Optimizing Conductor Position for Minimizing Magnetic Field Crosstalk Errors in Circular Sensor Arrays

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Abstract - Abstract - *Current measurement is integral to power system monitoring and control, essential for activities like load balancing and fault detection. Magnetic field sensors are the preferred methods, offering precision, isolation, and minimal circuit interference. Circular sensor arrays are commonly used for their ability to detect current-related magnetic field changes. This research delves into conductor placements and crosstalk effects on current measurement accuracy in circular sensor arrays. It explores scenarios like concentric and off-center positioning, as well as how neighboring conductors influence array performance. Using numerical simulations and analytical modeling, this research thoroughly analyzes how circular sensor arrays respond to various conductor positions and crosstalk magnetic field conditions. This study shows that the accuracy of current measurement is highly affected by the conductor position relative to the sensor array and the influence of neighboring conductors generating crosstalk magnetic fields. Misalignment, lateral shifts, and crosstalk introduce errors, impacting sensitivity and accuracy. This research offers crucial insights for improving the design and optimization of circular sensor arrays for precise current measurement, considering conductor positioning and crosstalk magnetic field effects. Understanding these factors can significantly enhance the reliability and precision of the magnetic sensors.*

Key Words: Current measurement, magnetic field sensors, circular sensor arrays, conductor position, crosstalk magnetic fields

1. INTRODUCTION

The accurate measurement of current in power systems is crucial for ensuring efficiency and reliability. From load balancing to fault detection, precise current measurement is vital for effective monitoring and control. Magnetic field sensors have become a popular choice for non-invasive current measurement due to benefits like high accuracy and minimal circuit interference [1]. Circular arrays of these sensors have gained traction for their ability to effectively capture magnetic field variations associated with current flow. However, the accuracy and reliability of current measurements using circular sensor arrays can be influenced by various factors, especially the positioning of the conductor relative to the sensor array [2]. This study thoroughly examines the impact of conductor position on the accuracy and reliability of current measurement using circular sensor arrays. By exploring scenarios such as concentric alignment and off-center positioning, the research aims to evaluate the performance of the sensor array under different conductor positions. Additionally, the study investigates the crosstalk magnetic field due to an external conductor and its influence on current measurement [3], proposing improvements for the overall performance of circular arrays of magnetic field sensors for current measurement. Accurate current measurement is vital across various do mains such as electronics, power distribution, and automotive systems. Understanding current and employing precise measurement techniques is crucial for system efficiency, safety, and functionality [4]. Ampere's Circuital Law is a fundamental principle in current measurement, establishing a connection between the magnetic field circulation around a closed loop and the current flowing through it. This principle forms the basis of many measurement techniques and has been extensively researched and confirmed in academic literature [5].

In the realm of current transformers (CTs), these devices are pivotal in converting high currents into manageable levels for accurate and safe measurement. Studies have explored diverse CT design aspects, optimization strategies, and practical applications. Notably, a paper titled "Peculiarities of current sensors used in contemporary electric energy metering devices" delves into CT design considerations and proposes core loss compensation techniques to enhance energy metering accuracy. While CT-based current measurement may encounter challenges like bulkiness, saturation at high currents, limited accuracy at low currents, and frequency restrictions, it offers galvanic isolation and precision. However, magnetic field sensor-based methods like Hall Effect sensors present advantages such as compact size, lighter weight, improved frequency response, and easier installation compared to CTs [6-7]. Hall Effect sensors particularly excel in high-frequency applications, providing a viable alternative to traditional CTs for certain use cases [8]. Shunt resistors are essential in current measurement, allowing for accurate measurement by detecting the voltage drop across a known resistance. Research, such as

"Evaluation of current measurement accuracy for a power module with integrated shunt resistors," has focused on improving the performance and reliability of these components. Shunt resistor-based current measurements have drawbacks, including voltage burden, power dissipation, and sensitivity to temperature fluctuations. Shunt resistors introduce additional resistance into the circuit, affecting its performance and requiring careful calibration. In contrast, magnetic field sensor-based methods like Hall effect sensors offer non-intrusive, accurate measurements without these limitations, making them preferable in many scenarios [9]. In the realm of current measurement, Rogowski coils have emerged as an alternative to traditional magnetic field sensor-based methods, particularly excelling in measuring alternating currents (AC) with high accuracy and minimal disturbance to the measured circuit. Named after the physicist Walter Rogowski, these flexible current sensors operate based on Faraday's law of electromagnetic induction. They offer advantages such as flexibility for easy installation and adaptation to various conductor shapes and sizes, as well as non-intrusive measurement without introducing additional resistance, minimizing system perturbations [10-11]. Zhang et al.'s "Design and Optimization of Rogowski Coil for High Accuracy Current Measurement" contributes to advancements in this technology by addressing aspects of performance enhancement, such as linearity, sensitivity, and noise immunity [12]. However, despite their advantages, Rogowski coils exhibit limitations, including susceptibility to external electromagnetic interference, necessitating careful calibration and signal processing to compensate for nonlinearities and phase shifts inherent in the design. These factors can pose challenges in high-precision current measurement applications, especially in environments with significant electromagnetic noise [13-14]. When compared to Rogowski coils, magnetic field sensor based current methods like Hall effect sensors and current trans formers provide advantages including immunity to electromagnetic interference, easy installation, and suitability for both AC and DC measurements. Liu et al.'s "Comparison of Rogowski Coil and Hall Effect Sensor for Current Measurement in Power Electronics" presents a detailed analysis of Rogowski coils and Hall effect sensors, showcasing their respective strengths and weaknesses in power electronics applications. These magnetic field-based methods exploit the interaction between electric cur rents and magnetic fields to accurately measure current flow [15]. Hall effect sensors, in particular, utilize the Hall effect to detect and quantify currents. Recent innovations have introduced tunnel magneto resistive (TMR) sensor arrays for interference rejecting current measurement, further enhancing measurement capabilities and reliability in various applications [16]. Hall effect sensors function by detecting the magnetic field perpendicular to the current path, providing benefits such as high sensitivity, fast response times, and low power consumption. They find applications in diverse fields like automotive systems and industrial automation. Ongoing research focuses on enhancing sensor design, calibration techniques, and signal processing algorithms to elevate accuracy and reliability. Chan et al.'s work introduces a coreless electric current sensor with circular conductor positioning calibration, showcasing advancements in sensor technology for precise current measurement [17]. The use of tunnel magneto resistive (TMR) sensor arrays has gained attention for interference-rejecting current measurement due to their enhanced noise immunity and crosstalk rejection capabilities. Chen et al.'s study presents an interference-rejecting current measurement method utilizing a TMR sensor array, pro viding valuable insights into interference mitigation and sensor array optimization. Magnetic field-based current measurement methods, while advantageous, are susceptible to crosstalk effects caused by nearby conductors or magnetic sources. Understanding and mitigating crosstalk is crucial to ensuring accurate and reliable current measurements [18]. Furthermore, the influence of conductor positioning on crosstalk in circular arrays of Hall sensors has been investigated by Itzke et al., shedding light on factors affecting measurement accuracy and strategies for minimizing crosstalk effects [19]. In conclusion, magnetic field-based current measurement methods, including Hall effect sensors and TMR sensor arrays, offer versatile solutions for accurate and interference-resistant current measurement. Ongoing research efforts to optimize sensor de sign, calibration techniques, and crosstalk mitigation strategies continue to drive innovation in this field, paving the way for advancements in current measurement technology.

