Ω

4. RESULTS

4.1. Rogowski Coil Performance Analyses in Frequency Domain

In Figures 8 and 9, the responses of the Rogowski coils to unit input voltage are evaluated in terms of magnitude and phase against frequency and this is called Bode plot.

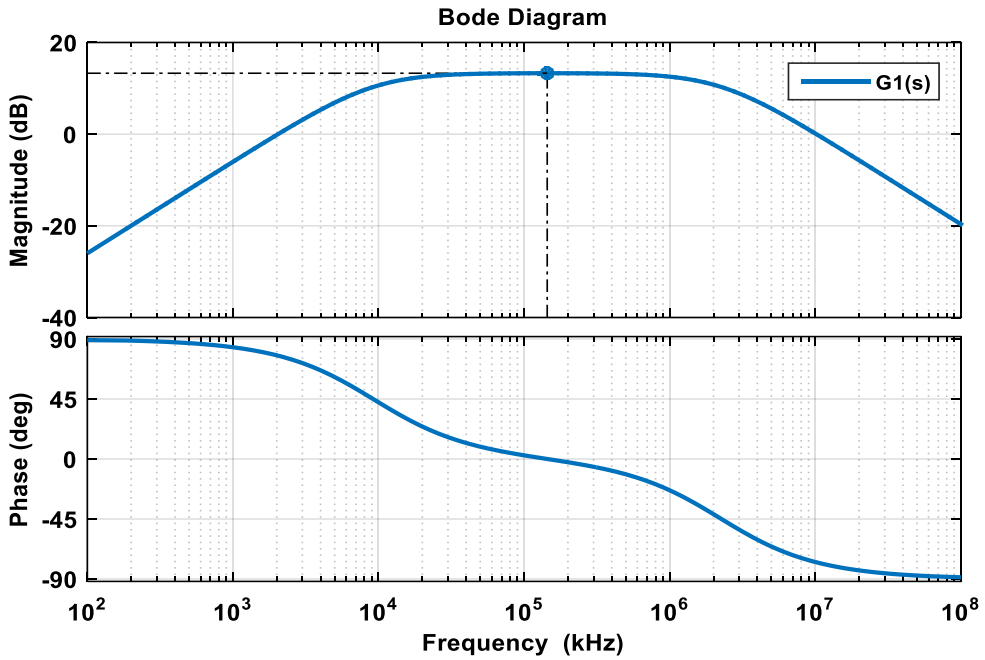


Figure 8 Frequency response of Rogowski coil (first model)

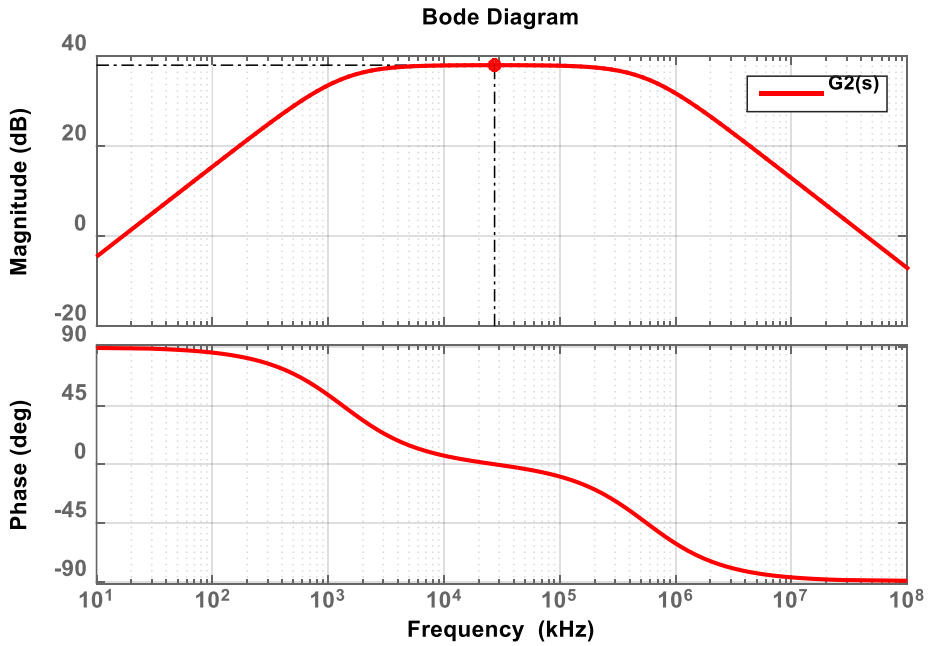


Figure 9 Frequency response of Rogowski coil (second model)

