

Optimum Design of Square Air-Core Electromagnetic Coil System

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Abstract- Designs of electromagnetic (EM) coil have attracted a lot of attention in the research community due to its applications in several areas of human endeavours. However, the optimal selection of coil wire size and current in the design of Square Air-Core Multi-turn Multilayer Electromagnetic Coil (SAMMEC) with significant wire diameter for both safe and cost-effective products has not been given enough research attention. Therefore, the equation for the flux density produced by a rectangular loop of wire was adopted in the modelling of SAMMEC with significant wire diameter. A coil design chart was constructed based on the developed model and design specifications. Both the feasible and non-feasible design regions and the line of optimum magnetic flux density were identified on the constructed chart. The appropriate wire size and current for the coil were both determined from the design-chart. The diameter, length, resistance, copper loss, and weight of the selected wire for the generation of 0.06 T flux density were found to be 0.00326 m, 267.01 m, 0.5502 Ω , 263.87 W, and 19.86 kg respectively. The selected wire can produce an optimum flux density of 0.066 T with current of 24 Amp and associated copper loss of 316.92 W.

Keywords- Air core, Electromagnetic coil, Magnetic flux density, Multilayer, Multi-turn

1 INTRODUCTION

The importance of EM coil designs cannot be overemphasized in the fields of physics and engineering as it serves as the basis for the realization of a large number of scientific and industrial systems. Design of EM coils has attracted several attentions in the research community due to its application in many areas of human endeavours such as bio-electromagnetic experiments (Magdaleno-Adame, Olivares-Galvan, Campero-Littlewood, Escarela-Perez, & Blanco-Brisset, 2010), calibrations of magnetic field meter (IEEE, 1995; Kotter & Misakian, 1977), ultra-precision machining (Denkena, Dahlmann, & Krueger, 2016), sensor for vehicle detection (Mocholí-Salcedo, Arroyo-Núñez, Milián-Sánchez, Palomo-Anaya, & Arroyo-Núñez, 2016; Mocholí-Salcedo, Arroyo-Núñez, Milián-Sánchez, Verdú-Martín, & Arroyo-Núñez, 2016), water treatment (Ajiboye, Yusuf, Yusuf, & Ogunlela, 2020), magnetic resonance imaging and spectroscopy (Chapman, Doyle, & Pohost, 1992) and EM actuators (Kumar, Kumar, Srihari, & Dayakar, 2015) to mention but few.

However, the optimal selection of coil wire size and current in the design of SAMMEC with significant coil wire diameter to yield both safe and cost-effective products has not been given sufficient attention. SAMMEC is the class of electromagnetic coil wound on air core former with rectangular prism shape and of equal length and width. The first layer is the turns of wire which have direct contact with the core former, while the other layers have same number of turns as the first layer, but their turn lengths and widths increase in a consecutive order of winding.

Merritt and Ruben coils, which are square air-core coils, were among the coil arrangement analysed by (Magdaleno-Adame et al., 2010) for the generation of volumes of uniform magnetic fields. Misakian, M. (Misakian, 2000) developed the equations for the magnetic flux density produced by three rectangular loops of wire lying in the same plane, and the spatial components of the magnetic flux density at any arbitrary point were determined by summing up the respective contributions from each of the loops. In (Misakian, Sheppard, Krause, Frazier, & Miller, 1993), the equation for the calculation of the resultant magnetic flux density generated at any arbitrary point between two co-axial multi-turn rectangular coils separated by a given distance was derived.

Presented in (IEEE, 1995; Kotter & Misakian, 1977) are the formulas for calculating the z-component of the magnetic flux density produced by one turn, air-core rectangular coil. The required equation for finding the rms value of the magnetic flux density along the z-axis of a square exposure coil system (ECS) was presented in (Herceg, Juhas, & Milutinov, 2009) and used to calculate the magnetic flux density of an ECS containing four separate coils. The analytical solution for the calculation of magnetic flux density of double loop air-core rectangular coils was presented in (Mocholí Belenguer, Mocholí Salcedo, Milián Sánchez, & Arroyo Núñez, 2018) and applied for traffic sensor intelligent transportation system. Applying the principles of superposition, the equation for calculating the magnetic flux density along z-axis produced by square Helmholtz structures (Ghaly & Khan, 2019) was derived. The analytical determination of the resultant component of the magnetic flux density generated by a square coil at any arbitrary point in the x, y, z- surface was presented in (Mocholí-Salcedo, Arroyo-Núñez, Milián-Sánchez, Palomo-Anaya, et al., 2016). A method for calculating the magnetic flux density produced by both square and circular air core coils for wireless power transfer systems in electric vehicles was discussed in (Luo & Wei, 2016).

