Analysis of Rogowski Coil Shielding Effectiveness with External Vertical Magnetic Field Using FEM

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***Abstract*— Rogowski coil (RC) is shielded to reduce the effect of disturbed magnetic fields and magnetic coupling between RC and external magnetic fields. For proper design of magnetic shielding of the RC, shielding effectiveness must be calculated. The magnetostatic approach is used for analyzing shield effectiveness. This paper discusses the proposed magnetic circuit model considering hollow cylindrical structure having rectangular cross section of shielding. Magnetic shielding effectiveness in RC is examined under an external vertical magnetic field. Shielding effectiveness is calculated by considering the horizontal and vertical air gap inevitable for magnetic shielding. For validation purpose a wide range of design parameters are considered and designed using ANSYS Maxwell. Finite Element Method (FEM) is used in the simulation and its results are reported. Simulation results shows that, the magnetic shielding effectiveness relates to the relative permeability of the shielding and airgap in shield. From the results it is observed that, shield effectiveness for vertical air gaps is greater than horizontal air gaps for the range of shielding thicknesses and distances under study. The impact of relative permeability on magnetic shield effectiveness has been investigated. Results of simulations indicate that shield effectiveness is not affected for shield designed with higher relative permeability materials.**

Keywords—* *Airgap, FEM, Magnetic shield, Rogowski coil, Shielding effectiveness, Vertical magnetic field

I. INTODUCTION

ROGOWSKI Coil (RC) is widely known as a primary current sensor. They have been used for current measurements in high-voltage applications for several decades. Their non-ferromagnetic cores, RCs can measure currents over a wide range without saturation. RCs are susceptible to external magnetic fields, which is a weakness. Magnetic shielding reduces magnetic coupling between RCs and external magnetic fields [1]-[2].

For many years, current comparators have used magnetic shielding to reduce stray and external magnetic fluxes [3],[4]. It is important for Rogowski coils to be shielded magnetically to prevent leakage of currents in their ratio windings and stray magnetic flux, the static stray flux is particularly crucial for large direct-current comparators [5]. In order to measure shielding efficiency, the magnetic field at a point without the shield can be compared with the magnetic field at the same point with the shield. In order to properly design of shield for the Rogowski coil, an efficient method of calculating shielding effectiveness is needed [6].

In [7] discussed, three types of stray and leakage magnetic fields/flux are associated with Rogowski coils. Their field directions vary based on their coil axis orientation. These are the vertical, horizontal, and dipole-type fields also magnetic shielding that reduces leakage fields generated by ratio windings has also been investigated considering magnetostatic approach.

Magnetic shielding without air gaps has been examined in the literature using magnetic circuits [8],[9], numerical methods [10]-[12] as well as experiments [8]. As discussed in [13], magnetic shielding reduces electromagnetic errors and electrostatic shielding reduces capacitive errors in transformer-like devices. A magnetic circuit approach was used to compute the double-layer magnetic shielding under horizontal external magnetic fields discussed in [14]. There is an analysis of the impact of magnetic shield with air gaps on adverse effects caused by stray flux from vertical and horizontal directions. It also presents some simple formulas for calculating the shielding effectiveness of horizontal and vertical air gaps. In addition, FEM and experiment results are presented in [5].

This paper discusses the proposed model of magnetic circuit consist of rectangular shell shield structure considering external vertical magnetic field. This magnetic circuit model considering hollow cylindrical structure having rectangular cross section of shielding that could be used to examine magnetic shield effectiveness in Rogowski coil. It is necessary to take into account the air gap inevitable for magnetic shielding in order to calculate its effectiveness. In this paper horizontal and vertical airgap are consider while calculating shield effectiveness.

A rectangular cross section of Rogowski coil is surrounded by four tape-wounded on magnetic cores with horizontal air gaps, as shown in Figure 1. In power system applications, tape-wound magnetic cores are chosen because of their simplicity. This Fig.1 illustrates a half-section of a magnetic shield containing of a hollow shell having rectangular cross section surrounding a nonmagnetic core of Rogowski coil. The primary current having a fundamental frequency of 50 Hz, which can be determined using RCs in high voltage power systems. Magnetic shielding structures with cylindrical shapes can also be built with vertical air gaps. Therefore, the proposed method can be applied to devices with vertical and horizontal air gap.

