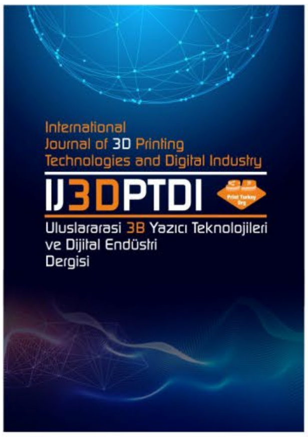

ULUSLARARASI 3B YAZICI TEKNOLOJİLERİ
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INTERNATIONAL JOURNAL OF 3D PRINTING
TECHNOLOGIES AND DIGITAL INDUSTRY

ISSN:2602-3350 (Online)

URL: https://dergipark.org.tr/ij3dptdi

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Bu makaleye şu şekilde atıfta bulunabilirsiniz (To cite to this article): *Aydın G. M., Yıldırız G., Yıldırız E., "Investigation to the V-I Characteristics of Rogowski Coils with Magnetic Filaments by Regression Analysis" Int. J. of 3D Printing Tech. Dig. Ind., 9(1): 122-128, (2025).*

DOI: 10.46519/ij3dptdi.1654785

Araştırma Makale/ Research Article

Erişim Linki: (To link to this article): https://dergipark.org.tr/en/pub/ij3dptdi/archive

INVESTIGATION TO THE V-I CHARACTERISTICS OF ROGOWSKI COILS WITH MAGNETIC FILAMENTS BY REGRESSION ANALYSIS

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(**Received:** 10.03.25; **Revised:** 08.04.25; **Accepted:** 11.04.25)

ABSTRACT

The efficiency and magnetic saturation performances of the 3D printed magnetic composite cores are currently a bit far from competing with silicon steel in traditional motor topologies and transformer applications. However, the flexibility provided in 3D design and the rapid advancement in the production technologies are rapidly reducing the gap between these performances. Linear V-I characteristics can be obtained in the 3D printing magnetic cores using the filaments produced by mixing magnetic powders such as Iron, Nickel, Cobalt with polymer in different ratios. This makes them suitable for the Rogowski Coil (RC) applications. RCs are required to have linear V-I characteristics in order to measure low and high currents with the same sensitivity in the defined current measurement range. In this paper, nickel-filled filaments produced by mixing nickel and polymer in different ratios were used for the production of flexible RC cores. The V-I characteristics of RCs produced using 40% and 60% nickel-filled filaments and air-core RC have been modeled using the linear regression analysis. The success of the mathematical models has also been tested with four different error analyses. The proven mathematical models of the RCs will provide new inspiration to the researchers for magnetic applications. Optimal RC designs can be investigated using the mathematical models in the Finite Element Analysis (FEA) package programs.

Keywords: Nickel-Filled Filament, Flexible Magnetic Core, Rogowski Coil.

1. INTRODUCTION

In many electric motors and transformers used today, since magnetic fluxes move in two axes, oriented or non-oriented silicon steels are used as core material. In addition, soft magnetic composite (SMC) cores are also used in complex geometry or innovative electrical machine designs due to their 3D magnetic flux paths [1-3]. The eddy current losses of the SMC cores are lower than the cores formed by packing silicon steels due to particulate structure of SMCs. The stator or rotor core of any motor can be obtained after the silicon steels is cut with a mold or laser, aligned appropriately, pressed, riveted, welded, etc. On the other hand, an SMC core produced by additive manufacturing can be produced in a single process. On the other hand, an SMC core produced by additive manufacturing can be produced in a single process. In addition, the use of SMC provides designers with flexibility for the development of new core models. Iron-cobalt (FeCo), iron-nickel (FeNi) and iron-silicon (FeSi) alloys are generally used in SMCs produced by additive manufacturing [4]. The costs and production methods of electromagnetic materials produced by additive manufacturing used in the electrical machines are explained comparatively in [5].

The magnetic saturation points of 3D printed SMC cores are lower than silicon steels. Experimental results of two 10W axial flux PM machines produced from grain-oriented (GO) steel and 3D printed SMC cores are compared in [6]. Accordingly, the SMC core model produced less torque at the same electrical loading, and also hysteresis losses should be taken into account. According to the experimental results presented in [7], the efficiency of the laser additively manufactured core induction motor is 2/3 of the efficiency of the reference conventional induction motor. The thermal dissipation performance of SMC is also lower than that of the laminated electrical steels [8]. These results show that 3D printed SMCs are not yet ready for use in the conventional motor and transformer applications, but rapid progress is being made.