1.1 Motivation Behind This Study

Contactless current measurement techniques have significantly advanced electrical monitoring, offering improved safety and precision in various industrial applications. These techniques, utilizing technologies like Hall Effect sensors and Rogowski coils, enable current monitoring without direct physical contact with the conductors, ensuring electrical isolation crucial for preventing interference between the measurement system and the observed circuit. This non-invasive approach [20] is particularly valuable in environments where maintaining electrical isolation is paramount. Unlike conventional methods, contactless de signs provide a broader dynamic range and improved accuracy, particularly when measuring non-sinusoidal and high-frequency currents. These attributes are particularly advantageous in applications such as power quality monitoring and transient analysis, where accuracy under challenging conditions is essential. An important advantage of contactless current measurement lies in its immunity to core saturation, a limitation commonly associated with traditional current transformers. This immunity ensures consistent and reliable operation even in scenarios involving high currents or rapid changes in current flow. Furthermore, by directly sensing the magnetic field generated by the current without relying on magnetic cores, contactless technologies offer improved accuracy and performance. Research, such as the work presented in the paper "On the transformer core dynamic behavior during electromagnetic transients" [21], underscores the limitations of magnetic cores and suggests alternative approaches like Rogowski coils for enhanced measurement reliability. Contactless current measurement methods offer a distinct advantage by mitigating the influence of external magnetic fields, minimizing interference from neighboring conductors. Because these techniques do not require physical contact with the conductors being measured, they are inherently immune to crosstalk effects caused by nearby electrical systems. This immunity is crucial in complex industrial environments where multiple electrical systems operate in close proximity. Research studies, such as those conducted by Aiello et al., emphasize the significance of this immunity in ensuring the robustness and reliability of current measurement systems, positioning contactless techniques as indispensable tools in modern industrial settings [22].

1.2 Research Objectives

The primary goal of this research is to thoroughly examine how the positioning of a conductor within a circular array of sensors impacts current measurement accuracy, utilizing ANSYS for error calculation. This study aims to propose a compensating algorithm that can enhance measurement accuracy across different conductor positions and quantify the benefits of this algorithm through a comparative analysis of measurement errors. Accurate current measurement is crucial in applications like power distribution and electric vehicle charging systems, making circular arrays of sensors a promising technology for non-invasive current measurement. By conducting controlled experiments with the circular sensor array and a current-carrying conductor, the research will systematically vary the conductor's position to collect data for error calculation using ANSYS for precise numerical analysis. Analyzing how different conductor positions affect measurement errors will provide insights into enhancing the accuracy of current measurements. A compensating algorithm will be proposed to recalibrate measurement data based on the conductor's position, improving overall measurement precision in real-world applications. Moreover, this study will extend its inquiry to evaluate the impact of crosstalk magnetic fields on measurement accuracy. Through ANSYS simulations, the research will assess the error introduced by neighboring conductors and test the effectiveness of the proposed compensating algorithm in mitigating this error. This comprehensive approach will address practical challenges associated with non-invasive current measurement using circular sensor arrays, advancing current measurement technologies for various industrial applications.

2. INVESTIGATING THE IMPACT OF CONDUCTOR PLACEMENT ON CURRENT MEASUREMENT ACCURACY IN CIRCULAR SENSORAR RAYS

Circular sensor arrays are extensively utilized for current measurements across various sectors like power systems, industry, and automotive applications, offering benefits such as non-contact measurement, noise immunity, wide bandwidth, and high accuracy [2]. However, the accurate measurement can be influenced by the conductor's position relative to the sensor array. This study delves into how conductor position affects the accuracy of circular sensor array measurements by combining a theoretical model based on the Biot-Savart law [23] with experimental results. The theoretical model calculates the magnetic field at each sensor's location in the array, while Ampere's law derives the current from this magnetic field data. By exploring the intricate link between conductor placement and sensor accuracy, this research aims to offer a comprehensive understanding of optimizing circular sensor array performance for precise current measurements, emphasizing the importance of sensor positioning in enhancing measurement reliability [24].

2.1 Summing and Averaging Method

The Biot-Savart Law is a crucial concept in electromagnetism, offering a mathematical framework to describe the magnetic field resulting from a steady electric current. It serves as a foundational principle for comprehending the behavior of magnetic fields generated by electric currents across different physical systems. This report seeks to elucidate the Biot-Savart Law and describes how one can ascertain the current based on knowledge of magnetic flux magnitude. According to Biot-Savart's Law Magnetic Field due to current carrying conductor,

$$dB = \frac{\mu_0}{4\pi} \times I \times \frac{dl sin\theta}{r^2} \tag{1}$$

For the finite current-carrying conductor,

$$B = \frac{\mu_0}{4\pi} \times \frac{I}{p} (sin\phi_1 + sin\phi_2) \tag{2}$$

The magnetic field at a point "Q" situated at a distance "r" from an infinitely long straight conductor can be calculated using a simplified application of the Biot-Savart Law.

$$B = \frac{\mu_0}{2\pi} \times \frac{I}{p} \tag{3}$$

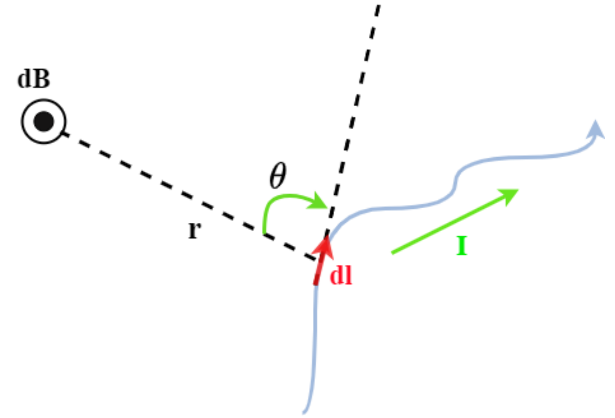


Fig-1: Biot-Savart law demonstration of the basic current carrying conductor.

