VŠB–Technical University Of Ostrava
Faculty Of Electrical Engineering And Computer Science
Department of Power Electrical Engineering

Numerical Analysis And Simulation of Rogowski Coil
Numerická analýza a simulace rogowského cívky

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VŠB - Technical University of Ostrava
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Diploma Thesis Assignment

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1. Introduction
2. Theory of operation (basic principle, advantages and disadvantages, design and construction)
3. Prepare and analyze the FEM model of Rogowski coil
4. Simulate the influence of external interference
5. Analyze output results of simulation
6. Final conclusion

References:

- John G. Webster, Halit Eren: Measurement, Instrumentation, and Sensors Handbook, CRC Press, 2014, ISBN 1439848912
- Myer Kutz: Handbook of Measurement in Science and Engineering, Wiley & Sons, 2016, ISBN 1119244765
- Mariam Chandra Gitta: Rogowski Coil, Sent Publishing, 2011, ISBN 6138577663
- Saadon, M.H.: Development of Rogowski Coil Current Transducer for High Voltage Application, Universiti Tun Hussein Onn Malaysia, Fakulti Kejuruteraan Elektrik dan Elektronik, 2015
- Conference papers, Research publications
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Declaration

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Acceptance

"I hereby agree to the publishing of the bachelor's/master's thesis as per s. 26, ss. 9 of the Study and Examination Regulations for Master's Degree Programmes at VŠB-Technical University of Ostrava."

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Abstract: This work illustrates an analysis of Rogowski coils for power applications, when operating under non ideal measurement conditions. The developed numerical model, validated by comparison with other methods and experiments, enables to investigate the effects of the geometrical and constructive parameters on the measurement behavior of the coil and we also study the behavior of Rogowski coils coupled with bar conductors under quasi-static conditions. Through a finite element (FEM) analysis, we estimate the current distribution across the bar and the flux linked by the transducer for various positions of the primary conductor and for various operating frequencies. Simulation and experimental results are reported in the text.

Key Word: Rogowski coil, numerical model, 3D model of Rogowski,1phase and 3phase system

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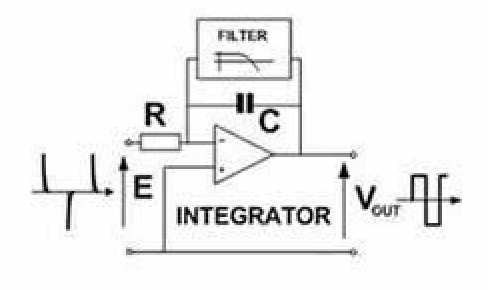
1. Introduction:

A Rogowski coil, named after Walter Rogowski, is an electrical device for measuring alternating current (AC) or high-speed current pulses. It consists of a helical coil of wire with the lead from one end returning through the centre of the coil to the other end, so that both terminals are at the same end of the coil. The whole assembly is then wrapped around the straight conductor whose current is to be measured. There is no metal (iron) core. The winding density, the diameter of the coil and the rigidity of the winding are critical for preserving immunity to external fields and low sensitivity to the positioning of the measured conductor.Since the voltage that is induced in the coil is proportional to the rate of change (derivative) of current in the straight conductor, the output of the Rogowski coil is usually connected to an electrical (or electronic) integrator circuit to provide an output signal that is proportional to the current. Single-chip signal processors with built-in analog to digital converters are often used for this purpose. [1]
The Rogowski coil is an old device for current measurement. It has been being modified and improved over acentury and is still being studied for new applications. Rogowski coil has various advantages over conventional magnetic current transformers(CTs). Not only it can be used instead of CT, butalso it has various utilizations in other fields. This paper providesa brief review on different aspects of the Rogowski coil and its advancement procedure, during last decades. In this literature,the history of the coil is brifely reviwed and its bases and applications are discussed. The Rogowski coil is analysed fromdifferent points of view include, different integration techniquesin the output stage, models for the Rogowski coil, experimentalmethods for parameter measurement in models and method fordetermining the damping resistor. At last, a breif review overdiffrent applications of the coil ends the paper.[2]. The Rogowski coil is an air-core coil, which measures both alternating and high speed impulse currents, based on Ampere's and Faraday's law. It was named after a German physician Walter Rogowski. Firstly, this type of transducer proposed in 1887, when A. P. Chattock from Bristol University was working on the better types of dynamos. He used a long coil on a plastic rod for measuring the magnetic reluctance. He attached the two ends of the coil to each other, and calibrated the device based on Ampere's law. In 1912, W. Rogowski and W. Steinhaus used Chattock's technique for magnetic potential measuring. In this manner, They performed various tests to ensure the validity of the coil measurementsThe main limitation regarding the Rogowski coil applications was about diminutive output in measuring low amplitude currents. In first stages, the coil usage was limited for measuring the high amplitude currents, with high variation rate, due to the fact that, the output of the coil is proportional to the derivative of the current. Nowadays, the Rogowski coils are able to measure low level currents, thanks to electronic devices. This coil does not have ferromagnetic core, therefore, it has a linear characteristic. Linear characteristic together with accurate electronic devices, make it possible to measure currents, form milli-amperes to mega-amperes, using Rogowski coil. Furthermore, the low cost of this device, comparing to the other measurement methods, makes the Rogowski coil an appropriate gadget for measuring high amplitude transient curren The output of the Rogowski coil was insufficient in conventional measuring methods, which was the main limit in past decades. However, nowadays by developments of microprocessor-based measurement devices, Rogowski coils are more suitable for various applications.[3]
In addition, Rogowski Coils make protection schemes possible that were not achievable by conventional CTs because of saturation, size, weight, and/or difficulty encountered when attempting to install current transformers around conductors that cannot be opened. An additional advantage of Rogowski Coil current

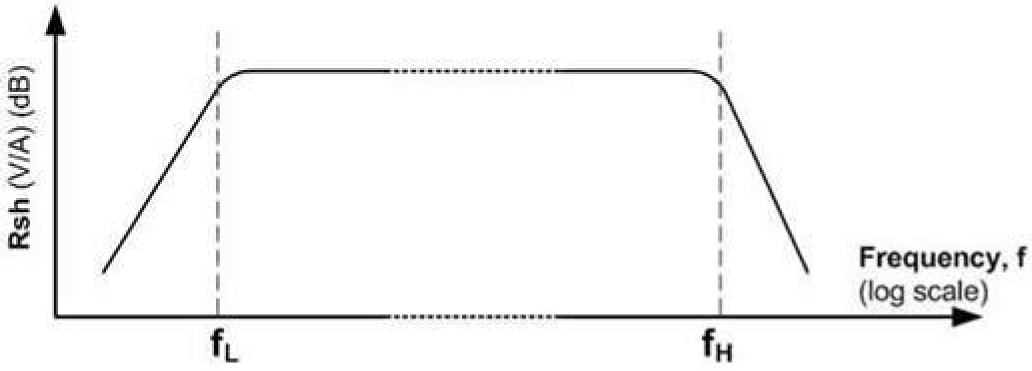
sensors is significantly lower power consumption during operation. Rogowski Coils are connected to devices that have high input resistance, resulting in negligible current flowing through the secondary circuit. Conventional CTs contain a ferromagnetic core that also consumes energy/power due to hysteresis losses. Rogowski Coils have no core losses. In fact, an operating Rogowski Coil has much smaller power loss than conventional CTs – which leads to significant savings of energy and ultimately reduced lifecycle costs. Rogowski Coils can replace conventional CTs for protection, metering, and control. Rogowski Coils have been applied at all voltage levels (low, medium, and high voltage). However, unlike CTs that produce secondary current proportional to the primary current, Rogowski Coils produce output voltage that is a scaled time derivative $di(t)/dt$ of the primary current. Signal processing is required to extract the power frequency signal for applications in phasor-based protective relays and microprocessor-based equipment must be designed to accept these types of signals.[4]

2. Theory of Operation

Basic Principal: An alternating or pulsed current in a conductor develops a magnetic field and the interaction of this magnetic field and the Rogowski coil local to the field gives rise to an induced voltage within the coil which is proportional to the rate of change of the current being measured. Provided the coil constitutes a closed loop with no discontinuities, it may be shown that the voltage E induced in the coil is proportional to the rate of change of the encircled current I according to the relationship $E=H.dI/dt$, where H, the coil sensitivity in (Vs/A), is proportional to NA.