The transformer cores were printed with Rustable Magnetic Iron filament consisting of a polymer matrix and a particulate phase of 40 wt% iron in [9]. Transformer cores were produced with 3D printing in different patterns and filling ratios and all of them have a linear V-I characteristic. According to these results, the magnetic filaments are useful for the RC applications where linear magnetic characteristics are required.

RCs are long-known current measuring devices that do not use high permeability magnetic cores, unlike current transformers. Their areas of use have become widespread with advanced signal processing techniques in recent years [10]. The secondary windings are wound on a hollow silicone rubber case in traditional RCs [11]. Since conventional RCs do not have saturation problems, they can measure both nominal current and currents well above nominal current with the same accuracy. Unlike current transformers, they have a linear V-I characteristic with their air-core structure [12]. They are low cost. They can operate in wide bands from a few Hz to a few MHz. Therefore, they are frequently used in the measurement of high currents and transient pulses [13-16].

Like traditional RCs, Printed Circuit Board (PCB) RCs are also air-core. PCB RCs are used not only for high currents [17] but also for monitoring switching states [18]. The secondary output signals are small in the measurement of small currents, since the magnetic permeability in air-core RCs is very low. In order to process low amplitude signals, their amplitudes need to be increased [19]. For this, the RC output signal can be connected to an active integrator circuit [20]. The integrator circuit can be an inverting or non-inverting integrator [21]. Apart for these, the hybrid integrator can be also used to reduce the measurement noises [22]. However, since error signals can also be amplified at the outputs of the amplifiers, it is important for measurement accuracy that the main signal is high. In order to eliminate this drawback, the use of three different superparamagnetic magnetite cores has been proposed in [23]. The use of magnetic powders and production technologies affect production costs to a certain extent. However, progress in the additive manufacturing technology is exciting and costs are expected to decrease as application areas become more widespread. Three different rigid RCs have been obtained by placing 50-100 nm Fe_3O_4 commercial magnetite powder, 5 μm Fe_3O_4 commercial magnetite powder and synthetic magnetite (Fe_3O_4) in the inner cavity of the RC case produced from polymer with a 3D printer. The researchers concluded that synthetic magnetite Nano powder is the best solution because it maintains its linearity up to high current values. However, the lack of flexibility of the RCs tested in this paper was ignored. A flexible RC has been developed by developing a composite magnetic core with manganese-zinc ferrite + permalloy + silicone rubber in [24]. However, no information was presented about the V-I characteristics of the flexible core RC.

In this paper, the V-I characteristics of flexible core RCs produced by directly use of nickel-filled filaments have been investigated. Taking into account measurement errors, the regression analysis has been performed for each produced RCs, and the mathematical models of the RCs have been derived. The error analyses and comparative results of the mathematical models based on linear regression have been shared.

2. PRODUCTION OF THE MAGNETIC CORE RCs

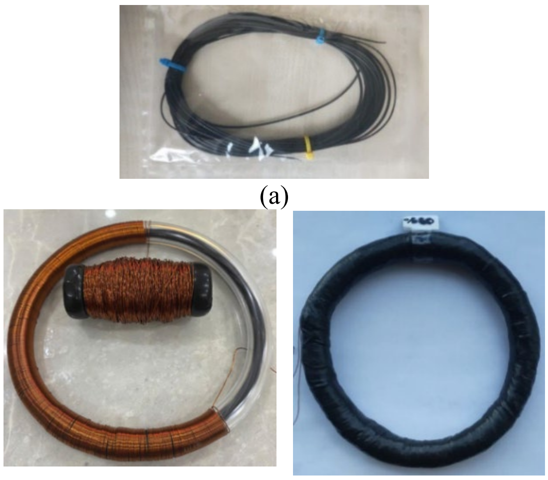
A combination of Polylactic Acid (PLA) or polymer derivatives with ferromagnetic powders can be used to produce flexible magnetic cores. For example, the filaments produced using PLA+Iron are often encountered in applications such as magnetic and biomedical devices [25]. In this paper, magnetic core RCs with flexibility like traditional RCs have been used. The magnetic properties of the filaments produced by adding iron, nickel or cobalt to the polymer can be increased. According to [26], the average particle size of the magnetic nanoparticles affects the magnetic properties of the filaments. In this paper, the magnetic filaments obtained using polymer with different alloy ratios and nickel filler with particle sizes up to 44 µm have been used to obtain the flexible magnetic cores. A single screw extrusion machine with a 2 mm nozzle has been used to product of nickel alloy filaments. Extra care should be taken to ensure homogeneous production in the extrusion process of filaments with metal particles. Thus, a uniform magnetic flux density can be achieved in the magnetic filament. In addition, the use of metal particles with high thermal conductivity may cause uneven cooling of the filament coming out of the nozzle [27]. So, a homogeneous filament production is important for thermal and magnetic performance.