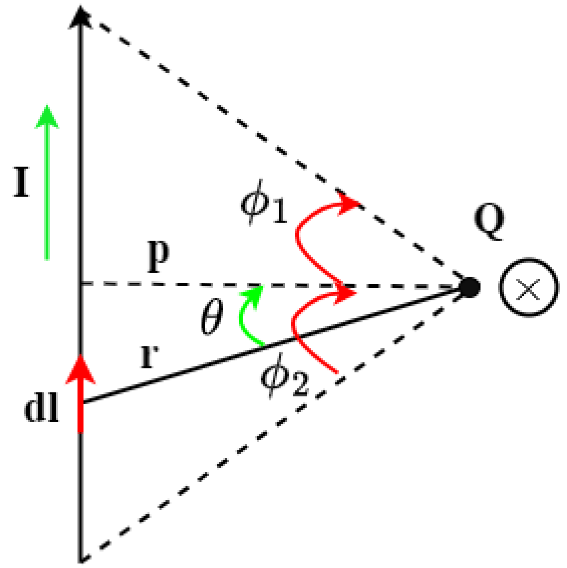


Fig-2: Biot Savart law demonstration of an infinite current carrying conductor.

As the Magnetic field can be measured from the sensor, so current can be calculated as,

$$I = \frac{2\pi . p}{\mu_0} \times B \qquad (4)$$

The Summing and Averaging methods are utilized for current measurement with magnetic field sensors, particularly in applications requiring high precision, such as power systems, motor control, and industrial automation. In the Summing method, multiple sensors are strategically positioned around the conductor carrying the current. Each sensor detects the magnetic field generated by the current, and their outputs are combined to yield a total current measurement. This approach enhances accuracy by considering the magnetic field distribution surrounding the conductor [25].

The Averaging method, while similar, involves deploying multiple sensors to measure the magnetic field, but instead of summing the outputs, they are averaged to produce a representative value. This technique reduces the impact of noise and inconsistencies in the magnetic field distribution, leading to a more dependable measurement. Both methods offer distinct advantages and are chosen based on the specific needs of the application, including desired accuracy, noise sensitivity, and cost. Additionally, signal processing techniques can be employed to further improve the accuracy and reliability of the current measurements [26].

For a circular array of sensor current can be calculated as,

$$I = \frac{2\pi . p}{\mu_0} \times \frac{1}{N} \times \sum_{j=1}^{N} B_j \qquad (5)$$

Where N = Number of sensors

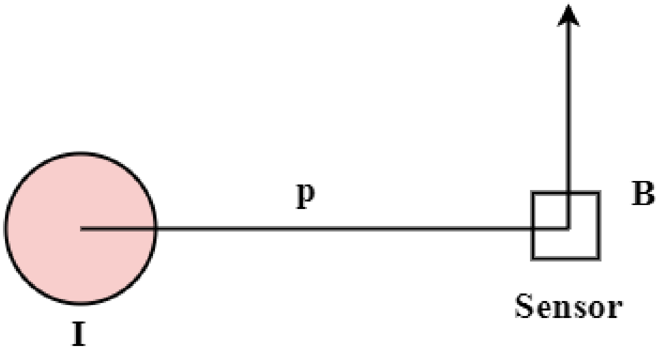


Fig-3: Arrangement of the conductor and sensor.

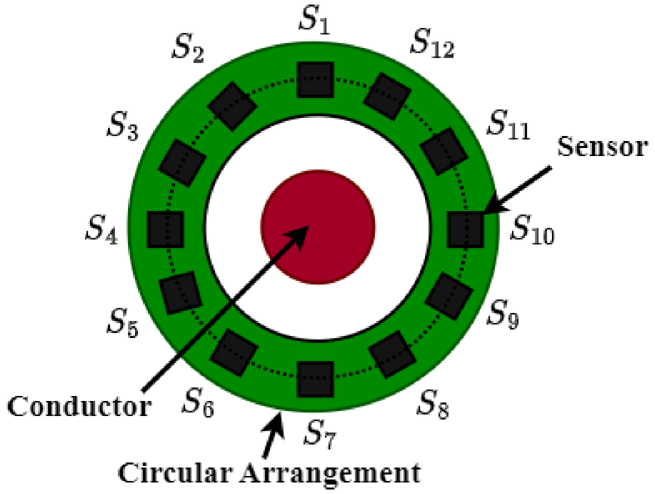


Fig-4: Conductor and a circular array of 12 sensor arrangement.

2.2 Simulation Results for Varying Conductor Positions

To analyze the impact of various conductor positions within a circular array of sensors, simulations were conducted using ANSYS Maxwell Software. A 4 sqmm conductor carrying a 16 amp current was positioned inside a circular array comprising 12 sensors, with the sensors located 3 mm from the conductor's center. Two distinct methods for altering the position of the conductor were employed: one involved shifting the conductor along its axis, while the other involved adjusting the conductor's position relative to the space between the sensors. This study aims to evaluate how these positional changes affect the accuracy of current measurements in the sensor array.

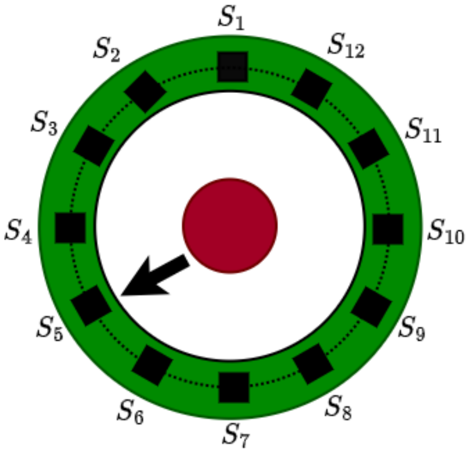


Fig-5: Conductor and a circular array of 12 sensor arrangement. Moving along the direction of the sensor.

