# Planar Electromagnetic Current Sensor for Distribution Transformer Application


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***Abstract*—Planar Rogowski Current Sensor works on the principle of electromagnetic induction as conventional iron core current transformers. In iron core current transformer, the core saturates beyond a certain current value which introduces nonlinearity in the desired output. Unlike iron-core current transformer, planar rogowski is an air core device and used for measuring alternating and transient currents. A Planar Rogowski current sensor suitable for high current measurements especially for the application of three phase distribution transformer is designed. In order to develop a sensitive and accurate Planar Rogowski current sensor a systematic approach involving electromagnetic analysis and simulation of printed circuit board (PCB) based rogowski current sensor is discussed. Design calculation is validated by developing prototype and testing. Sensitivity analysis and linearity in the output voltage is studied.**



***Keywords—Rogowski Coil, Finite Element Analysis, Current Sensor, Electromagnetics, Distribution Transformer***


## I. INTRODUCTION

**R**eliable and safe operations of smart grid demands reliable and safe sensors for several measurements. Though many sensors are available (i.e., Voltage, Temperature measurement) but when it comes to high current measurement in electrical distribution system, electrical industry still rely on conventional iron-core current transformers (CTs) which are bulky both in size & weight and saturate at higher currents. Comparatively Rogowski coils have less weight being coreless (air core) and output is linear [4] because of no magnetic saturation.

Rogowski coils were introduced in 1912 to measure magnetic fields. At that time, it could not be used for current measurements because the coil output power was not sufficient to drive measurement equipment [1]. With the parallel advancement in microprocessor based numerical relays since few decades, the doors are opened for low power and low burden planar rogowski current sensors for switchgear protection and control. Rogowski current sensing technology is going through significant technological advancement. Rogowski sensor is moving from toroidal flexible rogowski coil concept to printed circuit board based coil winding technology which calls for very thin wire winding on PCB itself. As now manufacturing of very thin wire winding on PCB is possible with extreme accuracy, it makes planar rogowski current sensors more accurate and cost effective compared to its predecessors. Rogowski coils do not use any magnetic material in their cores; hence the coils will not be saturated [1].

Currently, Electrical Utilities are using online energy monitoring and SCADA systems. Observing voltage, current, power factor at various nodes on distribution system gives a lot of information which leads to loss and cost saving for utilities. In the course of the development of smart-grid infrastructure, electrical power distribution systems need smart and reliable sensors for monitoring and control of real time energy consumption.

It is well known fact that most of the distribution transformers (DTs) operate on unbalance loading condition; hence it is essential to monitor online loading of transformers to take corrective measures including maintenance of DTs so that their life can be enhanced. The suitability of planar rogowski current sensor is therefore undertaken for development.

## II. DESIGN

The planar rogowski current sensor consists of multiple PCB based sensors (B1-B6). These multiple sensors are normally mounted on a single base board PCB as shown in Fig.1.

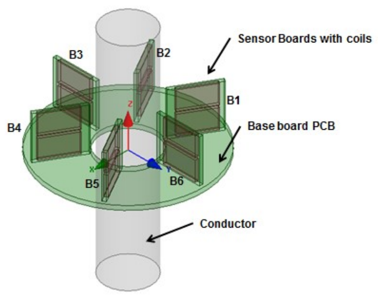


Fig.1. Planar Rogowski model

Each sensor board has multiple windings and multiple numbers of turns and all coils are connected together through a conduction path provided on base board. The sensitivity of individual sensor PCB depends upon orientation with magnetic field, the number of layers, number of turns (tracing) etc. When this sensor is put nearby an alternating current carrying conductor, time varying magnetic field links with the coils and voltage is induced in the coils due to electromagnetic induction. The voltage generated is proportional to the rate of change of current di/dt and mutual inductance.

The main advantages [2] of air-cored planar rogowski current sensor over iron core current transformer are:

(1) Planar Rogowski has a far better response [3] to fast-changing currents, due to their lower inductance.

(2) Planar Rogowski is highly linear even when subjected to large currents.

(3) Less size and less weight compared to iron core CT.

(4) More accurate and sensitivity of Planar Rogowski current sensor is high.