To obtain an output voltage VOUT proportional to I it is necessary to integrate the coil voltage E; hence an electronic integrator is used to provide a bandwidth extending down to below 1Hz.The op-amp integrator, in its simplest form, with an input resistor Rsh and feedback capacitor C has an output $Vout=(1/CR)\int Edt$. The overall transducer gain is therefore given by, $Vout=RshI$, where $Rsh=H/CR$ is the transducer sensitivity (V/A).The relationship Vout proportional to I is valid throughout the transducer bandwidth. The bandwidth is defined as the range of frequencies from fL to fH for which sinusoidal currents can be measured to within 3dB of the specified sensitivity Rsh.At low frequencies the integrator gain increases and in theory will become infinite as the frequency approaches zero. This would result in unacceptable dc drift and low frequency noise; hence the integrator gain has to be limited at low frequencies. This limitation is achieved by placing a low pass filter in parallel with the integrating capacitor. The low pass filter sets the low frequency bandwidth fL, typically this is less than 1Hz.



Rogowski coil and integrator frequency response

Furthermore, due to the distributed inductance and capacitance of the Rogowski coil there is a high frequency bandwidth fH, (generally 1MHz or greater) above which the measurement is attenuated and significant phase delay occurs. The bandwidth of the electronic integrator and the length of cable connecting the integrator to the coil also influence this limit.

Over many years, PEM has developed mathematical models of the Rogowski coil, cable and integrator allowing us to develop reliable, accurate current transducers in a variety of sizes for an ever growing market.

Using a Rogowski coil to measure AC or fast transient currents has many advantages over other methods of current measurement:

Simple to retro-fit, the clip-around Rogowski coil sensor is thin, lightweight, flexible and robust

Coil size is not dependant on the magnitude of the current to be measured

Non-Intrusive (presents the equivalent of only a few pH to the circuit under test)

Wide-bandwidth devices with predictable frequency response, ideal for power quality measurement or monitoring complex waveforms.

Intrinsically safe - No danger of an open circuit secondary.

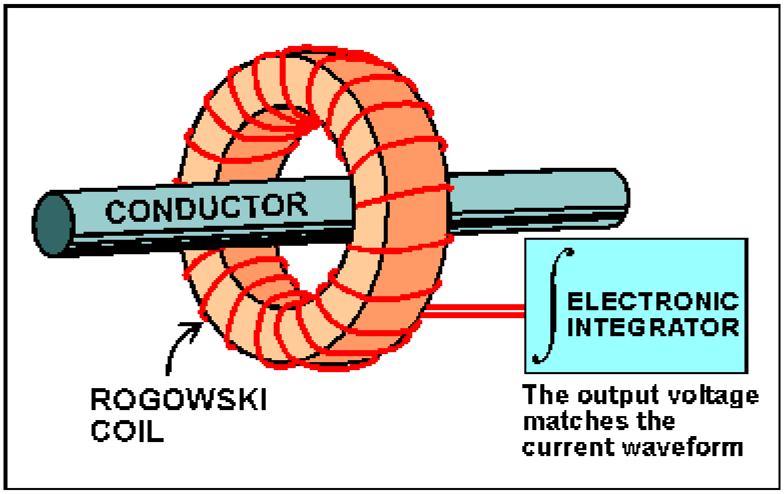
Galvanic isolation

Excellent linearity (Rogowski coils have no magnetic materials to saturate)

Capable of taking huge overload currents without damage

Immune to DC Currents - as a result it can measure small AC currents in the presence of a large DC component. [5]

The direct output from the coil is given by Vout=M dI/dt Where M is the mutual inductance of the coil and dI/dt is the rate of change of current. To complete the transducer the voltage is integrated elect
accurately reproduces the current waveform.



2.1:Coil and Integrator

The combination of a coil and an integrator provides an exceptionally versatile current- measuring system which can be designed to accommodate a vast range of frequencies, current levels and conductor sizes. The output is independent of frequency. It has an accurate phase response and can measure complex current waveforms and transients.

2.2:Linearity:

One of the most important properties of a Rogowski coil measuring system is that it is inherently linear. The coil contains no saturable components and the output increases linearly in proportion to current right up to the operating limit determined by voltage breakdown. The integrator is also inherently linear up to the point where the electronics saturates. Linearity makes Rogowski coils easy to calibrate because a transducer can be calibrated at any convenient current level and the calibration will be accurate for all currents including very large ones. Also, because of their linearity, the transducers have a very wide dynamic range and an excellent transient response

2.3:CoilWinding:

With a Rogowski coil it is important to ensure that the winding is as uniform as possible. A non-uniform winding makes the coil susceptible to magnetic pickup from adjacent conductors or other sources of magnetic fields. We have developed special machines for making accurate windings. Coils come in a range of styles including rigid and flexible coils but we have developed several other variations to meet specific needs

2.4:OutputIndication:

The output from the integrator can be used with any form of electronic indicating device that has an input impedance greater than about 5kohm such as a voltmeter, oscilloscope, transient recorder or protection system

2.5:Split Coils:

Some designs of coil can be fitted on the conductor without the need to disconnect the conductor. Most flexible coils can be fitted this way and it is also possible to build split rigid coils. Split iron-cored devices such as current transformers are subject to appreciable amplitude and phase errors if the halves are misaligned by even a small amount. Rogowski coils do not have this problem. Misalignment of the joining faces of a split Rogowski coil has only a small effect on the amplitude and no effect on the phase. [6]

Conventional iron-core current transformers (CTs) are typically designed with rated secondary currents of 1 Amp or 5 Amps, to drive low impedance burden of several ohms. Figure 1 shows the principle of a CT connection. ANSI/IEEE Standard C57.13™-2008 specifies CT accuracy class for steady state and symmetrical fault conditions. Accuracy class of the CT ratio error is specified to be ±10% or better for a fault current 20 times the CT rated current and up to the standard burden. CTs are designed to meet this requirement. But, if the standard burden is connected to the CT secondary and the RMS value of a symmetric fault current exceeds 20 times the CT rated current or if the RMS value of a fault current is smaller than 20 times the CT rated current but contains DC offset (asymmetric current), the CT will saturate. The secondary current will be distorted and the current RMS value reduced. Traditional Rogowski Coils consist of a wire wound on a non-magnetic core (relative permeability r=1). The coil is then placed around conductors whose currents are to be measured (Figure1-2).

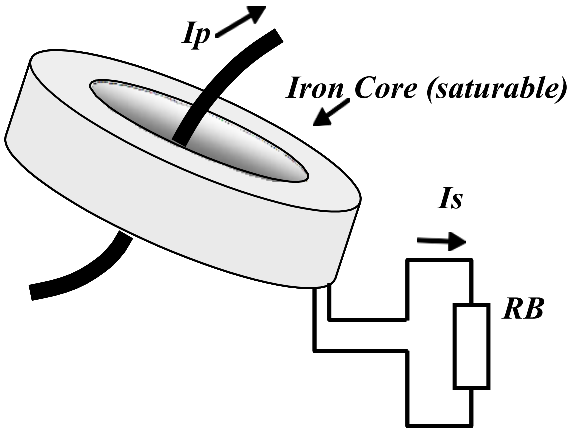


Figure 1 Current Transformer

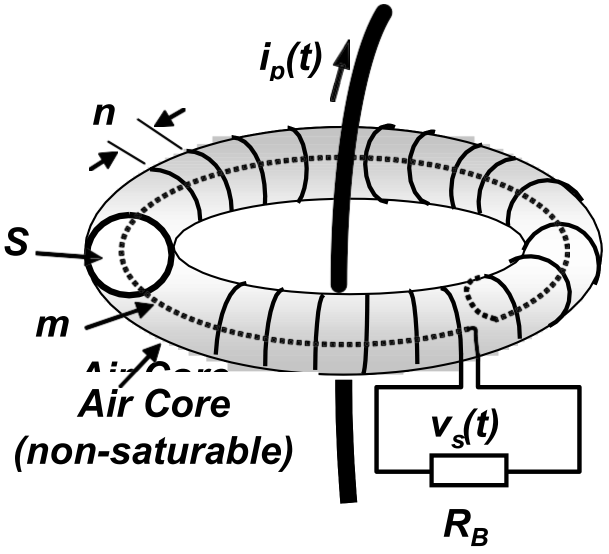


Figure 1-2. Rogowski Coil

As Rogowski Coils use a non-magnetic core to support the secondary windings, mutual coupling between the primary and secondary windings is weak. Because of weak coupling, to obtain quality current sensors, Rogowski Coils should be designed to meet two main criteria:

the relative position of the primary conductor inside the coil loop should not affect the coil output signal, and

the impact of nearby conductors that carry high currents on the coil output signal should be minimal.To satisfy the first criteria, mutual inductance M must have a constant value for any position of the primary conductor inside the coil loop. This can be achieved if the windings are:

1) on a core that has a constant cross-section S,

2) perpendicular to the middle line m (dashed line in Figure 2-2 that also represents return wire through the winding), and

3) built with constant turn density n. Mutual inductance M is defined by the formula:

$$M = \mu_0 n S$$

Where μ0 permeability of air.