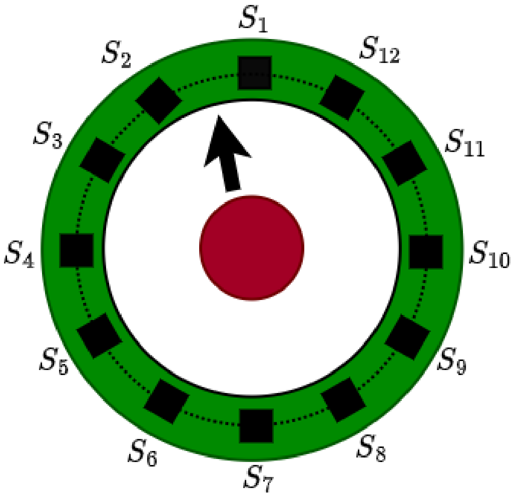


Fig-6: Conductor and a circular array of 12 sensor arrangement. Moving between the sensors

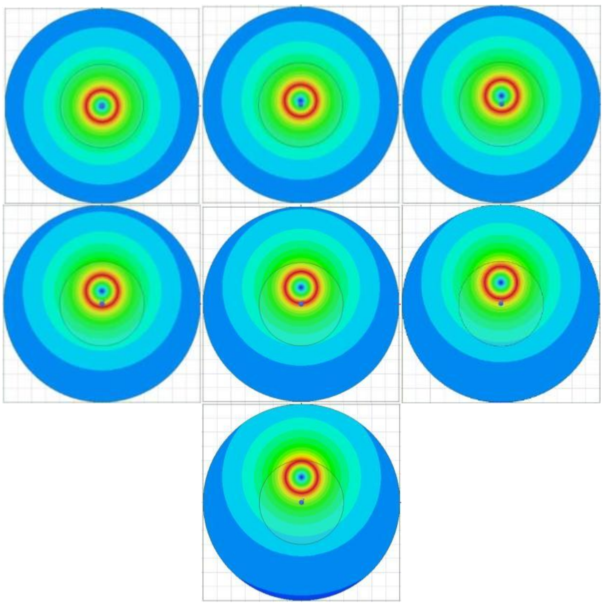


Fig-7: Magnetic field magnitude of a Conductor placed inside a circular arrays ensor arrangement moving along the direction of the sensor.

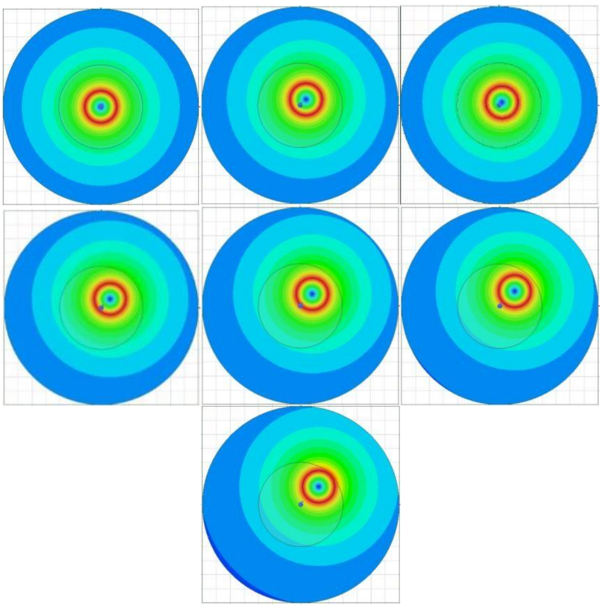


Fig 8: Magnetic field magnitude of a Conductor placed inside a circular array sensor arrangement moving between the two sensors.

To mitigate the increased errors caused by off-center con ductors incircular sensor arrays, a novel algorithm has been developed to reduce measurement inaccuracies. This algorithm focuses on refining mathematical expressions to optimizecurrent measurements, even in the presence of conductor displacement.

Table -1: Measurement of error percentage with respect to distance displaced in mm when moving along the direction of sensor.

Distance (in mm)	Error Percentage
0.0	0.02338
0.4	0.6200
0.8	1.1930
1.2	2.5613
1.6	4.8223
2.0	8.3677
2.4	11.8633

Table -2: Measurement of error percentage with respect to distance displaced in mm when moving between the two sensors.

Distance (in mm)	Error Percentage
0.0	0.02338
0.4	0.3226
0.8	1.0966
1.2	2.4806
1.6	4.9823
2.0	8.4257
2.4	11.8633

2.3 Developing Models to Mitigate Conductor Position Effects in Circular Sensor Arrays

According to Bazzocchi and Rienzo, the magnetic field calculation for a conductor positioned outside the circular array, where $r > D$, follows a similar approach to that used for a conductor located inside the circular array, with the condition $D < r$. The angle γ relative to the direction of the current can be computed as follows:

$$\gamma(\alpha) = \alpha + \sum_{m=1}^{+\infty} \frac{1}{m}\left(\frac{D}{r}\right)^m sin(m\alpha) \tag{6}$$

By using magnetic scalar potential,

$$\vec{H} = -\nabla\psi \tag{7}$$

Also,

$$\psi(r,\alpha) = -\frac{I \times \gamma(\alpha)}{2\pi} \tag{8}$$

The tangential component of the magnetic field H_α can be calculated as,

$$H_\alpha = -\frac{1}{r}\cdot\frac{\psi(r,\alpha)}{d\alpha} = \frac{I}{2\pi r} + \frac{I}{2\pi r}\cdot\sum_{m=1}^{+\infty}\left(\frac{D}{r}\right)^m cos(m\alpha) \tag{9}$$

In a circular arrangement of N equally distributed magnetic field sensors, the discrete approximation of Ampere's law can be utilized with appropriate line segments Δs_i to calculate the current as follows:

$$\sum_{i=1}^{N} H_\alpha \cdot \Delta s_i \tag{10}$$

$$\frac{2\pi r}{N}\cdot\sum_{i=1}^{N} H_{\alpha,i} = I + \frac{I}{N}\cdot\sum_{i=1}^{N}\sum_{m=1}^{+\infty}\left(\frac{D}{r}\right)^m cos(m\alpha_i) \tag{11}$$

Where,

$$\alpha_i = \alpha_0 + (i-1)\cdot\frac{2\pi}{N} \tag{12}$$

So, the calculated current can be expressed as,

$$\tilde{I} = I + \frac{I}{N}\cdot\sum_{m=1}^{+\infty}\left(\frac{D}{r}\right)^m\sum_{i=1}^{N} c\,os\left(m\left(\alpha_0 + (i-1)\cdot\frac{2\pi}{N}\right)\right) \tag{13}$$

where,

$$\sum_{i=1}^{N} c\,os\left(m\left(\alpha_0 + (i-1)\cdot\frac{2\pi}{N}\right)\right) = f(m) \tag{14}$$