## III. Winding Arrangement

- Coil is wound on sensor board.
- Multiple layers of winding of certain thickness equally.
- Adjacent windings are insulated from each other.
- Conductor thickness and distance between two conductors is distributed equally.
- All bottom coils are connected in series and in return path all top coils are connected in series.
- All the windings are wound in clockwise direction.

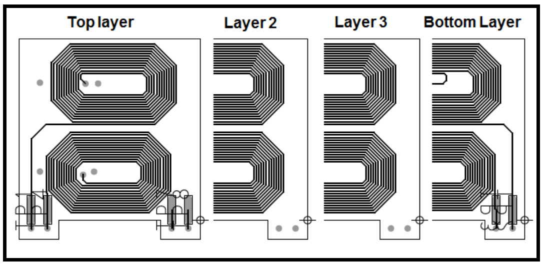


Fig.2. Winding arrangement in a sensor board

- Sensor boards are mounted and soldered over a PCB base board.
- PCB base board having tracks connects all sensor boards in series.
- Output voltage can be increased with increase in number of coils and sensor boards.
- Coils can have horizontal or vertical arrangements.
- The turns are uniformly distributed over the PCB sensor board with equal spacing between turns.
- Inner diameter of a planar rogowski sensor can be designed to suit according to the conductor diameter.
- The closer the coils from the conductor, more the flux linkage and hence more output voltage is generated for a given current.

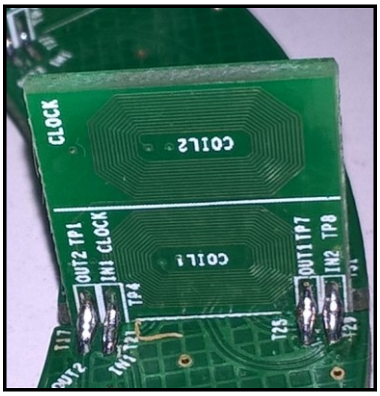


Fig.3. Sensor board with coils

## IV. Electromagnetic Analysis & Simulation

The output voltage generated by planar rogowski current sensor can be easily predicted by calculation as well as electromagnetic simulation.

Output equation : $V = N\omega\Phi$

Where,

$N$ = Number of coil turns

$\omega$ = Angular frequency

$\Phi$ = Magnetic flux linkage with coil

The magnetic flux ($\Phi$) can be found out by magnetic field (B) and the effective coil area (A) for which the coil is designed. And to calculate magnetic field we can find it by

$B = \mu_0 I / 2\pi r$ (Tesla)

$\mu_0$ is the Permeability of air, which is equal to $4\pi \times 10^{-7}$ H/m. I is the current flowing through conductor A, r is the radius of ID and OD of coil from center in meter. Similarly, magnetic field can be evaluated from simulation analysis. A pictorial view of a 3D simulation of a typical planar rogowski design is shown below:

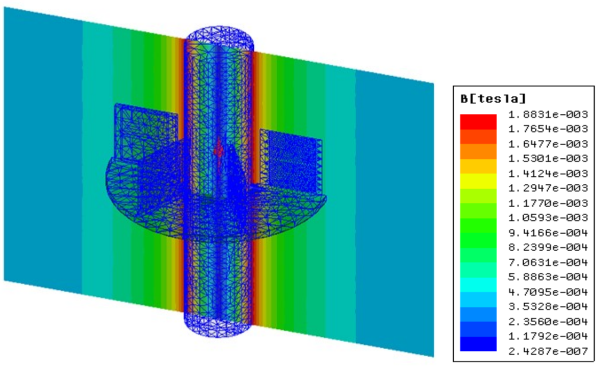


Fig.4. Electromagnetic Simulation of Planar Rogowski

ANSYS, Maxwell FEM simulation software is used to simulate 3D Eddy current electromagnetic analysis of a planar rogowski design. 100A alternating current is applied to conductor and average of maximum magnetic field is plotted in the effective area of the coil to estimate the magnitude of magnetic field. The resultant magnetic field linking with a coil is found to be 0.85 mT for 100A current flowing through conductor. The output voltage was thus calculated from magnetic field.