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Section B- ELECTRICAL/COMPUTER ENGINEERING & COMPUTING SCIENCES
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Air-core coil arrangements had been traditionally adopted in coil design to guarantee certain spatial distribution of EM fields when fed by an electric current (Azpurua, 2012). High peak amplitude magnetic flux density was produced by an air-core electromagnetic coil, the core also provided a space for accommodating the substance to be magnetically treated (Basharat, Ding, Cai, Li, & Fang, 2017). The resulting flux density produced by an air-core coil is a linear function of current without saturation which allows easy analysis. As pointed out by (Misakian, 2000), it can be inferred that the square geometry loop is convenient because the expressions for the three spatial components of the flux density are in closed form. For simplification of system model, square coil is encouraged instead of a rectangular coil (Luo & Wei, 2016). It should be noted that the homogeneity of the magnetic field produced by a pair of square coil system is higher compared to its circular counterpart (Ghaly & Khan, 2019), as the coil length and width are the same. The design of air-core, square-shaped electromagnetic coil is considered in this study due to the aforementioned advantages associated with this type of coil.

The dependency of the magnetic flux density on coil wire diameter was not analytically established in most of the reported works in the literature; and in a few reports where it was established (Basharat et al., 2017), its investigation was not discussed. This led to the general assumption that all the turns of wire in the coil contribute equally to the resultant magnetic flux density (Azpurua, 2012), however, this is not true for a multi-turn, multilayer coil with significant coil wire diameter. Even though the effect of coil wire diameter on the wire cross-sectional area using the current density was presented in (Azpurua, 2012; Hashemi & Gharaei, 2019), the effect on the length of the coil wire was not investigated. To address the challenges associated with the design of SAMMEC with significant coil wire diameter, in this study, the coil model was developed and the coil design-chart was constructed using the model and the design specifications. Using the chart, the corresponding values of wire diameter and current can be determined for a specified value of flux density.

2 METHODOLOGY

In this section, the coil system model equations for the proposed coil system were developed. The developed model equations were used based on the design specifications to design the coil. Also, the wire parameters were determined to provide bases for wire selection.

2.1 MODELLING OF PROPOSED SQUARE COIL SYSTEM

The geometry of a square coil with the length and width of the first layer turn equal to l_1 and coil height of h is shown in Figure 1. The coil has n layers in the x-y plane and m turns per layer along the z-axis. Based on these layers and turns arrangement with the coil geometry, the formulas for determining the dimensions of a turn in a given layer were derived, as shown in equations (1) - (5) for the first four layers and the n^{th} layer. The equations for the determination of the distance from the centre of each of the turns in the layers to an arbitrary point P along the z-axis were also derived as shown in equations (6) - (10) for the first four turns and m^{th} turn along the z-axis.

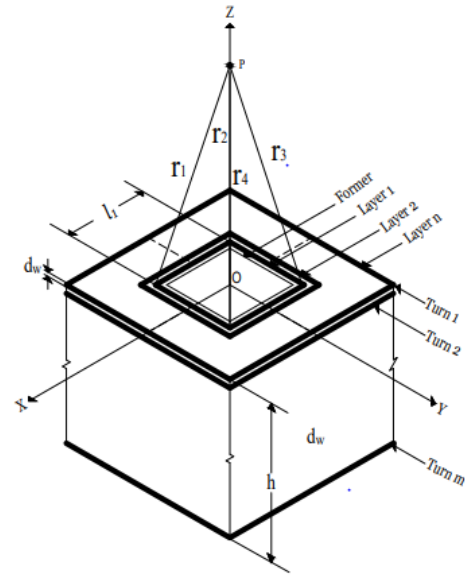


Fig. 1: Geometry of the proposed square coil

$$l_1 = 2a \quad (1)$$

$$l_2 = l_1 + 2d_w \quad (2)$$

$$l_3 = l_2 + 2d_w \quad (3)$$

$$l_4 = l_3 + 2d_w \quad (4)$$

$$l_n = 2a + 2(n-1)d_w \quad (5)$$

where:

l = length/width of the side of a square turn of copper

wire along x- or y-axis in metres

n = index of the coil layers in the x-y plane

a = half of the length of the side of a square turn of copper wire along x- or y-axis in metres

d_w = coil wire diameter in metres

$$z_1 = e \quad (6)$$

$$z_2 = e + d_w \quad (7)$$

$$z_3 = e + 2d_w \quad (8)$$

$$z_4 = e + 3d_w \quad (9)$$

$$z_m = e + (m-1)d_w \quad (10)$$

where:

e is the distance in metres from the center of the first turn in a layer of a square turns on x-y plane to point P along z-axis.

m = index of the square turns in the coil along z-axis.