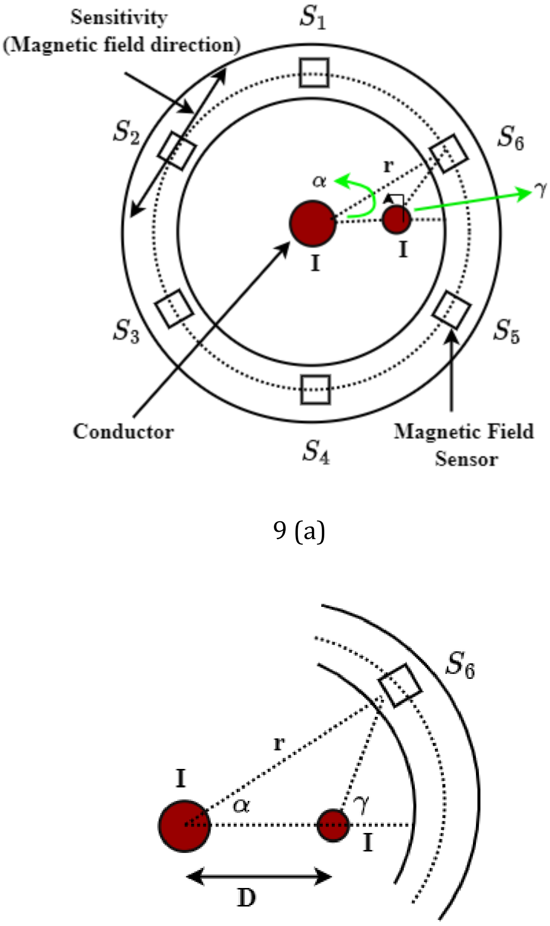
So, the calculated current from a circular array of N equally distributed ideal magnetic field sensors can be expressed as,

$$I' = I + I \cdot \sum_{k=1}^{+\infty} \left(\frac{D}{r}\right)^{kN} cos(kN\alpha_0) \tag{15}$$

And measured errors as,

$$\varepsilon = I' - I = I \cdot \sum_{k=1}^{+\infty} \left(\frac{D}{r}\right)^{kN} cos(kN\alpha_0) \tag{16}$$

Considering the new mathematical expression for error calculation, an improved percentage of error was achieved for off-center conductors. Below is the updated percentage of error according to this new method.



9 (a)

9 (b)

Fig-9: The system's geometry is represented as in the above figure: Sensors S_1 to S_6 are magnetic field sensors (e.g., Hall effect sensors) positioned at a radius r from the center of the array. The conductor I can be horizontally displaced by a distance D from the center of the sensor array. The angles α and γ represent the angles between sensor S_6 and the conductor I at the center and at the displacement distance D, respectively.

Table -3: Measurement of error percentage after implementing the new equation for distance displaced in mm moving along the direction of the sensor

Distance (in mm)	Error Percentage
0.0	0.0015
0.4	0.0051
0.8	0.0098
1.2	0.0122
1.6	0.0738
2.0	0.1506
2.4	0.4401

Table -4: Measurement of error percentage after implementing the new equation for distance displaced in mm moving between the two sensors

Distance (in mm)	Error Percentage
0.0	0.0015
0.4	0.0036
0.8	0.0092
1.2	0.0107
1.6	0.0702
2.0	0.1513
2.4	0.4175

3. CIRCULAR CONDUCTOR POSITION CALIBRATION FOR CORELESS CURRENT SENSING SYSTEMS

Electric current measurement methods frequently rely on magnetic fields to accurately assess the flow of current through a conductor. This approach enables precise measurements without direct contact with the conductor, making it particularly advantageous in situations where traditional contact methods may be impractical. At the core of magnetic field-based current measurement is the Biot-Savart Law, a fundamental principle that describes the interaction between electric currents and magnetic fields.

This law provides a mathematical framework for determining the magnetic field generated by a steady current in a conductor, allowing researchers and engineers to accurately calculate the magnetic field strength at any point around the current-carrying conductor. In this chapter, we will explore the complex relationship between magnetic fields and electric currents, highlighting how the Biot-Savart Law forms the foundation for current estimation techniques [17]. By elucidating the theoretical underpinnings of magnetic field-based current measurement and showcasing the practical applications of the Biot-Savart Law, we aim to provide a thorough understanding of the advanced methodologies employed in contemporary current sensing technologies.

Two prevalent methods for current measurement using magnetic field sensors are the Summing and Averaging methods. These techniques are commonly used in applications requiring precise current detection, including power systems, motor control, and industrial automation. In the Summing method, multiple sensors are arranged around the current-carrying conductor, with each sensor measuring the magnetic field induced by the current. The outputs from these sensors are combined to produce a total current measurement, enhancing accuracy by accounting for the magnetic field distribution around the conductor [25].

In contrast, the Averaging method also employs multiple sensors to measure the magnetic field, but instead of summing the outputs, they are averaged to yield a representative value. This approach helps to reduce the impact of noise and irregularities in the magnetic field distribution, resulting in a more reliable measurement. Both methods possess distinct advantages and are chosen based on specific application requirements, including accuracy, noise sensitivity, and cost considerations. Additionally, signal processing techniques can be applied to further improve the accuracy and reliability of current measurements [26].

The summing and averaging methods for current measurement face challenges, especially when the conductor is off-center or arranged within a circular array of sensors. In these situations, measurement accuracy can significantly decrease. When the conductor is not centered, the magnetic field distribution becomes uneven, leading to inaccuracies in sensor readings. The summing method, which combines sensor outputs, may unintentionally amplify these errors, resulting in less precise overall measurements. Similarly, in a circular sensor arrangement, accurately capturing the magnetic field variations becomes complex, potentially leading to inconsistencies, particularly at different locations along the conductor's circumference. As a result, the overall measurement error tends to rise, undermining the reliability of the collected data. Addressing these challenges typically requires implementing corrective measures, such as sensor calibration, advanced signal processing algorithms, or alternative measurement approaches designed to accommodate off-center conductors and circular sensor arrays.

A new calibration technique for conductor positioning is proposed to tackle the increased errors associated with these methods. This circular conductor positioning calibration utilizes three magnetic field sensors positioned at known locations around the conductor. These sensors measure the magnetic flux density generated by the current flowing through the conductor. The distances from the center of the conductor to each sensor are then incorporated into the calibration algorithm to estimate the relative position of the conductor accurately [24].