For this reason, the filament production temperature has been kept in the range of 210-220 °C. Magnetic filaments with a diameter of 1.75 mm have been obtained with constant tension at the nozzle exit. Before the production, a drying process was carried out at 80 °C for 6 hours to remove moisture from both the nickel fillings and the polymer material. A part of the produced nickel alloy filament is seen in Figure 1a. These filaments have been placed inside 1.2 mm thick the plastic sheath of the RC without any further processing. Then, a secondary winding of 825 turns has been formed on the flexible magnetic RC core using 0.4 mm diameter H type enameled copper wire (Figure 1b). After the aluminum shielding has been applied on the windings, an insulating strip has been drawn for physical protection. The final RCs obtained are shown in Figure 1c. The outer diameter of the developed RCs is 140 mm and the inner diameter is around 114 mm.

Using the magnetic filaments produced with 40% and 60% nickel filling, two flexible core RCs and one air-core RC with the same physical properties have been produced. Thus, the effect of nickel filler ratio on the secondary voltage produced by flexible core RCs and error analysis could be comparatively investigated.

3. TEST METHODS OF THE MATHEMATICAL MODELS

Regression analysis is used to present a meaningful mathematical model between the inputs and the output of a system. When a system can be expressed mathematically, the resulting equation is also an estimation equation for intermediate and extreme values that cannot be measured experimentally. The analysis begins by examining the positioning of the numerical data on the analytical plane. This positioning gives an idea of the type of curve to be fitted. Linear regression, polynomial regression, exponential regression, etc. can be preferred depending on the distribution of experimental data. The V-I change of the experimental data of the RCs is expected to be linear [28-30]. Linear data distributions can also be defined with Sum of Sines, Fourier, and Gaussian. However, the mathematical equation to be obtained will be complex, and the equation performance will decrease since it will contain high-order components. Therefore, linear regression has been preferred in this paper. Linear regression analysis is shown in Eq. (1). Here, a represents the fixed effect of linear regression, b represents the effect depending on the variable, and they are calculated by Eq. (2) and Eq. (3), respectively.



(a) (b) (c)

Figure 1. The manufacturing processes of the flexible magnetic core RC: (a) Nickel alloy filament manufacturing, (b) Secondary winding of RC, (c) Final view of RC (%60 nickel filling)

$$y_t = a + bx_t \quad (1)$$

$$b = \frac{\sum_{t=1}^{n}(x_t-\bar{x})(y_t-\bar{y})}{\sum_{t=1}^{n}(x_t-\bar{x})^2} \quad (2)$$

$$a = \bar{y} - b\bar{x} \quad (3)$$

Error tests such as R^2 (Coefficient of Determination), Adj. R^2 (Adjusted Coefficient of Determination), RMSE (Root Mean Square Error) and MAPE (Mean Absolute Percentage Error Value) are used to test the accuracy of the regression analysis.

3.1. R^2 Test

The R^2 test measures the difference between the available data and the average of the data produced from the mathematical model. The coefficient of determination is a value between zero and one and essentially measures the proximity to one. The closer the result is to 1, the higher the success of the study is considered. Equality (4) defines the R^2 test. Here, n represents the number of samples, y_i represents the measurement data, and $\bar{y}_i$ represents the mathematical model outputs.

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(y_i - \bar{y}_i)^2}{\sum_{i=1}^{t} y_i^2 - \frac{\left(\sum_{i=1}^{n} y_i\right)^2}{n}} \tag{4}$$

3.2. Adj. R^2 Test

The increase in the number of data to be tested causes a natural increase in the R^2 value. As the number of data in the system increases, even if the difference between the measurement data and the mathematical model outputs increases, there is no significant decrease in R^2. In most cases, each variable added to the system will cause the value of R^2 to increase and approach to one. For this reason, in order to test the accuracy of the analyses with a large amount of data, the Adj. R^2 test, which supports the accuracy of the test, is also applied together with R^2 (5). Here, k represents the number of predictors.