The output voltage is proportional to the rate of change of measured current as given by the formula:

Because the Rogowski Coil primary and secondary windings are weakly coupled (to prevent the unwanted influence from nearby conductors carrying high currents) Rogowski Coils are designed with two wire loops connected in electrically opposite directions. This cancels electromagnetic fields coming from outside the coil loop. One or both loops can consist of wound wire. If only one loop is constructed as a winding, then the second wire loop can be constructed by returning the wire through (Figure 2) or near this winding (single-layer coils). If both loops are constructed as windings, then they must be wound in opposite directions (multi-layer coils). In this way, the Rogowski Coil output voltage induced by currents from the inside conductor(s) will be doubled if windings are identical.

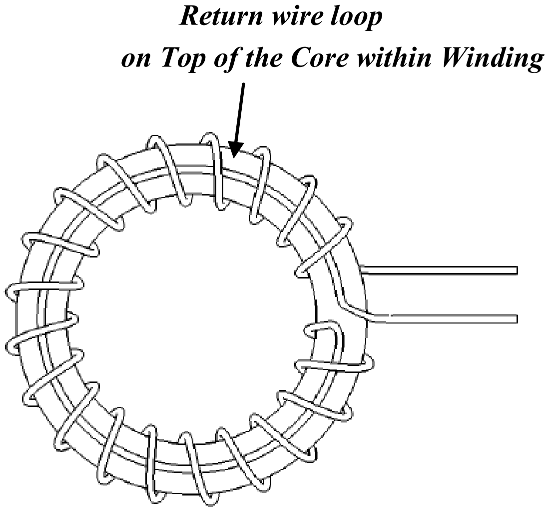
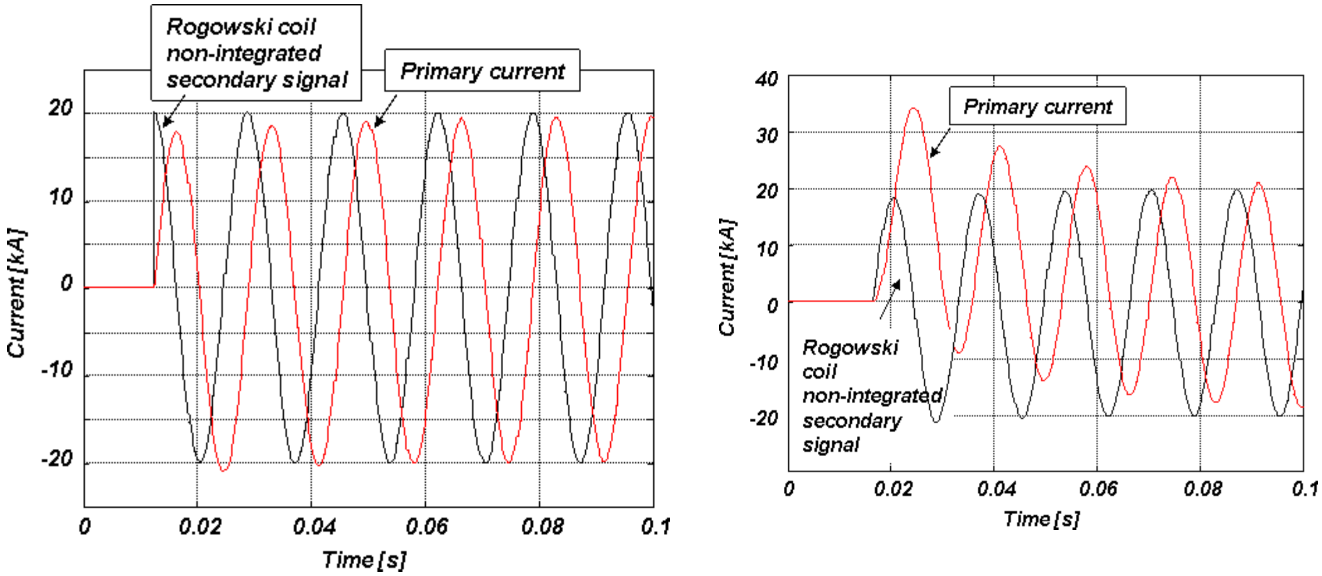


Figure 2. Rogowski Coil with the Return Wire Loop through the Winding

Return wire loopon Top of the Core within Winding Figure 2 Rogowski Coil with the Return Wire Loop through the Winding Figure 2 shows the equivalent circuit of an iron-core current transformer. Magnetizing current Ie introduces amplitude error and phase error. Since the CT iron-core has a non-linear characteristic it saturates at high currents, or when a DC component is present in the primary current. When the CT saturates, the magnetizing current increases and the secondary current produced decreases (ie. CT ratio error increases). This may negatively impact relay performance, resulting in delayed operation, non-operation, or unwanted operation in the case of differential protection schemes.

As the Rogowski Coil signal is a scaled time derivative, di(t)/dt of the primary current, signal processing is required to extract the power frequency signal for phasor-based protective relays. This may be achieved by integrating the Rogowski Coil output signals, or using non-integrated Rogowski Coil output signals in other signal processing techniques.Integration of the signals can be performed in the relay (by analog circuitry or by digital signal processing techniques) or immediately at the coil. To use the Rogowski Coil non-integrated analog signal, it is necessary to perform the signal corrections for both the magnitudes and phase angles. For phasor-based protective relaying applications, the Rogowski Coil secondary signal must be scaled by magnitude and phase-shifted for each frequency.Because the Rogowski Coil output voltage is proportional to the rate of change of measured current (di/dt) enclosed by the coil, the waveform of the Rogowski Coil output signal is different from the waveform of the measured current. For symmetric primary current faults, the Rogowski Coil secondary voltage signal is shifted in phase by 90 ° versus the primary current as shown in Figure 3a. For an asymmetric primary current fault, the DC offset will be attenuated by the Rogowski Coil and phase shifted as shown in 3b. However, the integrated signal accurately reproduces the primary current waveform.



(A) Symmetric Primary Currents

(B) Asymmetric Primary Currents

Figure 3; Rogowski Coil Non-Integrated Output Signals\

To achieve high accuracy, Rogowski Coils should be connected to devices that have high input impedance.Figure 4 shows the impact of the device input resistance on the secondary output voltage for an example of Rogowski Coil that produces 150 mV at rated current. In reality, different Rogowski Coils may have different requirements on the input resistance of connected devices. In addition, capacitances of the burden and/or connected cable may affect the phase error; nevertheless the effect of such capacitances is relatively small

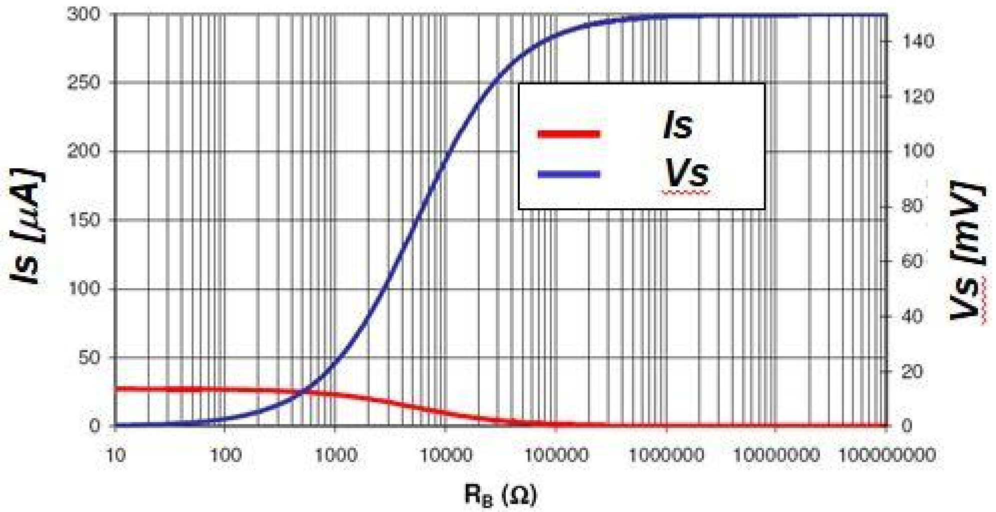


Figure 4 The Impact of Burden on the Rogowski Coil Output Voltage

[7]

2.6:Design and Construction:

Figure shows the construction of a Rogowski coil, an air-core current transformer that is especially well suited to measuring ripple currents in the presence of a DC component or measuring pulsed currents.