3.1 Coreless Current Sensing Scheme with Circular Conductor Position Calibration

As measurement errors become more pronounced, a new method is proposed: circular conductor positioning calibration. This approach involves positioning three magnetic field sensors at established locations around the conductor. These sensors measure the magnetic flux density generated by the current. By analyzing the collected data, the precise position of the conductor relative to the sensors can be determined, thereby ensuring accurate current measurements. The magnetic flux density B_1, B_2 and B_3 measured by sensors S_1, S_2 and S_3 can be expressed as,

$$B_1 = \frac{\mu_0 I}{2\pi R_1} \tag{17}$$

$$B_2 = \frac{\mu_0 I}{2\pi R_2} \tag{18}$$

$$B_3 = \frac{\mu_0 I}{2\pi R_3} \tag{19}$$

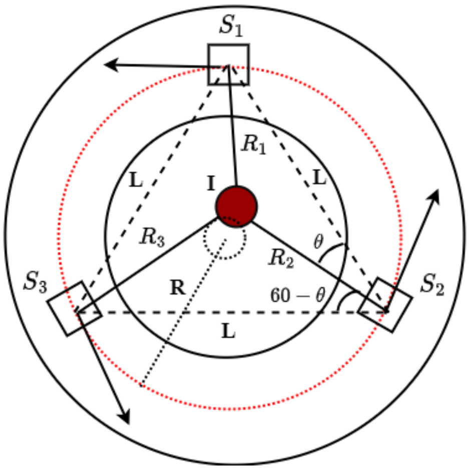


Fig-10: Coreless circular current sensor unit having three sensors.

Expressing R_2 and R_3 in terms of R_1,

$$R_2 = R_1 \times \frac{B_1}{B_2} = R_1 \times m \qquad (20)$$

$$R_3 = R_1 \times \frac{B_1}{B_3} = R_1 \times n \qquad (21)$$

From the triangle made by R_1, R_2, L and R_3, R_2, L ;

$$R_1^2 = L^2 + R_2^2 - 2LR_2 cos(\theta) \qquad (22)$$

$$R_3^2 = L^2 + R_2^2 - 2LR_2 cos(60 - \theta) \qquad (23)$$

From the equation (20), (21), and (22) we have,

$$cos(\theta) = \frac{L^2 + R_1^2(m^2 - 1)}{2LmR_1} \qquad (24)$$

From the equation (20), (21), and (23) we have,

$$cos(60 - \theta) = \frac{L^2 + R_1^2(m^2 - n^2)}{2LmR_1} = \frac{cos(\theta)}{2} + \frac{\sqrt{3}}{2} \cdot sin(\theta) \qquad (25)$$

So, putting the value of $cos(\theta)$ from equation (24), the value of $sin(\theta)$ becomes,

$$sin(\theta) = \frac{1}{\sqrt{3}}\left(\frac{L^2 + R_1^2(m^2 - n^2)}{LmR_1} - \frac{L^2 + R_1^2(m^2 - 1)}{2LmR_1}\right) \qquad (26)$$

We know that,

$$sin^2(\theta) + cos^2(\theta) = 1 \qquad (27)$$

Putting the values of $cos(\theta)$ and $sin(\theta)$ from equations (24) and (26) and rearranging equation (27) can be written as,

$$R_1^4(1 + m^4 + n^4 - m^2n^2 - m^2 - n^2) + R_1^2(-L^2m^2 - L^2n^2 - L^2) + L^4 = 0 \qquad (28)$$

Then further rearranging the equation (28) to get the only unknown value of R_1,

$$R_1 = \sqrt{\frac{2L^2}{m^2 + n^2 + 1 + \sqrt{3(2m^2 + 2n^2 + 2m^2n^2 - m^4 - n^4 - 1)}}} \qquad (29)$$

After calculating R_1, R_2 and R_3 can be calculated as,

$$R_2 = mR_1 \qquad (30)$$

$$R_3 = nR_1 \qquad (31)$$

Where,

$$m = \frac{B_1}{B_2} \quad \text{And} \quad n = \frac{B_1}{B_3}$$

3.2 Simulation Results for Coreless Current Sensing Systems

Simulations were performed using ANSYS Maxwell Software to examine the effects of different conductor positions within a circular sensor array. The probe radius was set to 18 mm, with a current of 16 A flowing through the conductor. Thirteen positions were chosen for analysis, including (0,0), (5,0), (10,0), (-5,0), (-10,0), (0,5), (0,10), (0,-5), (0,-10), (5,5), (-5,5), (-5,-5), and (5,-5). This diverse selection of positions enables a thorough investigation of the sensors' responses to various conductor placements. By leveraging mathematical formulations alongside the capabilities of ANSYS Maxwell Software, the simulation provides a detailed understanding of how different conductor positions influence magnetic field distribution and sensor readings within the circular array. This analysis is essential for optimizing sensor placement and enhancing the accuracy of current measurements in real-world applications.

When the conductor is positioned at the center of the probe, both the summing and averaging methods, as well as the proposed method, gives minimal error. At the central position, both methods recorded a current of 15.999 A, with an error percentage of just 0.0066%. The calculated results for various conductor positions using both the summing and averaging methods, along with the new proposed mathematical expression, are presented below.

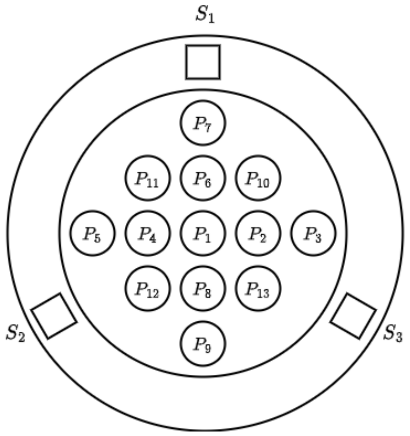


Fig-11: Coreless circular current sensor unit having three sensors with 13 positions.

Table -5: Measurement of error percentage by utilizing the summing and averaging method for different Positions.