$$Adj.R^2 = 1 - \frac{\sum_{i=1}^{n}(y_i - \bar{y}_i)^2}{\sum_{i=1}^{t} y_i^2 - \frac{\left(\sum_{i=1}^{n} y_i\right)^2}{n}} \; \frac{n-1}{n-k-1} \tag{5}$$

3.3. RMSE

RMSE is one of the error tests that measure the similarity between the measurement data and the mathematical model outputs in a system that is desired to be verified. When applying the RMSE error test, the standard deviation between the data is taken into account. RMSE focuses on the distribution in error values (6). The approach of the RMSE value to zero indicates the closeness between the measurement results and the mathematical model outputs. The closer the result is to zero, the more successful the test result is.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(y_i - \bar{y}_i)^2}{n}} \tag{6}$$

3.4. MAPE

MAPE is a test that calculates the percentage error in proportion. When applying the test, if there is a "zero" value among the measurement data, this data is not taken into account, as it will make the calculation undefined. If the MAPE error test result is below 10%, it indicates that the accuracy of the study is high. The smaller the MAPE error value, the higher the accuracy of the study. The MAPE calculation equation is given in Eq. (7).

$$MAPE = \left(\frac{100}{n} \sum_{i=1}^{n} \left|\frac{y_i - \bar{y}_i}{y_i}\right|\right) \tag{7}$$

4. EXPERIMENTAL FINDINGS AND REGRESSION ANALYSIS OF THE RCs

Epstein frame or single sheet test method is used to determine B-H curves of magnetic materials such as laminated steel [31]. However, these methods are not suitable for magnetic cores that can carry 3D flux. In this paper, toroid method [32] is considered to determine magnetic properties of flexible core RCs. The test setup created is shown in Figure 2. The current passing through the primary, a regulated AC power supply and a 50/1 ratio transformer have been used to change the primary current in the range of 5-400 A. The tests have been repeated separately for each RC developed.

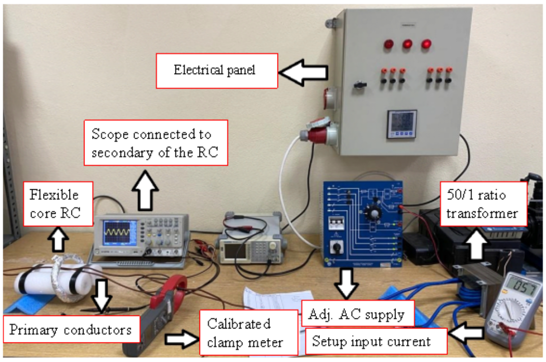
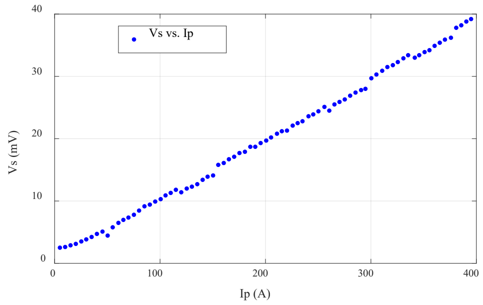
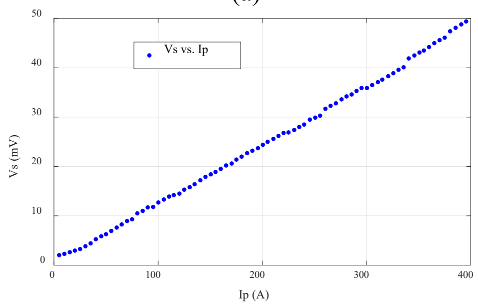


Figure 2. Test bench of the developed RCs [33].

According to the test results, the secondary voltages of air-core, 40% nickel-filled and 60% nickel-filled flexible magnetic core RCs increase linearly depending on the primary current, as seen in Figure 3. However, due to possible measurement errors due to the wide measurement ranges inherent in experimental studies, the graphs do not form a complete line. For this reason, linear regression has been used to find the mathematical model to be created with the measurement results. According to the regression analyses, the mathematical models obtained for the primary current versus secondary voltage (V_S-I_P) characteristics of the flexible core RCs produced using conventional air-core RC, 40% and 60% nickel-filled filaments are given in equations (8) to (10), respectively.