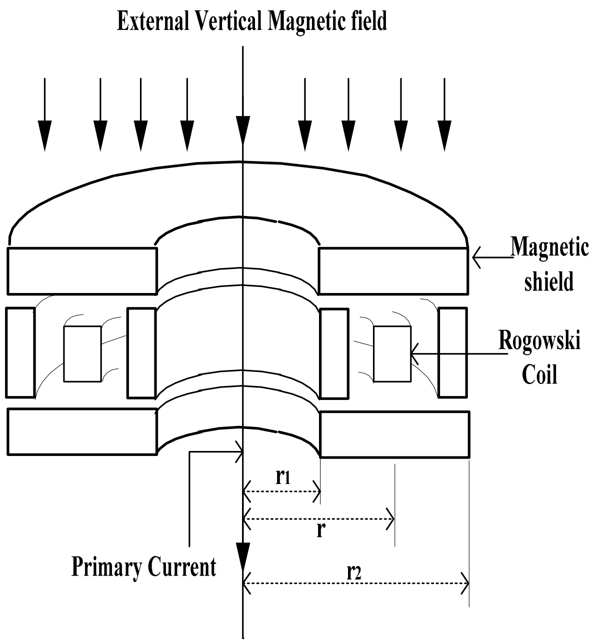

Fig. 1 cutaway view of the non-magnetic core of the Rogowski coil surrounded by the horizontal airgap of magnetic shield

In general, magnetic shielding effectiveness is determined the ratio of magnetic field intensity without a magnetic shield to magnetic field intensity with a magnetic shield. Magnetic shielding may, however, change magnetic field intensity vector magnitudes and directions differently depending on location. As part of the FEM simulations in this paper, before and after magnetic shielding, the average of magnetic field intensities is considered for calculating shield effectiveness.

II. THEORY OF MAGNETIC CIRCUIT MODEL

The shielding effectiveness is computed by averaging the magnetic field intensities before and after magnetic shielding for comparator without considering the airgap in shield for external horizontal and external field. The shielding effectiveness S is expressed as

$$S = \frac{\overline{H_0}}{\overline{H_T}} \tag{1}$$

where, $\overline{H_0}$ and $\overline{H_T}$ are before and after magnetic shielding the average magnetic field intensities in the Rogowski coil, respectively,

Shield axis is perpendicular to external magnetic field, corresponding magnetic shielding effectiveness of Rogowski coil without airgap as given in (2). Similarly, the external magnetic field direction is parallel to shield axis, corresponding magnetic shielding effectiveness of Rogowski coil without airgap in (3) that explained in [6].

$$S_H = \frac{\mu_s}{\mu_0}\frac{8}{l^2}\frac{ab(c-a)}{c-b-2a} \tag{2}$$

$$S_V = \frac{8}{3}\frac{\mu_s}{\mu_0}\frac{ab}{c(c-a)} - \frac{2a}{c} + 1 \tag{3}$$

where, S_H is the shield effectiveness for horizontal external field and S_V is the shield effectiveness for Vertical external field

Magnetic shielding effectiveness values for horizontal external fields are higher than those for vertical external fields due to less reluctances of horizontal magnetic shells with no air gaps in the literature [5]. Hence horizontal external field will not be discussed in this paper. To analyse the magnetic shielding effectiveness of complicated structures, thus Finite Element Method (FEM) was employed. However, previous studies overlooked the air gap adverse effects. This paper examines the adverse effects of shielding with air gaps with an external vertical magnetic field.

III. MAGNETIC SHIELD WITH HORIZONTAL AND VERTICAL AIR GAP

A rectangular cross section of Rogowski coil is surrounded by four tape-wound magnetic shields with horizontal and vertical air gap as shown in Fig 2. and Fig3. The magnetic shield consisting of a toroidal hollow shell surrounding with rectangular cross of magnetic shield to a Rogowski coil. Rogowski coils have a non-magnetic core which allows them to measure high currents without saturation.

The thickness of magnetic shield, distance between shield and coil, outer length of square magnetic shield, height of Rogowski coil and horizontal or vertical air gap are a, b, c h & g respectively. The distance between point entering the flux and leaving the flux in magnetic shield is l. The permeability of shield and air are μ_s and μ_0 respectively. Consider the Rogowski coil axis is parallel to the external magnetic flux. In this case, both the left and right air gaps are 'g'. The non-magnetic core of Rogowski coil has unity relative permeability (μ_0).