The simulation plots in Figures 8 and 9, are the bode diagrams of the transfer functions in Equations (10) and (31) that include generic terminating impedances of 50 Ω and 10 Ω in parallel with capacitance 1.41 pF and 5.7 pF respectively. Now, considering Figure 8, it can be seen that there is a band of frequencies between 100 MHz (10^5 kHz) and 1000 MHz (10^6 kHz) where the input and output are in phase such that the output is proportional to the input. Hence, the resulting frequency corresponding to this point is 144 MHz and the gain

of the coil is 13.3 dB. In the case of Figure 9, there is a band of frequencies between 10 MHz and 100 MHz at which the coil has a gain of 38 dB and the corresponding frequency is 27.4 MHz. In Figures 8 and 9, the phase responses of the Rogowski coils were 103^o and 90.7^o respectively.

4.2 The Rogowski Coils Performance with Integrator in Frequency Domain

Figures 10 and 11 show the responses of the Rogowski coils with integrator in terms of magnitude and phase against frequency when unit input voltage is applied.

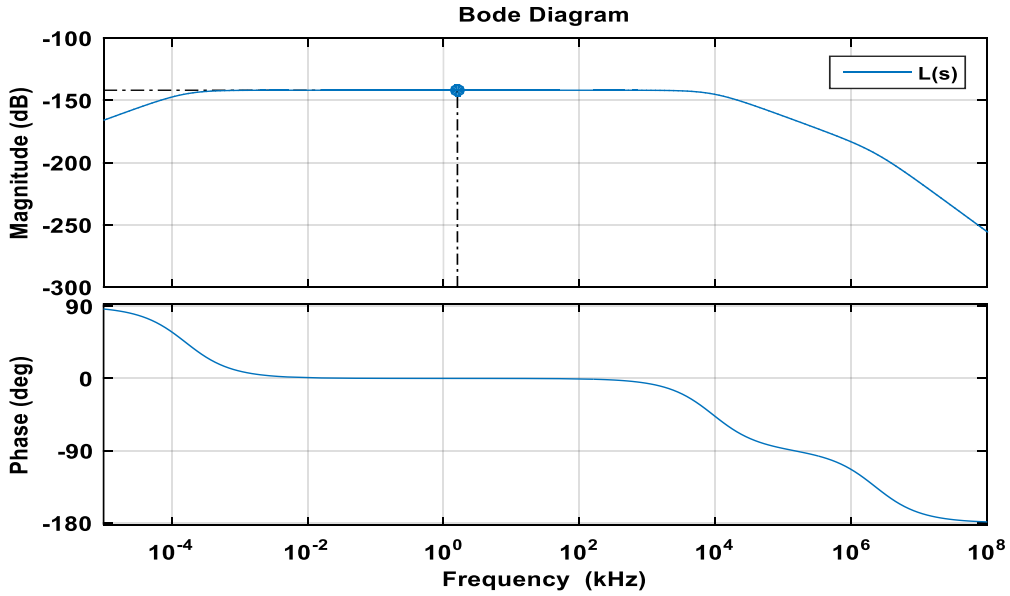


Figure 10. Frequency response of Rogowski coil with integrator (with respect to second model)