It should be noted that m and n are the number of turns per layer and number of layers, respectively expressed in equations (11) and (12).

$$m = \frac{h}{d_w} \quad (11)$$

$$n = \frac{N}{m} \quad (12)$$

where: N is the number of turns in the coil.

By inspection, from the developed equations by (Misakian, 2000) for calculating the magnetic flux density

produced by the air-core rectangular loop of wire, the equations for finding the magnetic flux density produced by SAMMEC with significant coil wire diameter was derived. Substituting the general equation for the turn length and the distance from the centre of the turns to point P that is equations (5) and (10) into the equations developed by (Misakian, 2000) yielded the expression for parameters $C_{1,n}$ to $C_{4,n}$ in equations (13) to (16) and that for parameters $d_{1,n}$ to $d_{4,n}$ in equations (17) to (20). These parameters are for all the turns in the coil. Equations (21) to (24) express the wire turns corner distance from point P ($r_{1,n,m}$, $r_{2,n,m}$, $r_{3,n,m}$ and $r_{4,n,m}$) as a function of coil physical dimensions, distance from the center of the coil to point P, and coordinate of point P. The x-, y- and z-axis components of magnetic flux density as a function of parameters d , C , and r ; distance from the centre of the coil to point P; the coordinate of point P and the C , d and r index is as expressed in equations (25) to (27) respectively. And finally, the expression for the resultant flux density (B_T) at point P as the resultant of the three components is as shown in equation (28).

$$C_{1,n} = \frac{l_n}{2} + x \quad (13)$$

$$C_{4,n} = -\left(\frac{l_n}{2} + x\right) \quad (14)$$

$$C_{2,n} = \frac{l_n}{2} - x \quad (15)$$

$$C_{3,n} = -\left(\frac{l_n}{2} - x\right) \quad (16)$$

$$d_{1,n} = y + \frac{l_n}{2} \quad (17)$$

$$d_{2,n} = y + \frac{l_n}{2} \quad (18)$$

$$d_{3,n} = y - \frac{l_n}{2} \quad (19)$$

$$d_{4,n} = y - \frac{l_n}{2} \quad (20)$$

$$r_{1,n,m} = \sqrt{\left(\frac{l_n}{2} + x\right)^2 + \left(y + \frac{l_n}{2}\right)^2 + (z - z_m)^2} \quad (21)$$

$$r_{2,n,m} = \sqrt{\left(\frac{l_n}{2} - x\right)^2 + \left(y + \frac{l_n}{2}\right)^2 + (z - z_m)^2} \quad (22)$$

$$r_{3,n,m} = \sqrt{\left(\frac{l_n}{2} - x\right)^2 + \left(y - \frac{l_n}{2}\right)^2 + (z - z_m)^2} \quad (23)$$

$$r_{4,n,m} = \sqrt{\left(\frac{l_n}{2} + x\right)^2 + \left(y - \frac{l_n}{2}\right)^2 + (z - z_m)^2} \quad (24)$$

where r_1 , r_2 , r_3 and r_4 are the distances from the corner of the square turns of wire in the layers to the point P.

Note that n and m are as earlier defined and also $C_{1,n} = -C_{4,n}$; $C_{2,n} = -C_{3,n}$; $d_{1,n} = d_{2,n}$;

and $d_{3,n} = d_{4,n}$.

$$Bx_{n,m} = \frac{\mu I}{4\pi} \left(\sum_{i=1, j=1, k=1}^{4,n,m} \left[\frac{(-1)^{i+1}(z-z_k)}{r_{i,j,k}[r_{i,j,k}+d_{i,j}]} \right] \right) \quad (25)$$

where I is the loop current in amperes.