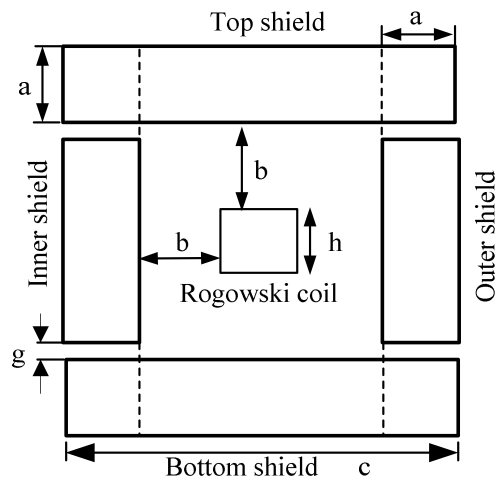

Fig.2 Magnetic circuit model with horizontal airgap

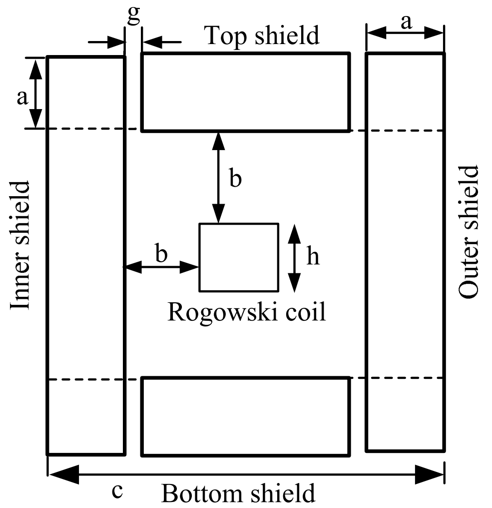

Fig.3 Magnetic circuit model with vertical airgap

As a result of the external vertical magnetic field, the flux is separated into three fluxes: Φ_1, Φ_2 , and Φ_3, to account for the flux entering on the sides and from the top shield given in (4), (5) and (6). To account for the flux entering from the sides and the top, a vertical magnetic field produces three fluxes 1, 2, and 3. Due to the high permeability of shielding materials, flux entering from inner and outer sides of shield is neglected. hence, fluxes incoming and leaving shielding are intended according to design parameters.

$$\Phi_1 = \mu_0 H_0 \pi[(r_2 - a)^2 - (r_1 + a)^2] \quad (4)$$

$$\Phi_2 = \mu_0 H_0 \pi[a(a + 4r_1)] \quad (5)$$

$$\Phi_3 = \mu_0 H_0 \pi[a(4r_2 - a)] \quad (6)$$

where, r_1 and r_2 is inner and outer radius of toroidal core as shown in Fig. 1.

For a vertical external magnetic field, the formulas in [5] assume equal flux distributions in the inner and outer shields. As a result, when thicknesses and distances of magnetic shielding have been changed, these assumptions lead to errors in the analysis of effectiveness of magnetic shield. Hence magnetic circuit model for toroidal shape of Rogowski coil with a vertical external magnetic field is proposed in this paper.

This paper proposes a magnetic circuit that accounts for the cylindrical or toroidal shape of RCs in the presence of a vertical external magnetic field. Magnetic shielding of current comparators can also be examined and designed using the proposed magnetic circuit model. Magnetic shielding effectiveness for vertical external magnetic field, for horizontal air gap is,

$$S_{Vh} = \frac{c - 2a}{cg}\left(\mathrm{a} + \mathrm{g} - \frac{a(3c - 3a - 4g)}{3(c - a) + 4g(\mu_s - 1)} \right) \quad (7)$$

Magnetic shielding effectiveness for vertical external magnetic field, for vertical air gap is,

$$S_{Vv} = \frac{c - 2a}{cg}\left(2\mathrm{a} + \mathrm{g} - \frac{2a(3c - 3a - 2g)}{3(c - a) + 2g(\mu_s - 1)} \right) \quad (8)$$

IV. FEM SIMULATION RESULT

A FEM simulation performed by the ANSYS Maxwell [15]. Simulation studies are conducted in 2-D instead of 3D to maximize computer memory, speed up simulations, and minimize energy percent error. This 2-D structure of Rogowski coil is design and simulated in magnetostatic solver in order to calculate shield effectiveness. A uniform magnetic field is created which represents an external vertical magnetic field of 1000 A/m on which a nonmagnetic core of Rogowski coil is placed with a magnetic shield.

A. Effect of shield thickness and distance between the coil and shield on shield effectiveness considering horizontal air gap and vertical airgap

By varying the thickness of magnetic shield ‘a’ and distance between shielding and coil ‘b’ are used for calculating effectiveness of shield using the FEM simulations in magnetic circuit model. With steps of 5 mm, the thickness of shield and the distance between shield and coil are altered between 5 and 30 mm. The magnetic field distribution for horizontal airgap in the range of 0.8712 to 1.0923 mWb/m as shown in Fig.4. similarly for vertical airgap 0.8710 to 1.0924 mWb/m as presented in shown in Fig. 5.