Similarly, various simulations are carried out for different current and the output was evaluated which is shown in Table.1 below:

### *A. Output Calculation Table*

| Current (A) | Calculated Value (mV) | Calculated by FEM "B" Value (mV) |
|---|---|---|
| **100** | 11.07 | 10.69 |
| **200** | 22.14 | 21.42 |
| **300** | 33.34 | 32.12 |
| **400** | 44.42 | 42.83 |
| **500** | 55.49 | 53.54 |
| **600** | 66.56 | 64.25 |
| **700** | 77.63 | 74.95 |
| **800** | 88.70 | 85.66 |
| **900** | 99.90 | 96.37 |

Table.1

### *B. V-I Curve*

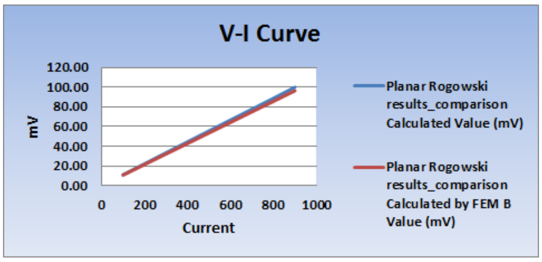


Fig.5. Calculated V-I Characteristic

In order to understand the accuracy of the above data, graph is plotted for calculated and simulated value. Plot shows that output mV generated by planar rogowski current sensor is linear in nature proportional to the input current.

Output magnitude increases with increase in magnitude of alternating current.

## V. Testing & Result

Design prototype was developed and tested and results are compared with calculations. During testing 0-1500A primary injection source was used. Current increased in 100A steps and linear output is observed in result.

### *A. Test Results*

| Current(A) | Calculated Value (mV) | Calculated by FEM "B" Value (mV) | Tested (mV) |
|---|---|---|---|
| **100** | 11.07 | 10.69 | 11.3 |
| **200** | 22.14 | 21.42 | 22.2 |
| **300** | 33.34 | 32.12 | 33.2 |
| **400** | 44.42 | 42.83 | 44.2 |
| **500** | 55.49 | 53.54 | 55.0 |
| **600** | 66.56 | 64.25 | 66.0 |
| **700** | 77.63 | 74.95 | 76.7 |
| **800** | 88.70 | 85.66 | 87.6 |
| **900** | 99.90 | 96.37 | 99.0 |

Table.2

### *B. V-I Curve with Test result*

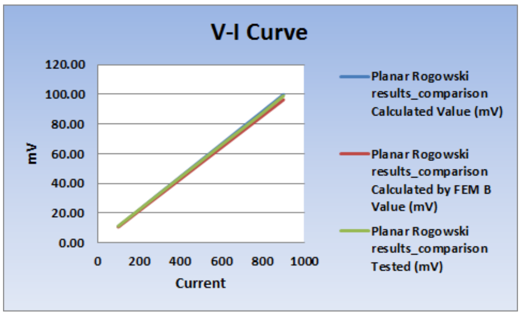


Fig.6. V-I Characteristic with Test Results

Studying the V-I characteristic of the plot, it is observed that Tested results are quite in line with the calculated value.

### *C. Sensitivity Analysis*

Further, Sensitivity analysis is done to predict error in output by performing FEM analysis.

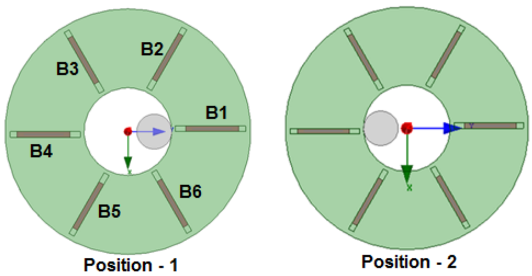


Fig.7. Sensitivity analysis

Conductor is positioned in center as well as extreme two positions and magnitude of magnetic field is noted in each coil individually by FEM analysis to analyze the error in output due to variation in positioning of planar rogowski current sensor.