Rogowski Coils For Precision Measurements and Protection

The raw output is proportional to the derivative of the current, and the current can be recovered by an integrator or a low-pass filter.

The output voltage is given by:

$$e = 4\pi \times 10^{-7}\, n \times (A/s)\, di/dt \text{ (MKS units)}$$

$$e = 3.19 \times 10^{-8}\, n\, (A/s)\, di/dt \text{ (inches)}$$

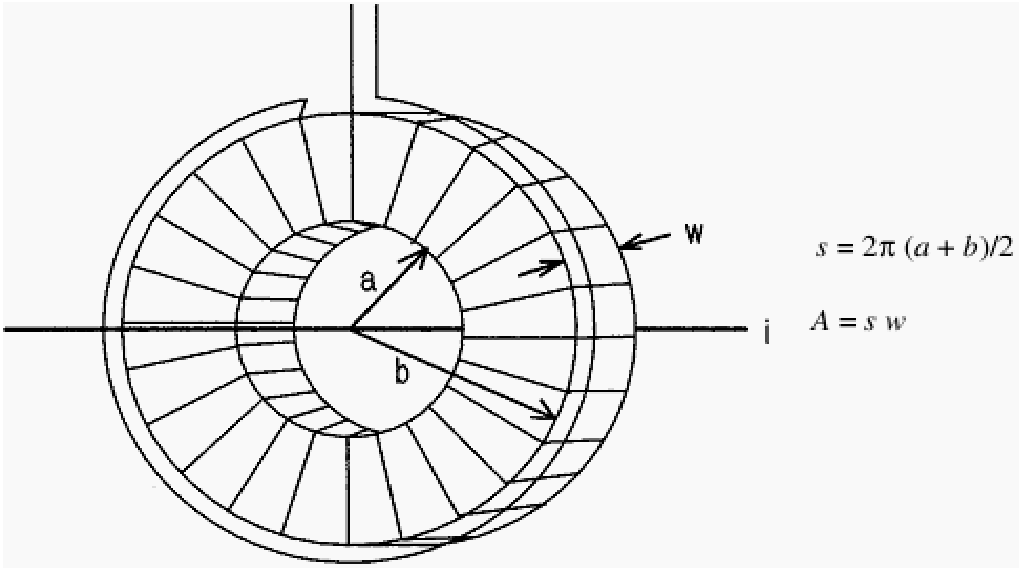


Fig 5: Rogowski coil construction

Where*:*

n is the number of turns
A is the cross sectional area of the toroid
s is the centerline circumference

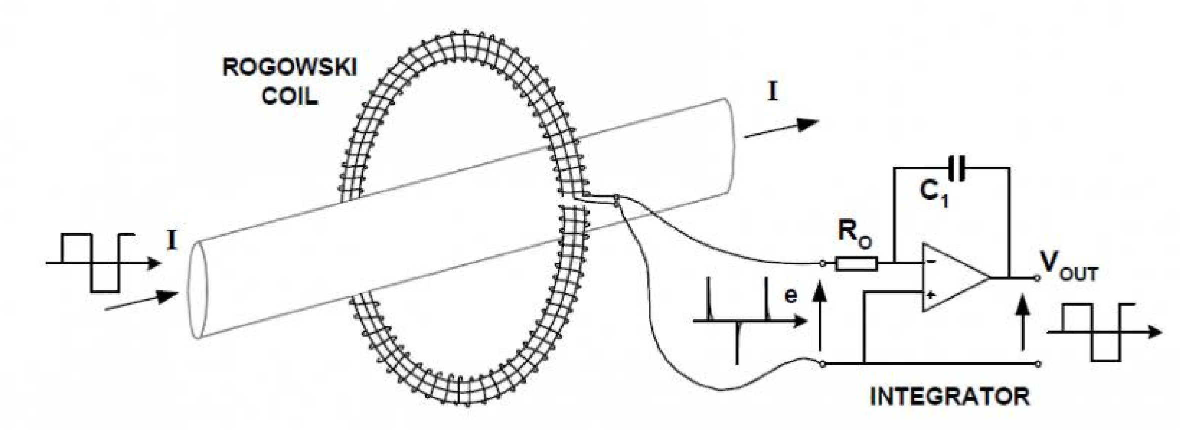
The coil is wound on an air-core form of suitable size for the current conductor. The windings hould be applied in evenly spaced turns in one direction only-not back and forth-so that capacitive effects are minimized.

The far end of the winding should be brought back around the circumference of the coil to eliminate the turn formed by the winding itself. The winding must generally be shielded, since the output voltage is relatively low. The shield should be applied so that it does not form a shorted turn through the opening, and the coil should be equipped with an integral shielded output lead with the ground side connected to the coil shield.[8]

2.7:How does Rogowski coil work?

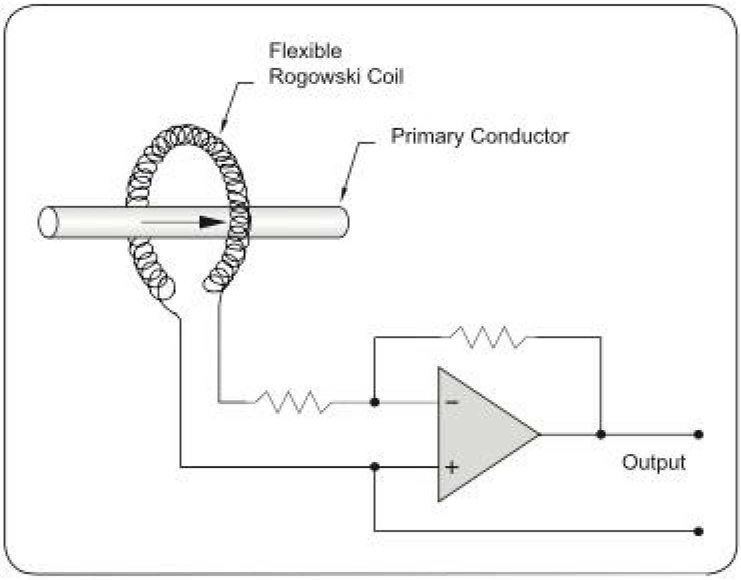
The theory of operation behind the Rogowski coil is based on Faraday's Law which states that the total electromotive force induced in a closed circuit is proportional to the time rate of change of the total magnetic flux linking the circuit.The Rogowski coil is similar to an AC current transformer in that a voltage is induced into a secondary coil that is proportional to the current flow through an isolated conductor. The key difference is that the Rogowski coil has an air core as opposed to the current transformer, which relies on a high-permeability steel core to magnetically couple with a secondary winding. The air core design has a lower insertion impedance, which enables a faster signal response and a very linear signal voltage.

An air-cored coil is placed around the current-carrying conductor in a toroidal fashion and the magnetic field produced by the AC current induces a voltage in the coil. The Rogowski coil produces a voltage that is proportional to the rate of change (derivative) of the current enclosed by the coil-loop. The coil voltage is then integrated in order for the probe to provide an output voltage that is proportional to the input current signal.



[6]

The Rogowski coil is a closed loop configuration that is wound over a nonmagnetic, constant cross-sectional area



The extreme flexibility of the coil allows it to be wrapped around cables and bus bars without disrupting the power or adding an energy burden to the line that is being measured. The linear output and flexible coil provide more versatile functioning than the traditional CTs; however, there are some downsides. Even though you can measure high amperage with no saturation, the coil inductance displaces the phase +90 degrees with respect to the input current, as shown below.