$$By_{n,m} = \frac{\mu I}{4\pi} \left(\sum_{i=1, j=1, k=1}^{4,n,m} \left[\frac{(-1)^{i+1}(z-z_k)}{r_{i,j,k}[r_{i,j,k}+(-1)^{i+1}C_{i,j}]} \right] \right) \quad (26)$$

$$Bz_{n,m} = \frac{\mu I}{4\pi} \left(\sum_{i=1, j=1, k=1}^{4,n,m} \left[\frac{(-1)^i d_{i,j}}{r_{i,j,k}[r_{i,j,k}+(-1)^{i+1}C_{i,j}]} - \frac{C_{i,j}}{r_{i,j,k}[r_{i,j,k}+d_{i,j}]} \right] \right) \quad (27)$$

where: Bx , By , and Bz are the x, y, and z components, respectively.

$$B_T = \left(\sum_{i=1, j=1}^{n,m} \left[(Bx_{i,j})^2 + (By_{i,j})^2 + (Bz_{i,j})^2 \right] \right)^{1/2} \quad (28)$$

2.2 COIL DESIGN

The coil design specifications for this study, based on Figure 1, are given in Table 1.

Table 1. Coil design specifications

S/N	Parameters	Value
1.	Required flux density at point P	0.06 T
2.	Core height (h)	4.5 cm
3.	Core length (l_1)	7.0 cm
4.	Core width (l_2)	7.0 cm
5.	Distance from the center of the first turn in a layer from point P (e)	0.0 cm
6.	Number of copper turns in the coil (N)	400

The resultant flux density at point P given in equation (28) is a function of the following parameters and variables: x , y , z , e , a , h , μ_0 , N , d_w and l_1 . Point P is on the z-axis, therefore the value of x and y at point P will be equal to 0. Since the value of e is equal to zero, point P will just be at the surface of the coil. The parameters a and h indicated in Figure 1 are the coil core dimensions and are constant once determined. To determine B_T in equation (28) any two of N , d_w and I can be varied simultaneously after selecting one of them. In this study, the value of N was selected and fixed while the value of d_w and I were varied because these two parameters have an established relationship in American Wire Gauge (AWG) standard chart.

Table 2. The extracted values of AWG, wire diameter and wire maximum

AWG	6	7	8	9	10	11	12	13
dw (mm)	4.11	3.67	3.26	2.91	2.59	2.3	2.05	1.83
I (Amp)	37	30	24	19	15	12	9.3	7.4

AWG	14	15	16	17	18	19	20
dw (mm)	1.63	1.45	1.29	1.15	1.02	0.91	0.81
I (Amp)	5.9	4.7	3.7	2.9	2.3	1.8	1.5

The diameter and maximum current-carrying capacity of the wire are related to AWG (Solaris-shop). Based on this relationship, the AWG value, corresponding wire diameter, and the maximum current value for the wires considered for the coil design in this study were extracted and presented in Table 2.

The relationship between the maximum wire current and wire diameter is shown in Figure 2, and it was used to generate equation (29) which relates the maximum current and wire diameter, by curve fitting the plots of Figure 2.

$$I = 2.1 \times 10^6 \times d_w^2 + 5.7 \times 10^2 \times d_w - 0.5 \quad (29)$$

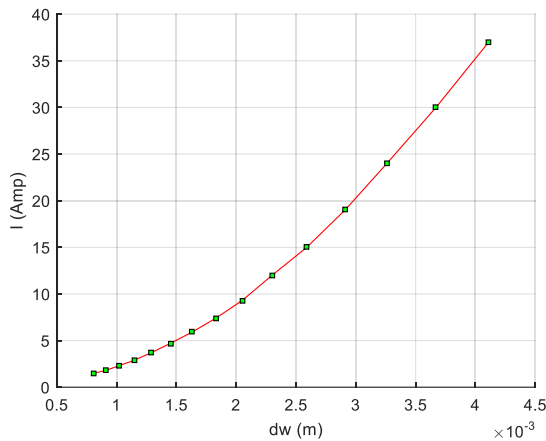


Fig. 2: Plot of wire maximum current against diameter

Using equation (28), the resultant flux density was plotted against the current for a given wire diameter for each of the possible wire sizes considered to construct the coil-design chart, as shown in Figure 3.