A nonuniform magnetic field between the outer and inner shields is illustrated in Fig. 4 and Fig. 5. Magnetic field lines enter the shield from the top surface of top shield, sides of top shield, interior surface inner shield, and outside surface of outer shield.

Magnetic shielding effectiveness value from simulation are illustrated in Table I and Table II for horizontal and for vertical air gap respectively. From Table I and Table II, it is noticeable that shield effectiveness for horizontal air gap is lesser than that of vertical air gap as per FEM simulation, because, external magnetic field are parallel to the gap in shield.

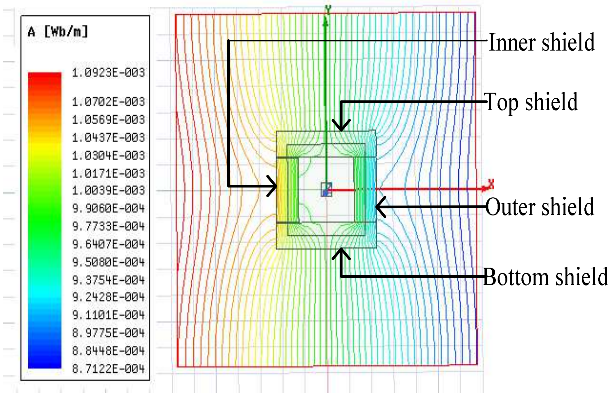

Fig.4 Magnetic field distribution for Rogowski coil with horizontal air gap for vertical external Field for a=10mm, b=10mm and g=0.2mm

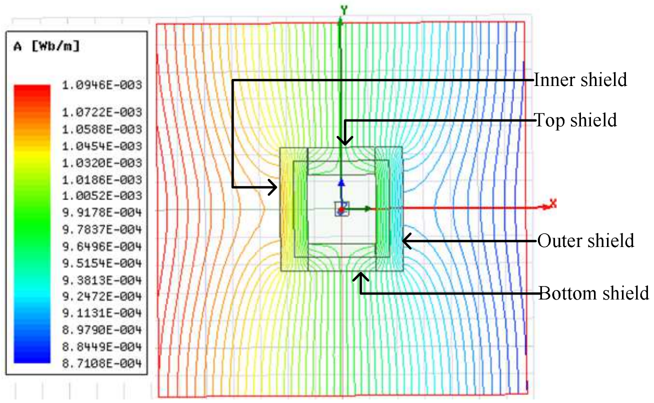

Fig.5 Magnetic field for Rogowski coil with vertical air gap for vertical external Field for a=10mm, b=10mm and g=0.2mm

TABLE I. MAGNETIC SHIELD EFFECTIVENESS FOR HORIZONTAL AIR GAP g=0.2mm

a\b (mm)	5	10	15	20	25	30
5	8.096	8.991	9.456	9.861	10.006	10.28701
10	13.297	14.419	15.358	15.915	16.398	16.70844
15	18.089	19.477	20.508	21.362	22.172	22.67574
20	22.691	24.236	25.529	26.553	27.412	28.11358
25	27.166	28.95194	30.364	31.416	32.530	33.33333
30	31.884	33.6587	35.038	36.24502	37.313	38.3226

TABLE II. MAGNETIC SHIELD EFFECTIVENESS FOR VERTICAL AIR GAP, g=0.2mm

a\b (mm)	5	10	15	20	25	30
5	19.716	17.319	16.226	15.540	15.047	14.781
10	46.345	37.690	33.592	31.632	30.235	29.019
15	80.499	62.781	54.723	50.114	46.911	44.899
20	119.426	91.840	78.878	71.157	65.846	62.635
25	166.56	124.607	105.298	94.051	86.639	81.638
30	214.722	160.097	133.742	118.637	108.732	101.40

B. Effect of change in airgap on shield effectiveness

In a magnetic shield, air gaps play a crucial role in shielding effectiveness. The relative permeability of shield is 4000, The shield thickness and distance between shield and coil are 10mm and 10mm respectively. shield air gap is altered from 0.2 to 1.8 mm. It is observed that shield effectiveness for horizontal air gap is lower than that of vertical air gaps as per FEM simulation shown in Table III, also There is a sharp decrease in shield effectiveness as the horizontal and vertical airgap increases; after g=1.2mm, there is little variation in shield effectiveness as given in Fig.6.