The Table.3 depicts the magnetic field values observed in all sensor boards (B1 to B6) for the conductor positioned in three different positions:

| Position | Centre | | Position - 1 | | Position - 2 | |
|---|---|---|---|---|---|---|
| Current(A) | 1 | 1500 | 1 | 1500 | 1 | 1500 |
| B1 | 8.53 | 12.80 | 12.76 | 19.25 | 6.20 | 9.27 |
| B2 | 8.45 | 12.68 | 9.52 | 14.39 | 6.93 | 10.41 |
| B3 | 8.48 | 12.68 | 6.88 | 10.27 | 9.88 | 14.79 |
| B4 | 8.48 | 12.76 | 6.13 | 9.23 | 12.87 | 19.31 |
| B5 | 8.41 | 12.72 | 7.03 | 10.48 | 9.48 | 14.25 |
| B6 | 8.43 | 12.66 | 9.81 | 14.76 | 6.86 | 10.35 |
| **Bavg** | **8.46** | **12.72** | **8.69** | **13.07** | **8.70** | **13.06** |
| Unit | uT | mT | uT | mT | uT | mT |
| **mV** | **0.11** | **160.02** | **0.11** | **164.39** | **0.11** | **164.35** |

Table.3

It was observed that with change in position of sensor there is little error in output at lower currents and at higher currents error can go up to +2.7% at 1500A for this particular design.

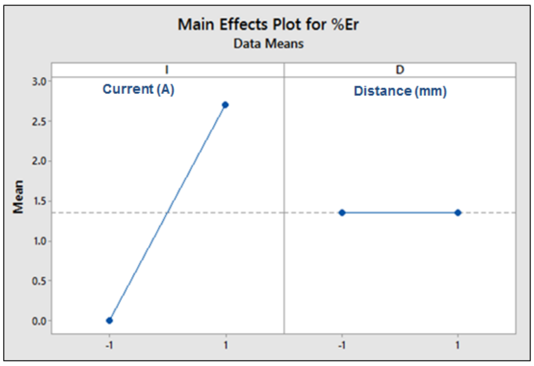


Fig.8. DoE of %Error in output with Current and Position variation

It can be seen from above DoE plot that variation in distance of conductor has not much significant effect in error in output. Hence, output voltage and %error can be predicted by performing electromagnetic simulation of planar rogowski current sensor.

## VI. Application & Prototype

Fundamentally, planar rogowski can be used everywhere for alternating current measurement. As stated earlier this planar rogowski is designed to use for current measurement of Distribution Transformer. Hence, this design concept is extended to develop a prototype suitable for 1 MVA Distribution Transformer.

Final Prototype consists of multiple sensor boards equally distributed in two parts of PCB. Base board is designed which can be split-up and coil winding of both side of sensor boards are connected with male-female connectors provided on base board.

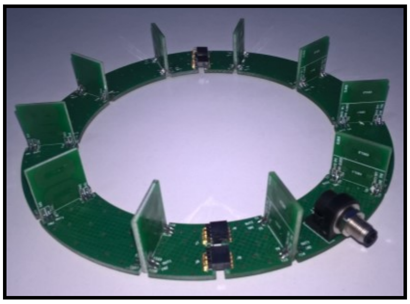

Fig.9. Prototype of Planar Rogowski Current Sensor

Prototype developed for the application of DT and as design can be separated into two parts, it makes the installation easy and there is no need to disconnect the conductor from output connection leads of transformer.

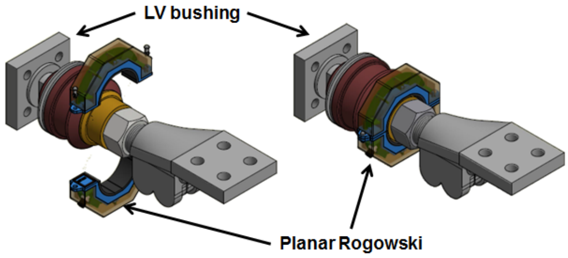


Fig.10. Mounting on Transformer Bushing

This sensor can be assembled in housing for environmental protection and both the half can be installed over a Transformer bushing with a snap-fit arrangement.

## VII. Conclusion

The design and simulation method to calculate output of planar rogowski current sensor is discussed. Application shown is to be used for current measurement at distribution transformer. Now, planar rogowski current sensor can be designed according to any requirement and application and output can be predicted by electromagnetic simulation analysis accurately.

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