Position	Current (Summing & Averaging Method)	Error%
(5,0)	16.28257	1.76606
(10,0)	17.29136	8.0710
(-5,0)	16.32813	2.05081
(-10,0)	17.10780	6.92375
(0,5)	16.33571	2.09818
(0,10)	19.10048	19.378
(0, -5)	16.15283	0.9551
(0, -10)	15.80377	1.22643
(5,5)	16.40311	2.51943
(-5,5)	16.20019	1.25118
(-5, -5)	16.87166	5.44787
(5, -5)	16.96221	6.01381

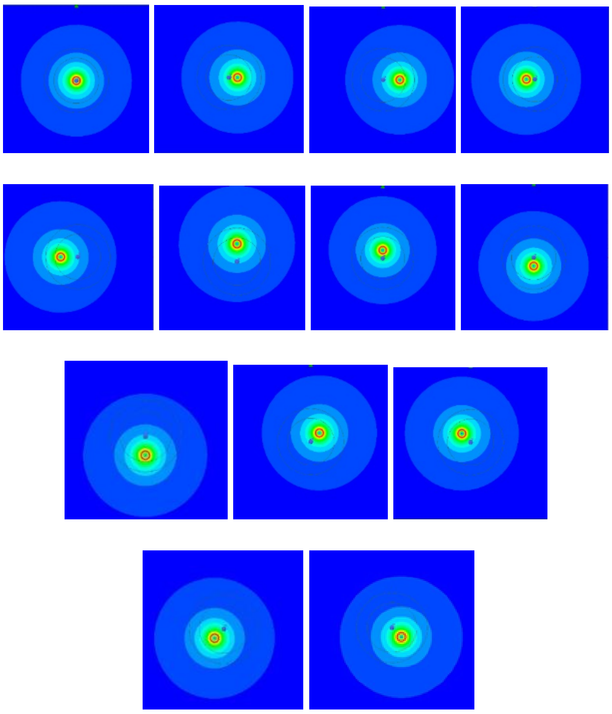


Fig-12: Magnetic field of a Conductor placed inside a circular array in 13 different Positions.

Table -6: Measurement of error percentage after implementing the new equation for different Positions.

Position	Current (Proposed Method)	Error%
(5,0)	16.0017	0.00106
(10,0)	16.0103	0.06437
(-5,0)	15.9908	0.05750
(-10,0)	15.9986	0.00875
(0,5)	15.9957	0.02687
(0,10)	15.9929	0.04437
(0, -5)	16.0002	0.00125
(0, -10)	16.0015	0.00937
(5,5)	16.0041	0.02562
(-5,5)	16.0004	0.0025
(-5, -5)	15.9939	0.03812
(5, -5)	16.0064	0.04000

4. IMPACT OF CONDUCTOR PROXIMITY ON CROSSTALK ERRORS IN CURRENT MEASUREMENT

Current measurement is vital in various electrical engineering applications, and magnetic field-based methods are often employed to provide non-invasive and secure measurement techniques. However, a significant challenge arises in scenarios involving multiple conductors, where crosstalk occurs [27]. This phenomenon happens when the magnetic field produced by one current-carrying conductor interferes with the measurements from a nearby conductor, leading to errors that compromise data accuracy and reliability [28].

This research study examines the interference caused by crosstalk magnetic fields using a circular magnetic sensor array to address this issue. By simulating real-world scenarios with external current-carrying conductors positioned at varying distances from the sensor array, we aim to analyze how conductor positioning affects measurement accuracy. Previous research has underscored the negative impact of crosstalk magnetic fields on the precision of current measurements, resulting from the interaction of magnetic fields generated by adjacent conductors.

While various strategies, including advanced sensor arrays and signal processing techniques, have been explored to mitigate these effects, there remains a need for further investigation into the specific factors influencing crosstalk, such as the distance between conductors and the configuration of the sensor array.

4.1 Crosstalk Mechanism in Current Measurement

In the field of current measurement using magnetic field sensors, crosstalk presents a significant challenge. This issue arises when the magnetic field generated by one current-carrying conductor, referred to as the external conductor (with current I_2), interferes with the measurements of another nearby conductor, known as the target conductor (with current I_1). As a result, this phenomenon introduces unwanted interference, which can lead to substantial distortions in the actual current reading of the target conductor.

Crosstalk occurs when both, the target and external conductors generate magnetic fields as current flows through them. These magnetic fields adhere to the inverse square law, meaning their strength diminishes with greater distance from the conductor [29]. The circular sensor array, intended to measure the magnetic field produced by the target conductor (I_1), can also pick up the magnetic field generated by the nearby external conductor (I_2). This crosstalk magnetic field can either add to or subtract from the desired signal, depending on their relative orientations, resulting in measurement distortion.

Several factors affect the magnitude of crosstalk and its impact on current measurement accuracy. The most significant factor is the distance (D) between the target conductor and the external conductor. As this distance increases, the crosstalk magnetic field weakens, resulting in reduced interference with the sensor array's measurements. Our simulations show that positioning the external conductor at least four times the radius of the sensor array substantially minimizes crosstalk errors.

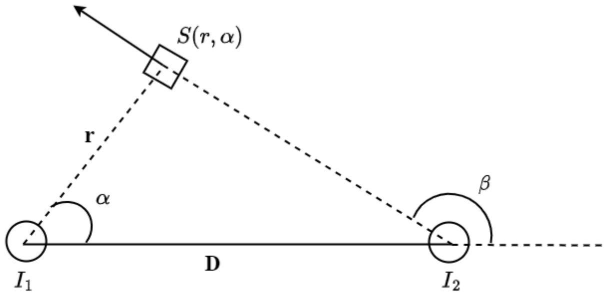


Fig-13: Representation of current under measurement $I1$ and the crosstalk current $I2$ in a polar coordinate system.

Additionally, the geometries of the conductors, including their shapes and sizes, can also influence crosstalk. Straight conductors generally produce more predictable magnetic fields compared to coiled or twisted conductors, which can create more complex field patterns and potentially increase crosstalk. Furthermore, the sensitivity of the sensor array plays a crucial role in its susceptibility to crosstalk; highly sensitive sensors may detect even weak crosstalk fields, resulting in larger measurement errors. Therefore, both the sensor design and material selection can significantly impact sensitivity to crosstalk. By understanding these factors and implementing mitigation strategies—such as increasing the distance between the sensor and conductor or employing shielding techniques—we can reduce crosstalk and achieve more accurate current measurements.

4.2 Simulation Setup

For the simulation study examining the effects of external conductor positions on a circular sensor array, ANSYS Maxwell 2D was employed. This powerful electromagnetic field simulation software is particularly effective for modeling and analyzing electromagnetic fields and forces in complex configurations of conductors and sensors.

The simulation setup featured a circular sensor array with a radius of 18 mm. Within this configuration, two currents were analyzed: I_1, flowing through the main conductor located at the center of the array, and $I2$, flowing through an external conductor. Both conductors were set to carry a current of 16 A.

This arrangement facilitates the investigation of magnetic field interactions and the resulting electromagnetic effects affected by the varying positions of the external conductor in relation to the sensor array.

To systematically investigate the spatial relationship and its influence on sensor readings, the external conductor was positioned at various specified distances from the center of the array. These distances were defined as multiples of the array's radius (r), specifically at 2r, 3r, 4r, 5r, 6r, 7r, 8r and 10r. This range creates a comprehensive gradient for observing how magnetic field strength and distribution change with distance, which is crucial for applications that require accurate detection of magnetic field anomalies or variations.