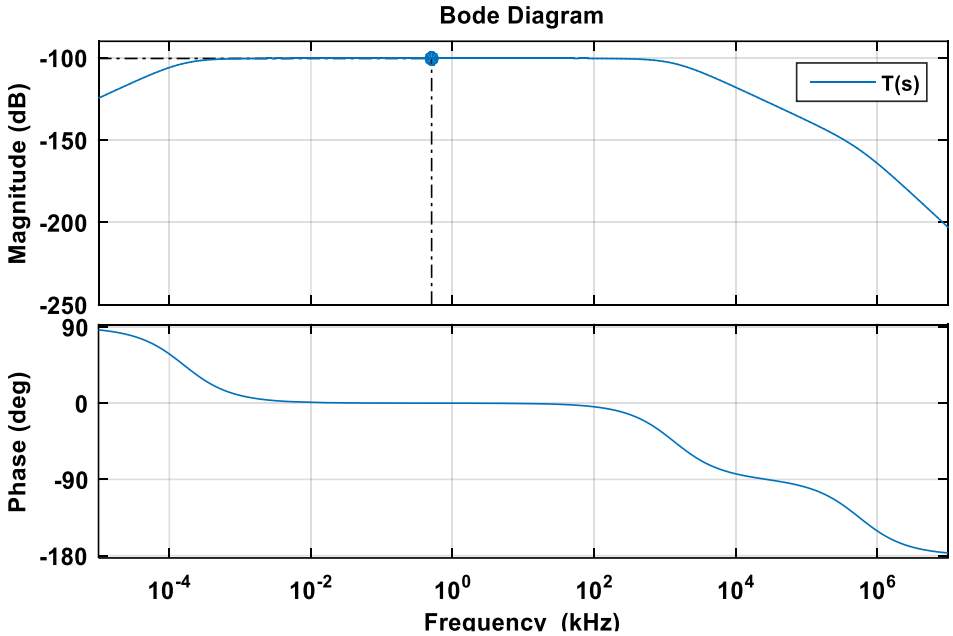


Figure 11 Frequency response of Rogowski coil with integrator (with respect to second model)

The response of the transfer function of the Rogowski coil model with integrator given by Equation (24) is tagged L(s) for the simulation result shown in Figure 10, while the response of the transfer function model in Equation (25) is tagged T(s) as shown in Figure 11. With respect to L(s), the addition of integrator causes the gain of the coil to be -142 dB at a frequency of 1.6 kHz (1600 Hz) and with a phase response of zero. In the case of Figure 11, the Bode plot revealed that the gain is -100 dB at a frequency of 0.507 kHz (507 Hz) and

the phase margin zero. It can be seen that the addition of the integrator with the Rogowski coil resulted in possibility of measuring a frequency from the range 0.1 Hz or 10^{-4} kHz (lower limit) to 10 10^{4} kHz or 10 MHz (upper limit). Thus, it is possible to measure fast switching transients (of frequency up to 10 MHz) while the capacity to accurately measure currents of 50/60 Hz is maintained.

4.3 Rogowski Coil Performances with Integrator and PID in Frequency Domain

In this subsection, the Rogowski coils are evaluated considering the addition of integrator and PID compensator. Figures 12 and 13 are the bode plots of each configuration with respect to the Simulink models in Figures 6 and 7 respectively. The simulations were conducted for the individual Rogowski coils considered in this work.

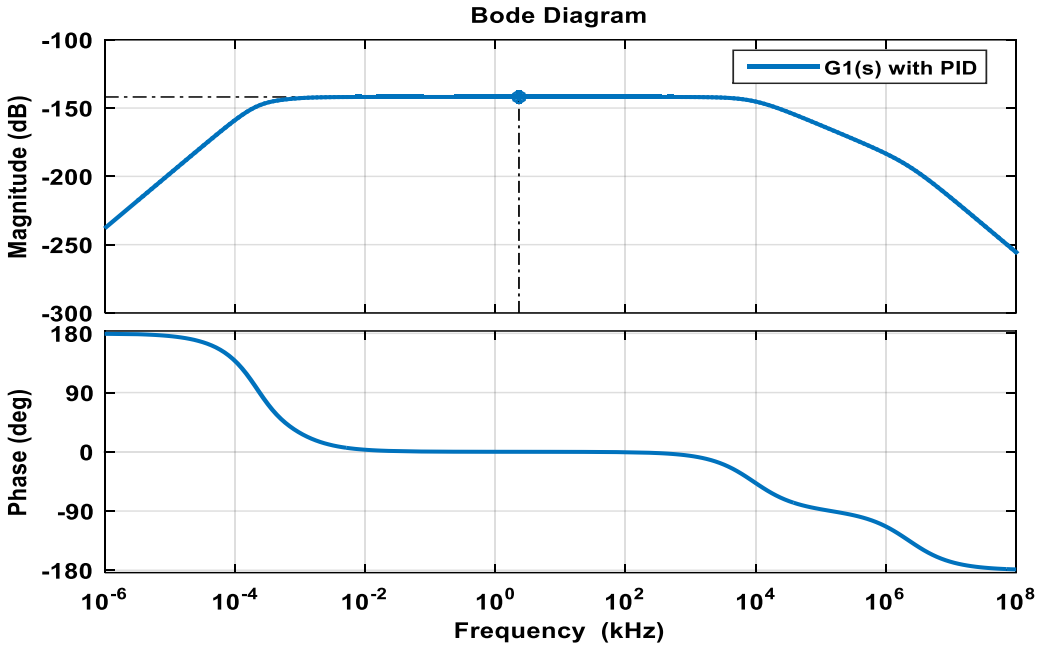


Figure 12 Frequency response of Rogowski coil with integrator and PID (first model)