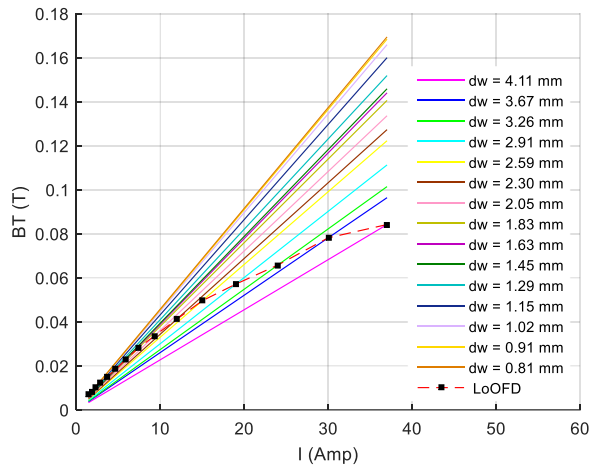


Fig. 3: The extracted coil-design chart

The range of current used for the plot is from the maximum current-carrying capacity of the wire with the smallest diameter to the maximum current-carrying capacity of the wire with the largest diameter. Also, by using the maximum current that can be carried by each of the wire sizes and equation (28) on the same axes of Figure 3, the maximum flux density that can be produced by the current in each of the wires was plotted against the current and is as shown with dash-dash line. This is a line of optimum flux density (LoOFD), as the peak flux density for each of the wires is obtained at the point of its intersection with that of the plot of flux density against current for a given wire diameter. The points of optimum flux density for each of the wires considered are also shown in black square spot in Figure 3.

2.3 DETERMINATION OF WIRE PARAMETERS

The technical and economic factors are the two major factors to be considered in magnetic wire selection in the construction of electromagnets. These factors depend on

electrical and physical parameters of magnetic wire as contained in the magnetic wire chart (Inc., 1996; Solaris-shop). The parameters considered in this study include the maximum current the wire can withstand, wire's resistance, and weight.

These electrical and physical parameters are functions of wire length because their values are normally given in "per kilometer" of the length of each of the wire. Therefore, the parameters are determined by firstly deriving the formula for calculating the length of the wire. The sectional view of the coil shown in Figure 1 is presented in Figure 4, illustrating the coil layers with the length and width of the first layer (l_1), length and width of the n^{th} layer, wire diameter (d_w) and coil height (h).

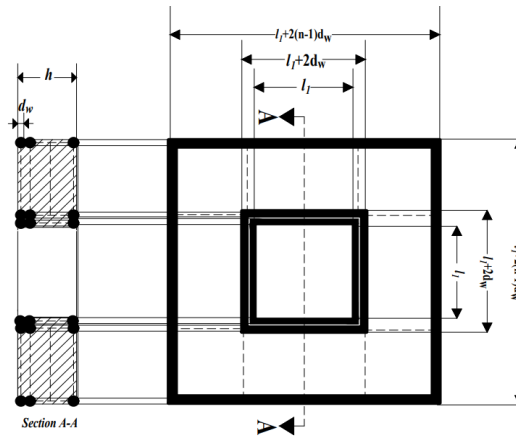


Fig. 4: Sectional view of the square coil

Considering Figure 4, the perimeters of a wire turn in the 1st, 2nd, 3rd, 4th, $(n-1)^{th}$ and n^{th} layers in the x-y plane are expressed in equations (30), (31), (32), (33), (34), and (35), respectively.

$$P_0 = 8a \quad (30)$$

$$P_1 = 8a + 4d_w \quad (31)$$

$$P_2 = 8a + 12d_w \quad (32)$$

$$P_3 = 8a + 20d_w \quad (33)$$

$$P_{n-1} = 8a + 4d_w + (n-2)8d_w \quad (34)$$

$$P_n = 8a + 4d_w + (n-1)8d_w \quad (35)$$

It can be seen that equations (31) - (35) follows arithmetic progression pattern with P_1 as the first term, $8d_w$ as the common difference, n as the number of terms and P_n as the last term. Therefore, the total length of wire in the entire layer with one turn per layer (L_T) and for the entire layers and turns (L_{ET}) is as expressed in equations (36) and (37) respectively.

$$L_T = P_0 + \frac{n}{2}(16a + 8nd_w) \quad (36)$$

$$L_{ET} = m \left[P_0 + \frac{n}{2}(16a + 8nd_w) \right] \quad (37)$$

The expression for the resistance of the wire (R_w), wire copper loss (P_w) and the weight of the wire (W_w) is as expressed in equations (38), (39), and (40) respectively.

$$R_w = \frac{L_{ET} \times R_{pkm}}{1000} \quad (38)$$

$$P_w = I^2 R_w \quad (39)$$

$$W_w = \frac{L_{ET} \times W_{pkm}}{1000} \quad (40)$$

where,

R_{pkm} = wire resistance Ohms per km

W_{pkm} = wire weight in kg per km

3 RESULTS AND DISCUSSIONS

As can be seen from Figure 2, the relationship between the maximum current a wire can carry and its diameter is non-linear, as revealed by equation (29) obtained by curve fitting the graph of Figure 2 is quadratic. The corresponding value of current for any given value of wire diameter or vice versa can be obtained from Figure 2 or through a calculation using equation (29).