Additionally, the study considered different configurations for the number of sensors within the array, including setups with 3, 4, 6, 8, and 10 sensors. This variation enables an evaluation of how sensor density and arrangement impact the accuracy and sensitivity of electromagnetic field detection.

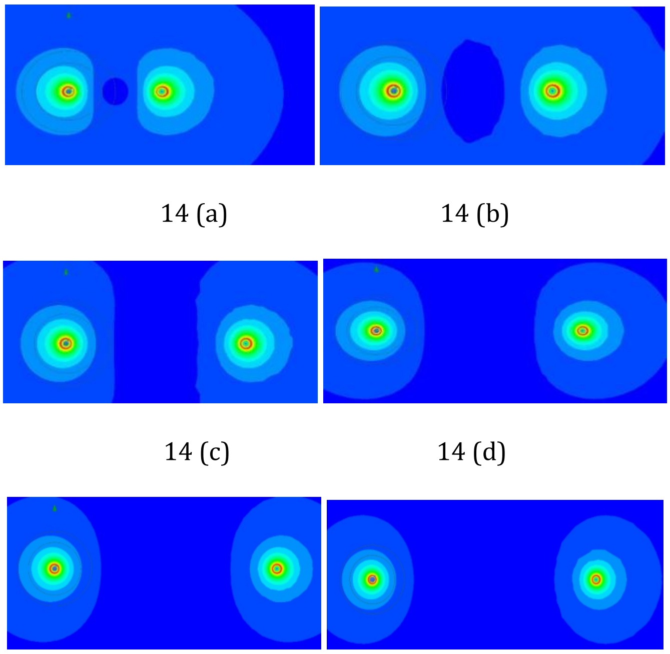
The materials and geometries of the conductors were chosen based on their electromagnetic properties and their relevance to the simulated scenarios. These choices are designed to closely reflect real-world applications, thereby increasing the practical significance of the simulation results.

With this detailed simulation setup, the research aims to gain insights into optimal sensor arrangements and external conductor placements for effective electromagnetic field mapping and monitoring. These insights could be crucial for developing advanced sensing solutions across various engineering and technological applications.

4.3 Simulation Results

The simulation is obtained by using the setup described above, and the simulation results were analyzed to produce two graphs. Below is more detailed information about the graphs:

Firstly, as the number of sensors in the array increased, the error due to external conductors decreased. This can be attributed to the improved spatial resolution and averaging effect provided by a larger number of sensors, allowing for better discrimination between the desired signal and external interference. A larger sensor array enhances the ability to pinpoint the exact location of the desired signal, thus minimizing the impact of noise and interference from external conductors. This finding is crucial as it highlights the importance of sensor quantity in improving measurement accuracy in environments with potential external interference.


14 (a) 14 (b)

14 (c) 14 (d)

14 (e) 14 (f)

Fig-14: Magnetic field of conductor placed inside the circular array of sensor and one external conductor for different distances.

Secondly, as the distance between the external conductors and the sensor array increased, the error in current measurement decreased. This suggests that increasing the distance reduces the influence of external conductors on the measurements, leading to more accurate results. When external conductors are further away, their electromagnetic fields have a diminished impact on the sensor array, thereby reducing measurement error. This finding emphasizes the importance of strategic placement of sensor arrays relative to potential sources of interference to enhance measurement accuracy.

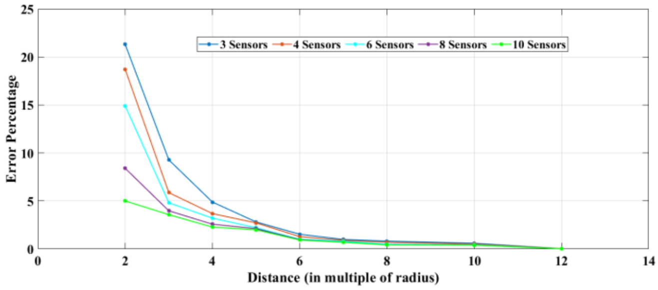


Fig-15: Distance vs Error graph as the number of sensors increased.

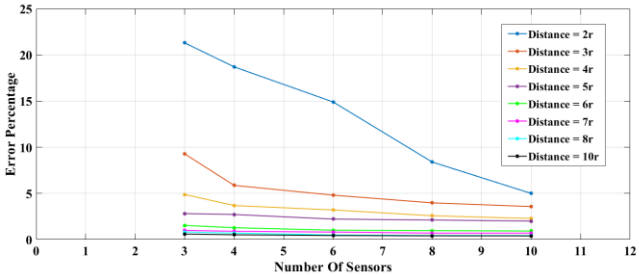


Fig-16: Number of sensor vs Error graph has the distance increased.

The two graphs visually represent these findings, highlighting the relationship between the number of sensors, the distance to external conductors, and measurement error. The first graph likely illustrates a downward trend in error with the increase in the number of sensors, demonstrating the advantages of a larger sensor array. Meanwhile, the second graph probably shows a reduction in error as the distance to external conductors increases, reinforcing the importance of spatial separation in minimizing interference.

Collectively, these graphs illustrate that optimizing both the number of sensors and their positioning relative to external conductors is crucial for achieving accurate measurements. The insights derived from these graphs can guide the design and deployment of sensor arrays across various applications, ensuring greater precision and reliability in measurements even in the presence of external conductors.

5. Conclusion

This research investigates the effects of conductor placement and nearby magnetic fields on the accuracy of circular sensor arrays for current measurement. We developed mathematical formulas to correct errors from off-center conductor positioning, validated through simulations showing that placing the conductor at least four times the sensor's radius away from others significantly reduces errors. This finding underscores the importance of precise conductor placement for optimal sensor performance. This research study also introduced a novel equation for different conductor positions within the circular array, providing an effective solution to measurement inaccuracies. By considering optimal placement and applying this equation, engineers can enhance the reliability and precision of current measurements, benefiting the field of electrical measurement and instrumentation. To evaluate external magnetic interference, the study simulated various scenarios, confirming that positioning an external conductor more than four times the radius from the target conductor greatly decreases measurement errors.

Future research can explore advanced signal processing techniques to reduce crosstalk and improve accuracy in circular sensor arrays. By employing adaptive filtering, spatial interference cancellation, and integrating machine learning for real-time adaptive compensation, researchers can enhance measurement reliability. These combined strategies will pave the way for more robust current measurement systems, effectively addressing the challenges of crosstalk and variability in conductor positioning.

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