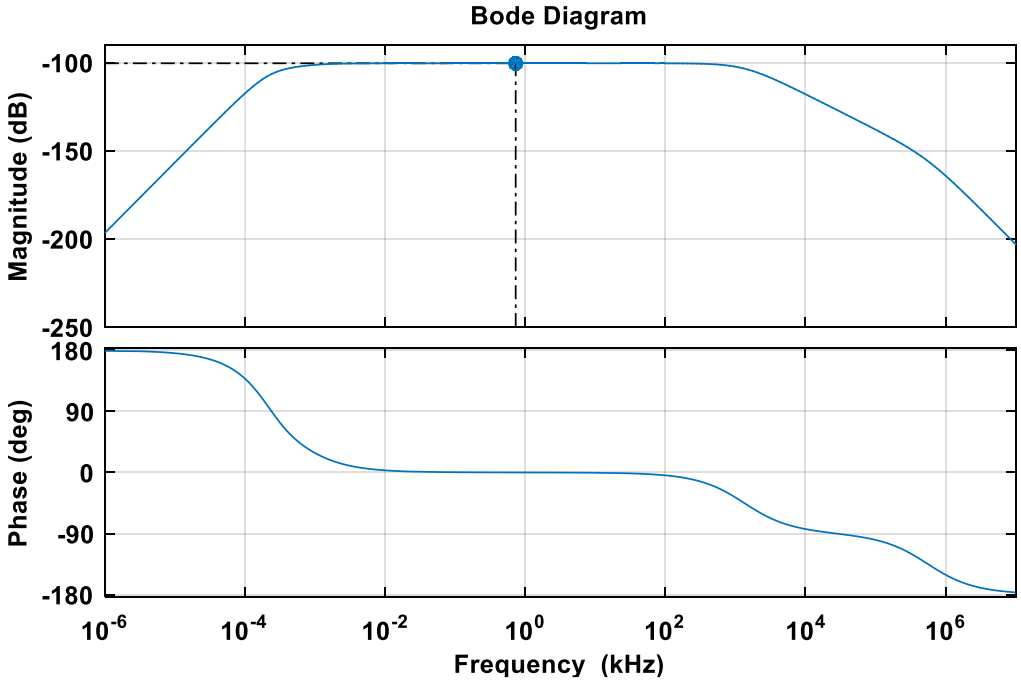


Figure 13 Frequency response of Rogowski coil with integrator and PID (second model)

The Bode plots shown in Figures 12 and 13 are those of the individual Rogowski coils with the addition of integrator and PID compensator. In the case of Figure 12, the Rogowski coil yielded output response of gain -142 dB at frequency of 2310 Hz (2.31 kHz) with zero phase margin (or error). For Figure 13, the Rogowski coil output response revealed a gain of -100 dB at frequency of 731 Hz (or 0.731 kHz) with zero phase margin. Looking at both figures, it can be seen that the introduction of the PID further improved the performance of the Rogowski coils in frequency domain such that with this system, it is possible to measure and detect current for fast switching transient and at the same time, retain the capacity to accurately measure currents of 50/60 Hz considering the fact that the lower limit of the frequency band is 0.1 Hz.

5. CONCLUSION

The performance behaviour of the individual Rogowski coil models considered in this paper has been evaluated in frequency domain using Bode analysis for three scenarios based on the configuration of the systems. In the first analysis, the Rogowski coils were evaluated in their conventional state and the frequency domain analysis revealed that the first model had a gain of 13.3 dB at frequency of 144 MHz and the second model had a gain of 38 dB at frequency of 27.4 MHz. Their phase margins (errors) were 103^{o} and 90.7^{o} respectively. The Rogowski coils band of frequencies from lower and upper limits were in the tens of MHz. An integrator was added to the Rogowski coils and the simulation results indicated that the frequencies of the coils were enhanced such that frequency of 50/60 Hz can be measured or detected together with frequencies in tens of MHz (up to 7 decades and more). PID compensator was designed and integrated with the individual Rogowski coils with integrator. The results revealed that the frequency limits of the coils were further improved such that lower limit of the frequency band was 0.1 Hz and this makes the coil more sensitive in measuring current even at very low frequency. Generally, two Rogowski coil models were simulated with the developed PID compensator and the results obtained revealed that the PID compensator provided similar results. Hence, by this, the PID provides improved robust and adaptive performance in the presence of varying parameters. This justifies the significance of using the two Rogowski coil models in this paper.

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