2.8:Rogowski Coil Phase Shift

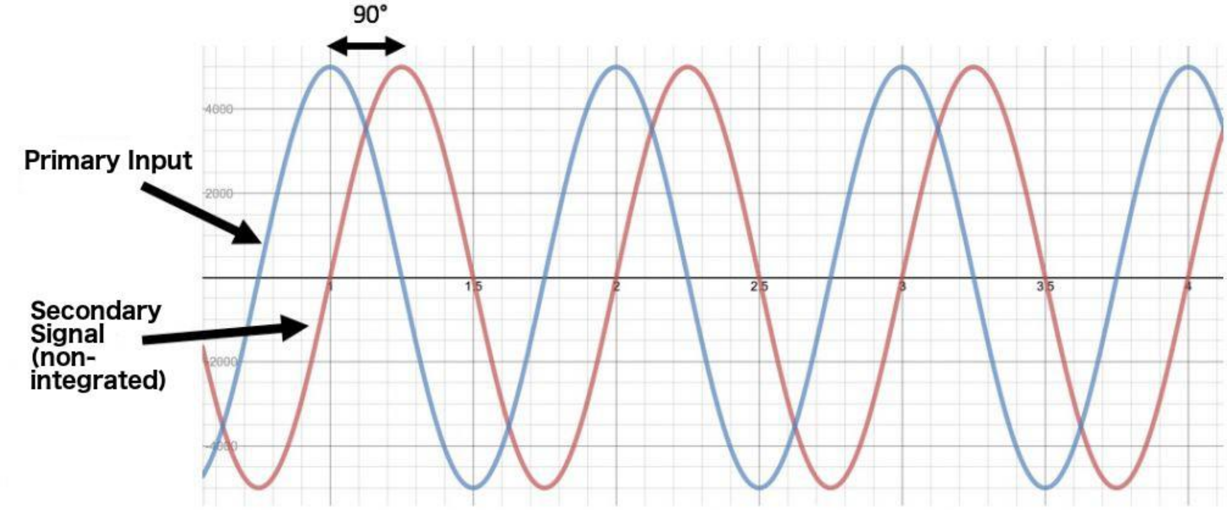


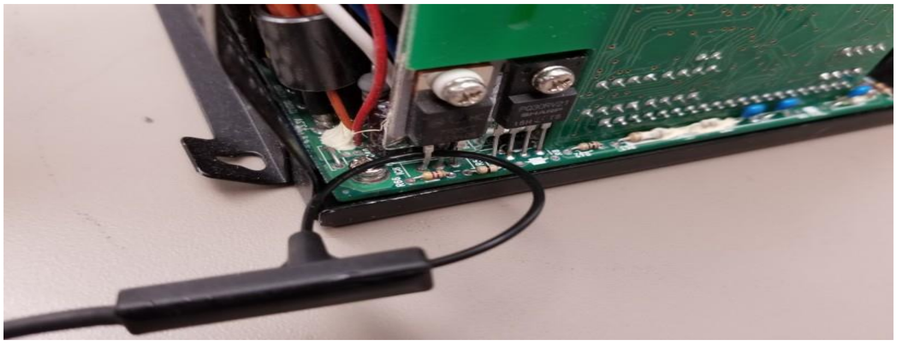
Fig 6: Rogowski Coil Phase Shift

[9]

2.9 Advantages

Rogowski coil current probes offer many advantages over different types of current transducers or sensing techniques.

Large current measurement without core saturation -- Rogowski coils have the capability to measure large currents (a very wide range from a few mA to more than a few hundred kA) without saturating the core because the probe employs non-magnetic “air” core. The upper range of the measurable current is limited by either the maximum input voltage of a measuring instrument or by the voltage breakdown limits of the coil or the integrator circuit elements. Unlike other current transducers, which get bulkier and heavier as the measurable current range grows, the Rogowski coil remains the same small size coil independent of the amplitude of current being measured. This makes the Rogowski coil the most effective measurement tool for making several hundreds or even thousands of amperes of large AC current measurements.



Very flexible to use -- The lightweight clip-around sensor coil is flexible and easy to wrap around a current-carrying conductor. It can easily be inserted into hard-to-reach components in the circuit. Most Rogowski coils are thin enough to fit between the legs of a T0-220 or TO-247 power semiconductor package without needing an additional loop of wire to connect the current probe. This also gives an advantage in achieving high signal integrity measurement.

Wide bandwidth up to >30 MHz -- This enables the Rogowski coil to measure the very rapidly changing current signal – e.g., several thousand A/usec. High bandwidth characteristic allows for analysing high-order harmonics in systems operating at high switching frequencies, or accurately monitoring switching waveforms with rapid rise- or fall-times.

Non-intrusive or lossless measurement -- The Rogowski coil draws extremely little current from the DUT because of low insertion impedance. The impedance injected into the DUT due to the probe is only a few pico-Henries, which enables a faster signal response and very linear signal voltage.

Low cost Compared to a hall effect sensor/transformer current probe, the Rogowski coil typically comes in at lower price point.

Limitations

AC only -- Rogowski cannot handle DC current. It is AC only.

Sensitivity - Rogowski coil has a lower sensitivity compared to a current transformer due to the absence of a high permeability magnetic core.

2.10 Disadvanteges

This type of coil also has some disadvantages over other types of current transformers.

The output of the coil must be passed through an integrator circuit to obtain the current waveform. The integrator circuit requires power, typically 3 to 24Vdc, and many commercial sensors obtain this from batteries.

Traditional split-core current transformers do not require integrator circuits. The integrator is lossy, so the Rogowski coil does not have a response down to DC; neither does a conventional current transformer (see Néel effect coils for DC). However, they can measure very slow changing currents with frequency components down to 1 Hz and less.

2.11 Applications:

Rogowski coil current probes have a large number of applications in broad power industries and power measurement applications. The following are some examples of Rogowski coil applications:

Flexible current measurement of power devices such as MOSFET or IGBT device as small as TO-220 or TO-247 package or around the terminals of large power modules

To measure power losses in power semiconductors

To monitor currents in small inductors, capacitors, snubber circuits, etc.

To measure small AC current on a conductor with high DC current or in the presence of a high DC magnetic field.

To measure high frequency sinusoidal, pulsed, or transient currents from power line frequency to RF applications

To measure current in motor drives and, in particular, power quality measurements in VSD, UPS or SMPS circuits

To evaluate switching performance of power semiconductor switches (double pulse tester).

Power distribution line monitoring or utilities pole probe monitoring

Smart grid applications

Plasma current measurement [10]

3. Analysis the FEM model of rogowski coil:

Rogowski coils are often employed for measuring high alternating currents or high current pulses .The basic principle of operation is based on the mutual coupling between the current transducer and the primary conductor. Apart from the ideal case, the mutual inductance M depends on the current distribution across the primary conductor and on the relevant positions between the active edges of the winding and the primary conductor itself. In many actual configurations, the accurate estimation of M should require a full electromagnetic analysis.Once we know the current distribution across the primary conductor, the estimation of M can be obtained from the geometry of the system by means of analytical or quasi-analytical methods. Biot-Savart’s law,partial inductance technique, or, more in general, magnetic energy method can be adopted to solve the problem.On the other hand, the current distribution across a massive conductor obeys to a diffusion equation and, except for particular geometries and paths of the primary conductor a numerical solution must be performed.Through a frequency analysis carried out by a commercial FEM code we estimate the variation of the flux linked by circular Rogowski coils with rectangular cross sections coupled with an infinitely long bar conductor. Our research objective consists in improving the design technique and possibly the calibration of such current transducers. In particular, we focus on Rogowski coils with small number of turns being the number of turns very critical in terms of variation of M.

3.1 BASIC CONFIGURATIONS

In Fig. 1, we show a schematic of a circular Rogowski coil with 8 turns crossed by a primary bar conductor. The internal and external radii of the torus are a = 3 cm and b =4,5 cm,respectively, while its height is w = 3,2 cm. Dimensions of the bar are width c = 3 cm and thickness d=0,5 cm. The primary conductor is assumed to be infinite in the axial direction.

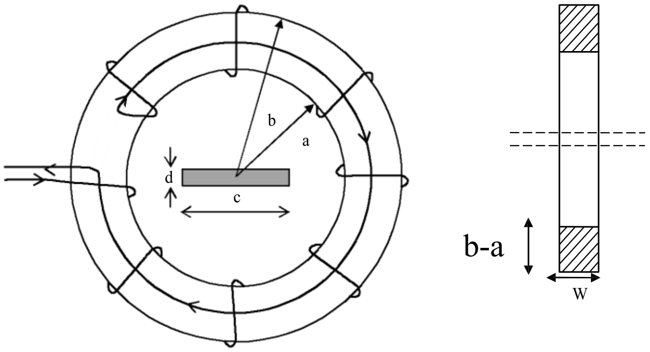


Fig. 7. Schematic representation of the reference configuration –position 1.

As to be expected the variation of M reduces significantly with the number of turns N. Indeed, as known from the theory, a Rogowski coil with a very small pitch, i.e., a very high number of turns, can be used to show experimentally the Ampère’s low.

In Fig. 2, we show the primary conductor shifted of 2,25 cm along the y-direction, while in Fig. 3 the bar is shifted of 1,45 cm along the x-axis.