It can be seen from Figure 3 that for a given value of current the value of flux density increases with a decrease in the value of wire diameter. This is due to the reduction in the distance of point P from the centre of the coil turns (Refer to Figure 1). Because the distance of point P from the centre of any of the coil turns is directly related to the wire diameter as can be seen in equation (10). The point of intersection of the LoOFD with the line of plot of magnetic flux density against the current for a given value of wire diameter gives the value of wire optimum flux density. Any point in the area above the LoOFD in Figure 3 is forbidding for the design because the wire material cannot withstand the resulting heat generated due to copper loss as the value of current in this area is higher than the permissible value for a given wire diameter. But any point below it is safe, it should be noted that the point may not be the optimum point for the wire diameter considered as the optimum points are along the LoOFD.

The coil-design chart of Figure 3 can be used for either optimal or cost-effective design of any size of air-core square electromagnet coil. It can be inferred from Figure 3 that if the wire production technology can be improved to reduce the wire resistance per unit length, the LoOFD will move up and the optimum magnetic flux density for each of the wire will be improved. If the wire resistance can be reduced to 0 Ω the imposition of the limit due to copper loss will not be necessary, the only factor that will then determine the value of flux density produced by any turn of wire will be the distance between point P and the centre of the turns of wire in the coil. Under this condition, the LoOFD will become vertical passing through the point of highest current (in this study 37 A) and connect all the lines generated by the plot of flux density versus current for each of the wire diameters. Then the optimum flux density will be achieved at the highest current for each of the wire diameters.

If this condition can be achieved the wire with the smallest diameter will produce the highest flux density for a given value of current while that with the largest diameter will produce the lowest flux density and the best to be selected as applied to this study will be the wire with a diameter of 0.81 mm which will produce a flux density of 0.06 T with current of 13.1 A. Since the desired flux density is 0.06 T and the wire resistance is finite, the appropriate wire size can be determined using Figure 3, and it can be seen from the figure that only 3 wires with diameter 4.11mm, 3.67mm, and 3.26mm out of the 15 wires present on this graph can produce this value of flux

density without the current exceeding the wire limit. Each of these wires size will produce this flux with a different value of current (26.4 A, 23.1 A, and 21.9 A for 4.11 mm, 3.67 mm, and 3.26 mm diameters, respectively). To select one out of the 3 wires their copper losses and weight which determine the technical and economic factors respectively were compared to create room for selection justification. The wire length, resistance, copper loss, and weight for each of the 3 wires, was obtained using equations (37), (38), (39), and (40) respectively, and is presented in Table 3.

Table 3. Parameters of the potential coil wires

Wire diameter (m)	Current (A)	Length (m)	Resistance (Ohm)	Copper loss (W)	Weight (kg)
0.00411	26.4	355.31	0.4604	320.91	42.00
0.00367	23.1	307.00	0.5017	267.69	28.79
0.00326	21.9	267.01	0.5502	263.87	19.86

Based on the design specifications in Table 1 and the value of wire parameters presented in Table 3, the optimal wire is that with 0.00326 m diameter because it has the lowest copper loss and weight followed by 0.00367 m diameter and the least suitable is the 0.00411 m diameter.

4 CONCLUSION

The model equations for the design of SAMMEC with significant wire diameter were developed. The relationship between the current and the wire diameter as contained in the AWG chart was both graphically and mathematically established. The graphical method for the design of SAMMEC with significant wire diameter was developed and the optimum flux density for each gauge of the magnetic wire considered in this study was established.

Furthermore, the equations for determination of the coil wire length and the parameters were also developed. The range of possible wire size for the design specifications and the corresponding value of current was determined from the coil-design chart. Based on the design specifications given in this study the diameter, length, resistance, copper loss, and weight of the selected wire were found to be 0.00326 m, 267.01 m, 0.5502 Ω , 263.87 W, and 19.86 kg respectively. The optimum magnetic flux density that can be produced by the selected wire is 0.066 T, while the corresponding current and copper losses are 24 A and 316.92 W, respectively.

In future work, finite element method is being proposed for the study of field distribution across the entire geometry of the coil rather than at a single point.

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