(a)



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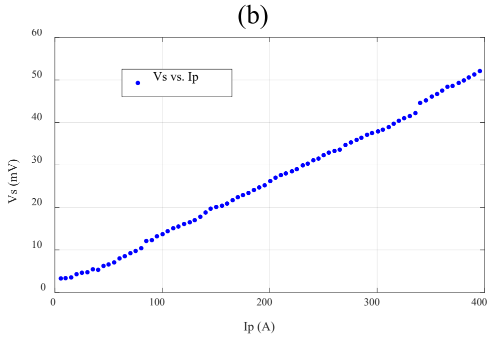


(c)

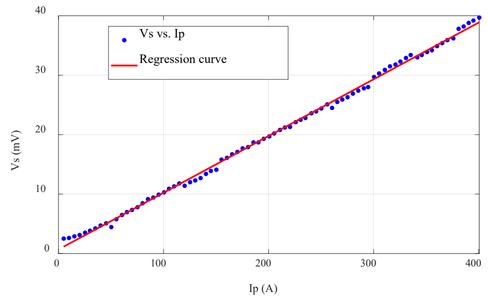
Figure 3. Secondary voltages of the developed RCs measured in the range of 5-400A: (a) Air-core, (b) 40% nickel-filled, (c) 60% nickel-filled.

$$V_{air-core} = 0,6863 + 0,09542 * I \quad (8)$$

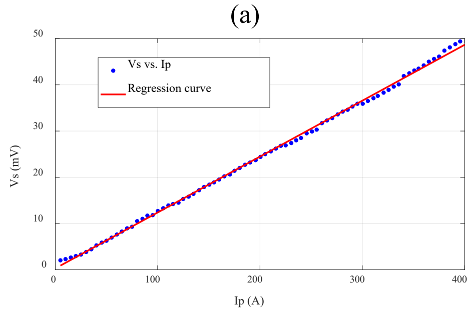
$$V_{\%40\_Ni} = 0,2752 + 0,121 * I \quad (9)$$

$$V_{\%60\_Ni} = 0,7674 + 0,1268 * I \quad (10)$$

The closeness of the mathematical models expressing the characteristics of the developed RCs (V_S-I_P) to the experimental results is shown in Figure 4. At high primary currents, the difference between the results of the mathematical model produced and the experimental results seems relatively greater. On the other hand, at low primary currents, the mathematical model and the measurement results are quite close. For the success of the mathematical models, the test methods examined in Section 2 were used and the results are presented in Table 1. A comparison of experimental results with air core, 40% nickel-filled and 60% nickel-filled RCs is given in Table 1. In the table, R^2 converges to one for all RCs. This shows that the experimental results and the mathematical model results are quite close to each other. The closeness of the R^2 value to one indicates that the mathematical model has high performance.



(a)



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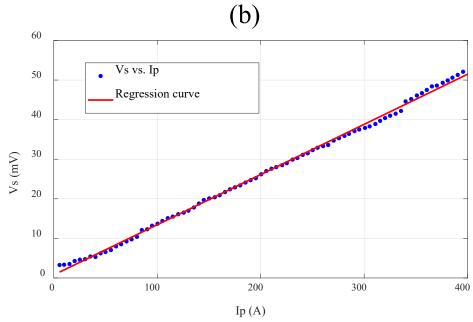

(c)

Figure 4. Experimental results and generated mathematical models: (a) Air-core, (b) 40% nickel-filled, (c) 60% nickel-filled.

Table 1. Comparison of the error tests

	Air-core RC	%40 Nickel-filled RC	%60 Nickel-filled RC
R^2	0.997916	0.998656	0.997929
Adj. R^2	0.997862	0.998621	0.997875
RMSE	0.504114	0.5130061	0.667632
MAPE(%)	3.913323	2.840462	3.97555

5. CONCLUSIONS

The V-I characteristics of the air-core RC and the flexible core RCs developed using nickel-filled filaments have been subjected to the regression analysis in this paper. Four different tests have been applied to the mathematical models of the RCs obtained by linear regression analysis, and high accuracy has been observed in all of them. Thus, for intermediate and extreme values that could not be realized experimentally, the secondary voltages of the examined RCs can be calculated using the mathematical models obtained by linear regression analysis. With a realistic mathematical model, it is possible to investigate new RC designs and optimal PLA+magnetic powder composite in the future studies. Using the mathematical models in numerical analyses such as FEA enables novel research topics such as magnetic performance and shielding design of the flexible RCs to be developed.

The slope of the mathematical model of the 40% nickel-filled flexible magnetic core RC is 26.80% higher than the slope of the linear model of the air-core RC. This ratio increased to 32.89% in the RC produced with 60% nickel-filled filament. It is seen that as the nickel filling ratio of the produced filaments increases, they contribute positively to the V-I characteristics without compromising the linearity properties in the flexible magnetic core RCs they are used in.

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