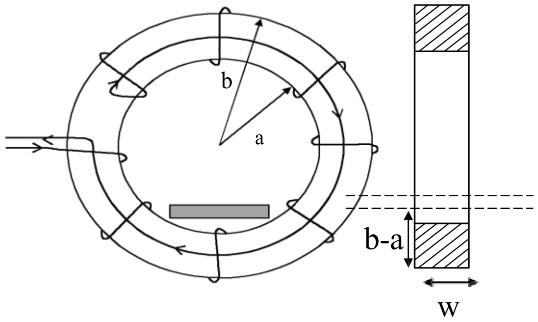


Fig. 8. Second configuration with the primary bar conductor shifted along the y-direction of 2,25 cm. Position 2

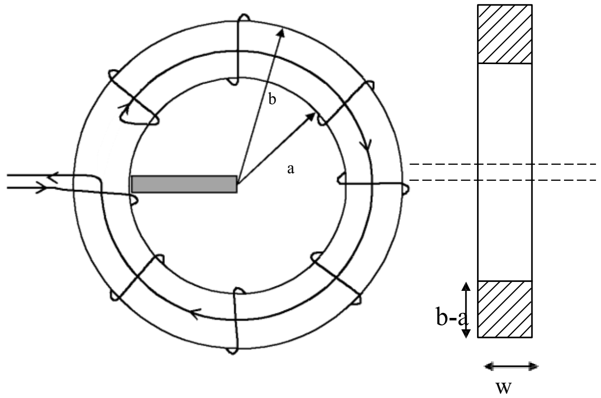


Fig 9:. Third configuration with primary bar conductor shifted along the x-direction of 1,45 cm. Position 3

3.2.FEM analysis

We adopted a time-harmonic quasi-static formulation to solve the field distribution of our problems. Thus, starting from the two Maxwell's equations :

$$\vec{E} = -i\omega\vec{A} - \nabla V \qquad (1)$$

$$\vec{B} = \nabla\times\vec{A} \qquad (2)$$

introducing two new potentials:

$$\vec{A'} = \vec{A} + \nabla\psi \qquad (3)$$

$$V' = V - i\omega\psi \tag{4}$$

and fixing the gauge

$$\psi = \frac{v}{i\omega} \tag{5}$$

we obtain the driving equation:

$$\nabla\times\mu^{-1}\nabla\times\vec{A} + i\omega\vec{A} = \vec{J}^{e} \tag{6}$$

We started our simulations solving a 2D problem representing an indefinite conducting cylinder. Simulation results have been compared with the analytical calculation and data were in complete agreement with respect to our purposes. Percentage differences were less than one part per ten thousand. In particular, the flux linked by the modelled Rogowski has been calculated through the circulation of the magnetic vector potential along its active edges and compared with the direct application of the Ampère's law. On the other hand, the current distribution across the round wire has been compared with the analytical solution expressed in terms of Bessel functions.
In Fig. 4, we show the colour map of the current density distribution through the bar at 200 Hz, 1000 Hz, and 2000Hz. For all the simulations the calculation of the flux linked by the Rogowski is done via the circulation of the magnetic vector potential A. The 2D computation domain is represented by a circular region of radius r = 0,15 m. The number of triangular-type elements is about 153000 corresponding to a number of degrees of freedom of about 307000.Simulations were performed on a 64-bit 16 GB Ram platform and the computational time for each simulation was about 1 minute.It is apparent how skin effects are practically negligible at 200 Hz, while they are significant at 2000 Hz. A rough estimation of the eddy current effect can be evaluated for a copper lamination by the calculation of the penetration depth δ

$$\delta = 1/\sqrt{\pi f \mu\sigma} \tag{7}$$

where σ is the electrical conductivity and μ the magnetic permeability. From (7) we obtain a penetration depth of about 4,7 mm, 2,1 mm and 1,5 mm at 200 Hz, 1000 Hz and 2000 Hz, respectively. In more detail, the hell blue color (upper image – 200 Hz and centre image – 1000 Hz) corresponds to a current density of 0,06 A/mm2, while the red colour (lower plot – 2000 Hz) indicates a current density value of about 0,35 A/mm2.

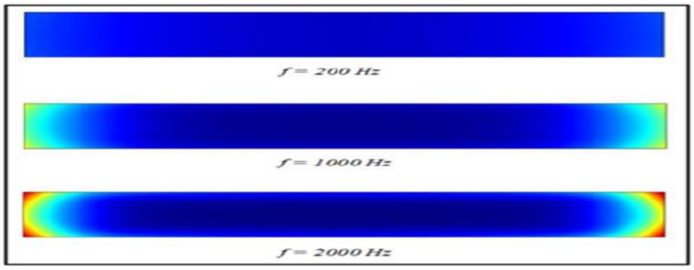


Fig.10: Current density distribution through the bar conductor at 200 Hz, 1000 Hz and 2000 Hz

In Fig. 5, we show the colour map of the magnetic field distribution in the computation domain. Data are evaluated at 2000 Hz

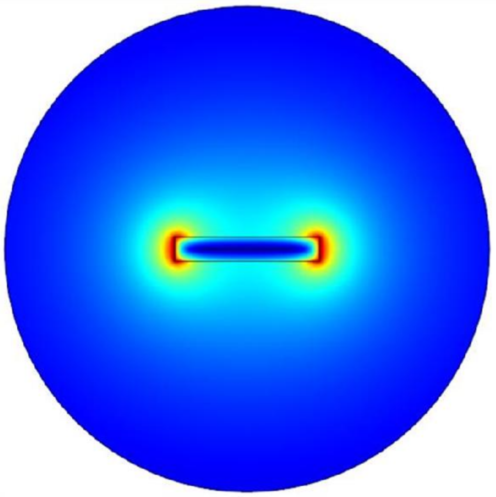


Fig.11:. Magnetic field (H) in the computation domain at 2000 Hz

An arbitrary function generator (Agilent 33220A) is connected to the loop via a transconductive power amplifier (not shown in the figure), so that it works as a current generator. A Labview© platform drives all the system through the IEEE 488© protocol. A sinusoidal current with amplitude 10 A is automatically set at each investigated frequency.The current through the circuit is measured by means of a hall probe. Another DMM – Agilent 34401A measures the induced voltage at the remote ends of the Rogowski coil.

3.3.Experimental Setup

In Fig. 6, it is shown a part of the adopted experimental setup. It is possible to recognize the bar, the Rogowski coiland the output signal cable. A one meter copper bar (thickness 0.5 cm, width 3 cm) is closed to form a rectangular loop of 4 m × 3 m to avoid proximity effects between the Rogowski coil and the rest of the circuit..

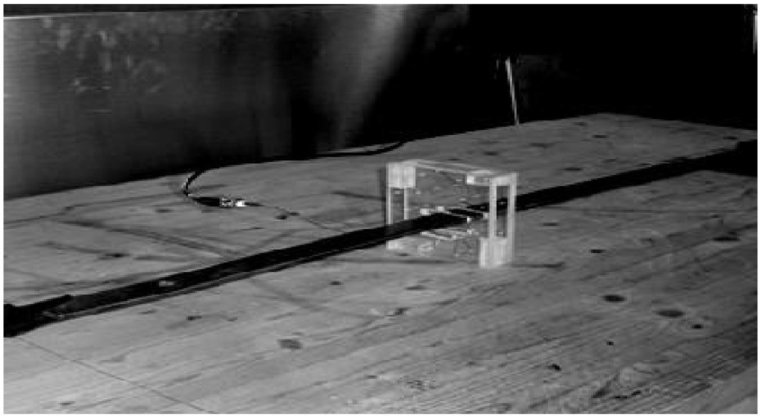


Fig.12:. Part of the adopted experimental setup

We wound two times eight turns on two plexiglas dielectric supports of thickness 8 mm and placed at a distance of 16 mm between the internal faces, obtaining a total height of 32 mm of the transducer. The internal and external diameters are 30 mm and 45 mm, respectively. In Fig. 7, it is shown the adopted Rogowski coil and a segment of the primary bar conductor placed as shown in Fig. 1.

Fig.13. Rogowski coil coupled with the bar conductor in the position 1.

In Table 1, we report the M values for the described configurations provided by the FEM simulation at 200Hz, 1000 Hz, and 2000 Hz. For all the simulations and measurements, position 1 refers to Fig. 1, position 2 to Fig.2 and position 3 to Fig. 3, and position 1 is the benchmark

TABLE 1. Mutual inductance values for the investigated configurations. (Values are in μH).

	f = 200 Hz	f = 1000 Hz	f = 2000 Hz
Position 1	43,49	43,49	43,49
Position 2	42,12	41,80	41,81
Position 3	45,41	46,30	46,55

In Table 2, the percentage variations with respect to the centred position are reported.