TABLE III. RELATION BETWEEN RELATIVE AIR GAP AND SHIELD EFFECTIVENESS

S. No.	Air gap (g) (mm)	Shielding Effectiveness (S_V)	
		Horizontal airgap	**Vertical Airgap**
1	0.2	14.41961	37.69043
2	0.4	7.934619	20.99915
3	0.6	5.701254	14.99886
4	0.8	4.581272	12.06553
5	1	3.891353	10.30437
6	1.2	3.394342	9.056185
7	1.4	3.062787	8.159306
8	1.6	2.822387	7.528834
9	1.8	2.626671	7.011375

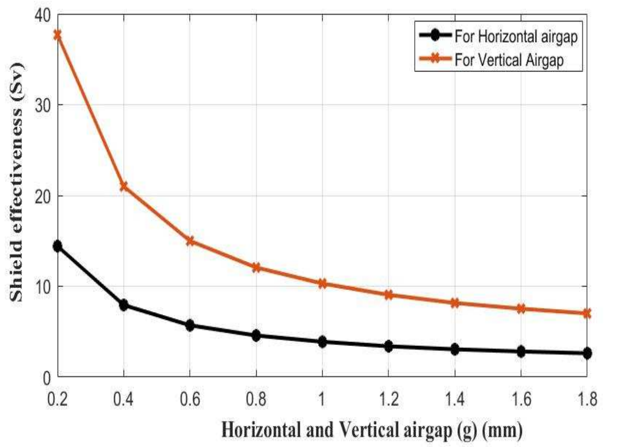

Fig.6. Relation between air gap and shield effectiveness for horizontal vertical airgap.

C. Effect of change in permeability on shield effectiveness

The shield effectiveness of vertical and horizontal air gap is affected by the relative permeability of the magnetic shielding material. Furthermore, for specified dimensions of shielding, the impact of relative permeability on magnetic shielding effectiveness was investigated by varying it between 1000 and 100000. The shield thickness and distance between shield and coil are 10mm and 10mm respectively. The effectiveness of magnetic shielding varies with relative permeability is described in Table IV, but up to the certain range. For more clarity purpose the graph is plotted between relative permeability of shield and magnetic shield effectiveness as shown in Fig. 7.

TABLE IV. RELATION BETWEEN RELATIVE PERMEABILITY AND SHIELD EFFECTIVENESS

S. No.	Relative permeability of shield (μ_s)	Shield effectiveness (S_V)	
		Horizontal airgap	Vertical airgap
1	1000	13.65187	32.31226
2	4000	14.41842	37.69043
3	10000	14.58232	38.98502
4	20000	14.63779	39.43604
5	40000	14.66569	39.66537
6	60000	14.67501	39.7424
7	80000	14.67967	39.78102
8	100000	14.68247	39.80422

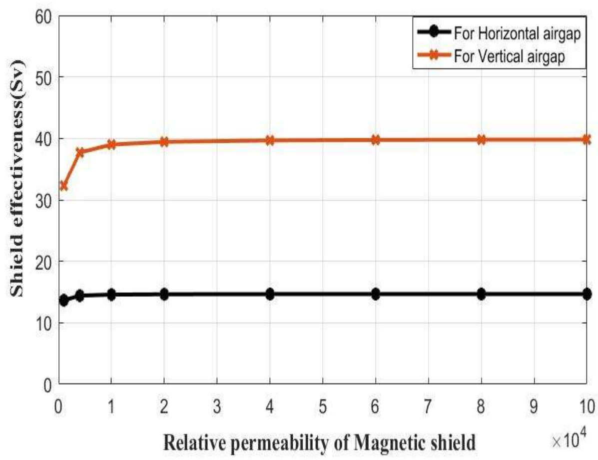

Fig.7. Relation between relative permeability of magnetic shield and shield effectiveness for horizontal and vertical air gap

V. Conclusion

A hollow rectangular cross-section circular magnetic shield with vertical and horizontal air gap model for Rogowski coil (RC) is proposed and developed using ANSYS Maxwell. The Finite Element Method (FEM) is used for calculating magnetic shielding effectiveness with sensible accuracy for a wide range of design parameters. From the simulations results, it is observed that vertical air gaps have greater shield effectiveness than horizontal air gaps for the shielding thicknesses and distances varied from 5 to 30 mm. The shield effectiveness for vertical airgap is nearly twice that of horizontal airgap. The effectiveness of shielding as a function of relative permeability and airgap in magnetic shield. Changes in the shield effectiveness is depending on horizontal and vertical airgaps up to 1.2 mm, and no changes is observed beyond 1.2 mm. Also, simulations are performed for investigating the impact of relative permeability of shielding material on shielding effectiveness. From simulation results, it is observed that shield designed with higher relative permeability materials.

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