TABLE 2. Percentage variation of M for the investigated configurations (simulated data).

	f = 200 Hz	f = 1000 Hz	f = 2000 Hz
Position 1	0	0	0
Position 2	-3,2	-3,9	-3,9
Position 3	+4,4	+6,4	+7,0

In Table 3, we report the measured percentage variations of M for the investigated configurations

TABLE 3. Percentage variation of M for the investigated configurations (measured data).

	f = 200 Hz	f = 1000 Hz	f = 2000 Hz
Position 1	0	0	0
Position 2	-3,0	-3,6	-3,8
Position 3	+3,9	+5,1	+5,6

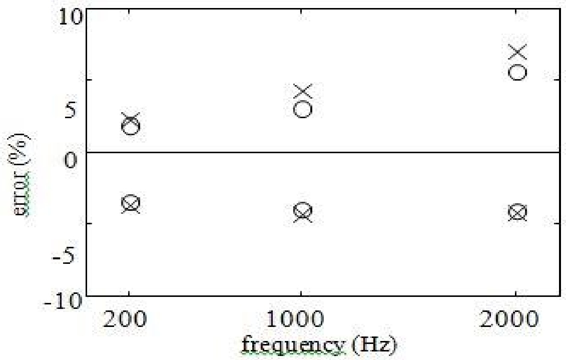


Fig.14. Measured (circles) and computed (crosses) variations of the induced voltage with respect to the benchmark for position 2 (lower plot) and position 3 (upper plot).

The obtained results are summarized in Fig. 8 that reports the measured (circle symbols) and computed (cross symbols) percentage variations of the mutual inductance M for the investigated configurations. At each frequency, lower and upper plots refer to position 2 and 3, respectively. Results show how the frequency and position play an important role and how it is important an accurate knowledge of the relevant positions among the active elements and calculation of the current density distribution for a correct reconstruction of the primary current.In particular, for our implemented geometries the maximum percentage variation of M has been observed at 2000 Hz from – 3,9 % up to + 7,0 % with respect to the benchmark. This can make the Rogowski an inaccurate transducer if such parameters are not taken into account.It is apparent how a numerical simulation can be a useful tool in the designing phase of air-cored current transducer. In addition, an accurate evaluation of the parameter M over the frequency range of interest can be very important for a correct reconstruction of distorted primary currents. Indeed, the intrinsic linearity of the Rogowski coil makes possible toevaluate the spectrum of the output voltage and then via the M(f) relation to obtain the nonsinusoidal primary current.Preliminary results appear to be promising for extending the FEM analysis to more complex geometries as that shown in Fig. 9. Further investigations are currently in progress to improve the design of such current transducers[11]

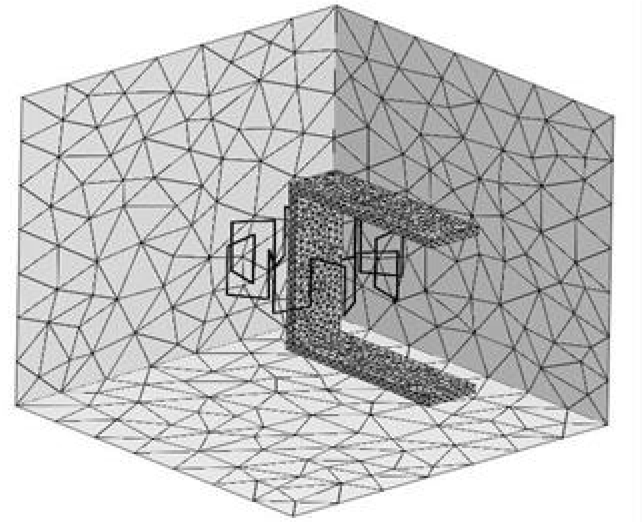


Fig 15:. 3D problem, rectangular C-shaped primary conductor.

3.4: Single phase system of rogowski coil:

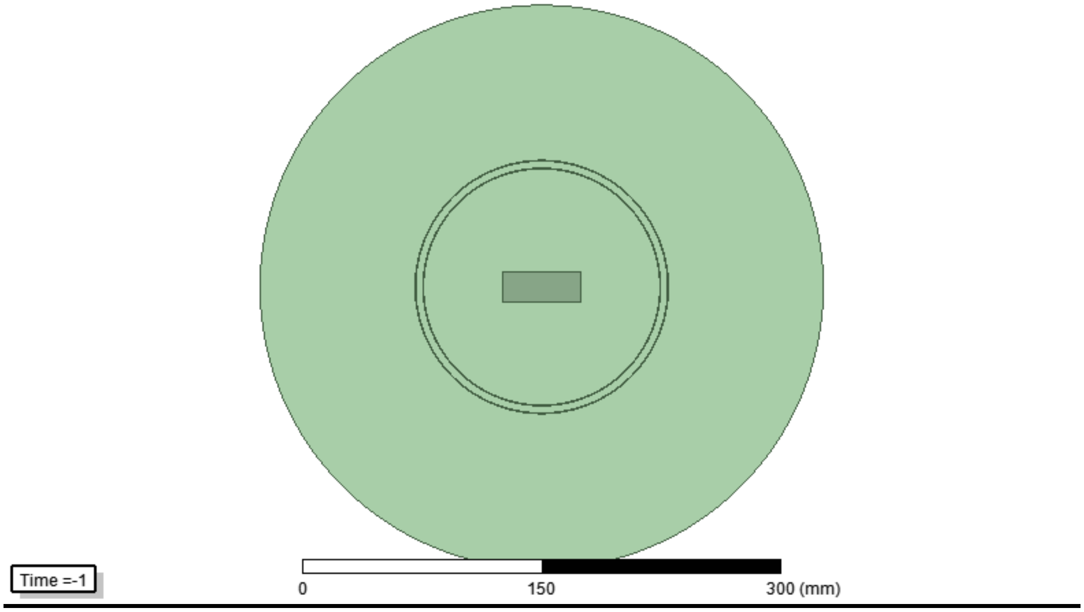


Fig 16:Single phase Rogowski coil

Table 4: Changing the phase shift 3phase Rogowski coil

Current	Frequency
200	50
200	100
200	150
200	300
200	400
200	500
200	600
200	700
200	800
200	1000

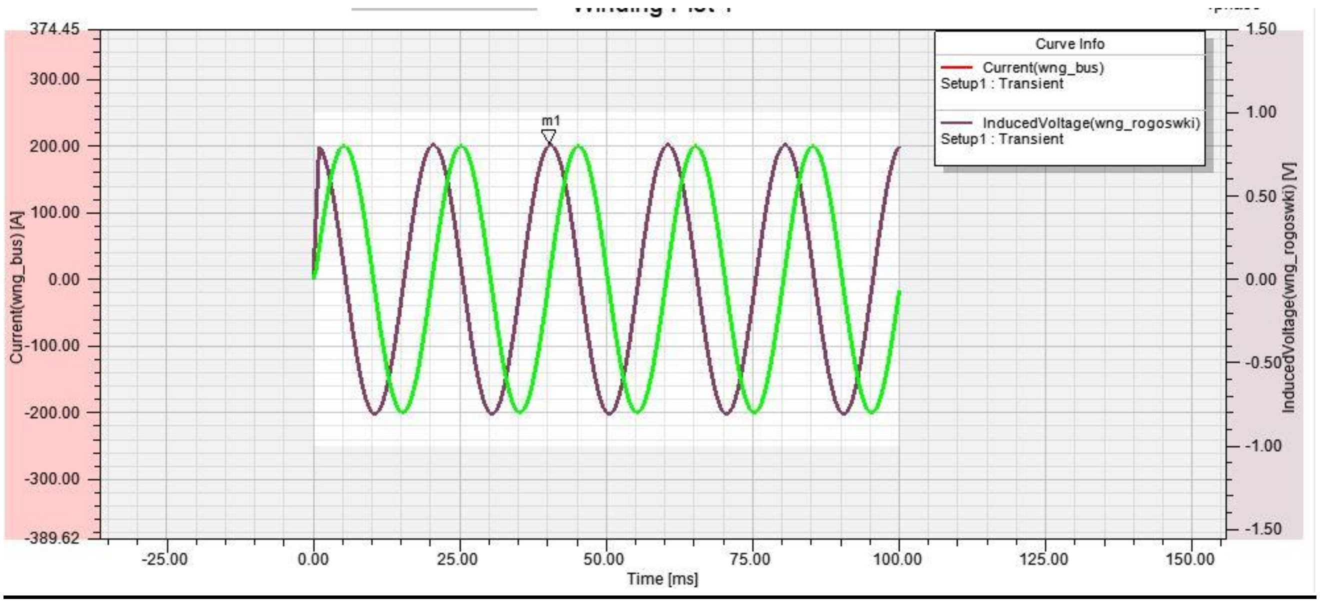


Fig17; Transient current and Induced voltage at 50Hz

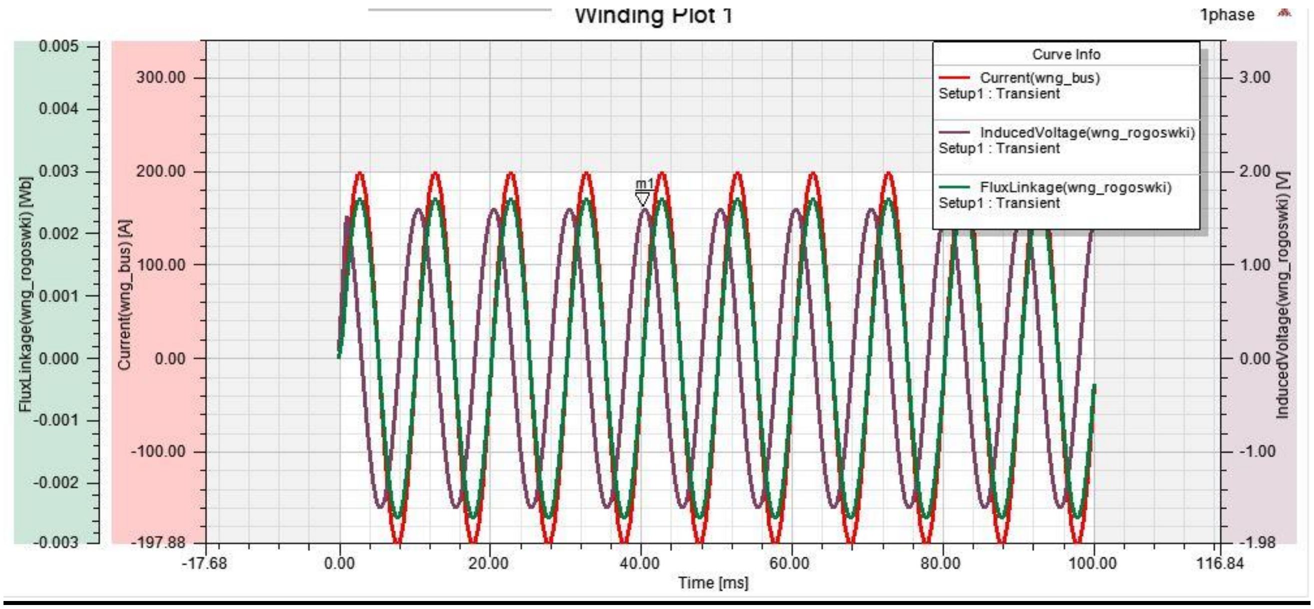
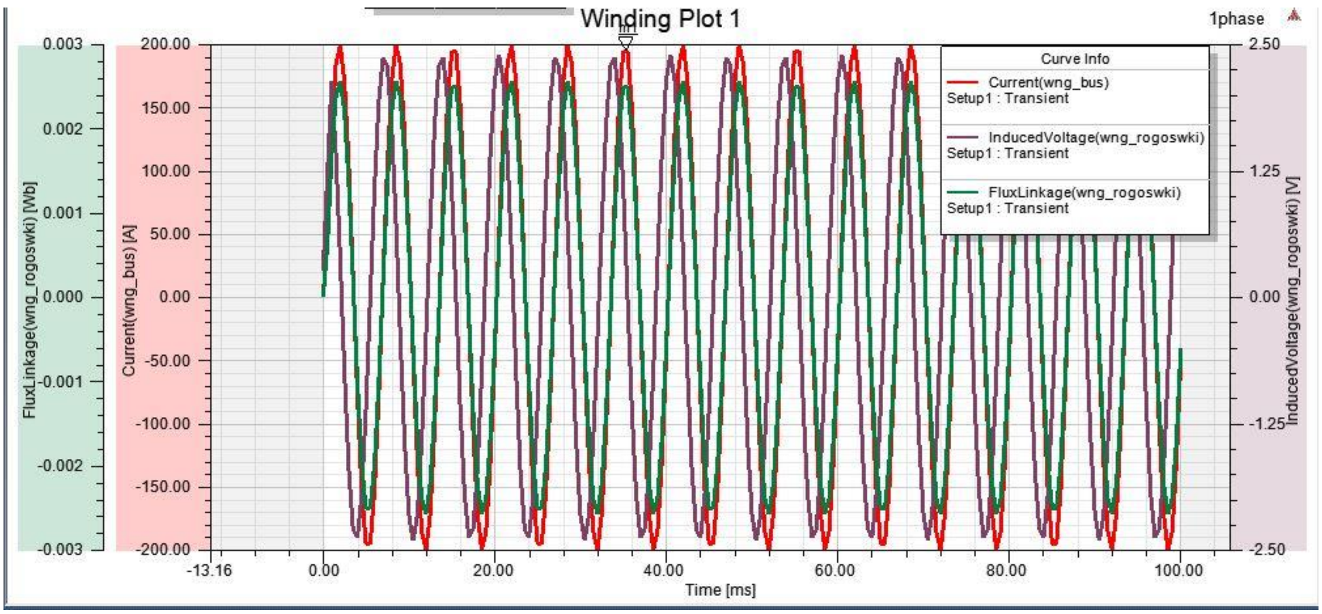


Fig 18; Transient current and Induced voltage at 100Hz



Fig;19 Transient current and Induced voltage at 150Hz

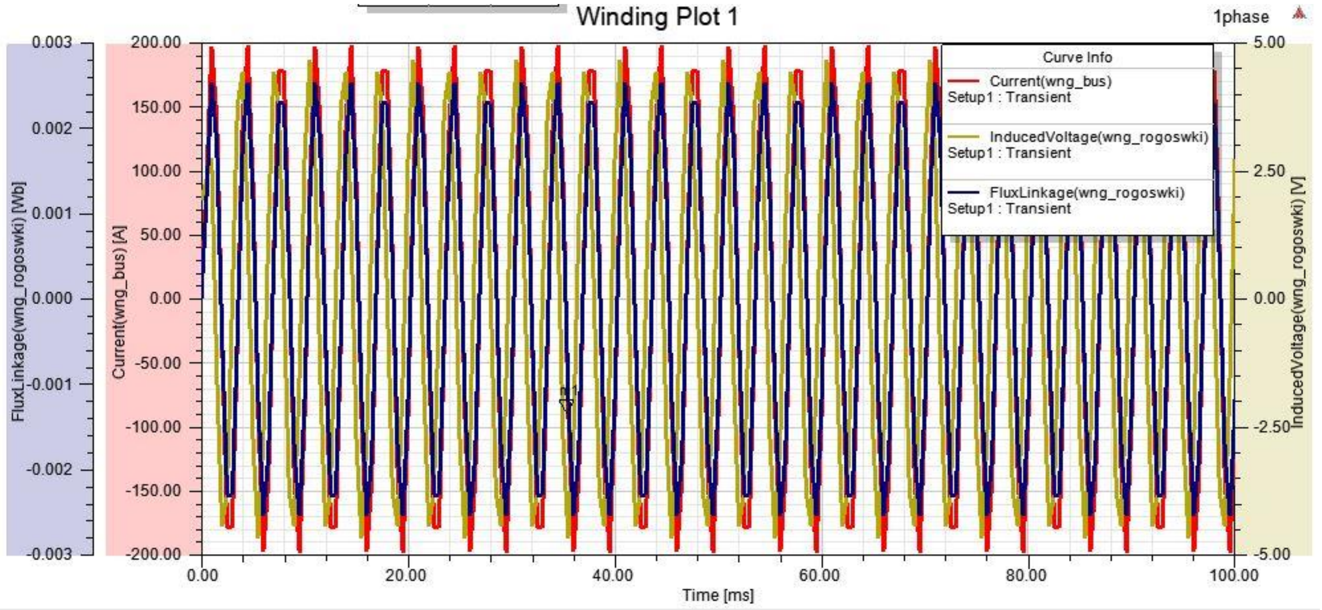


Fig20; Transient current and Induced voltage at 300Hz

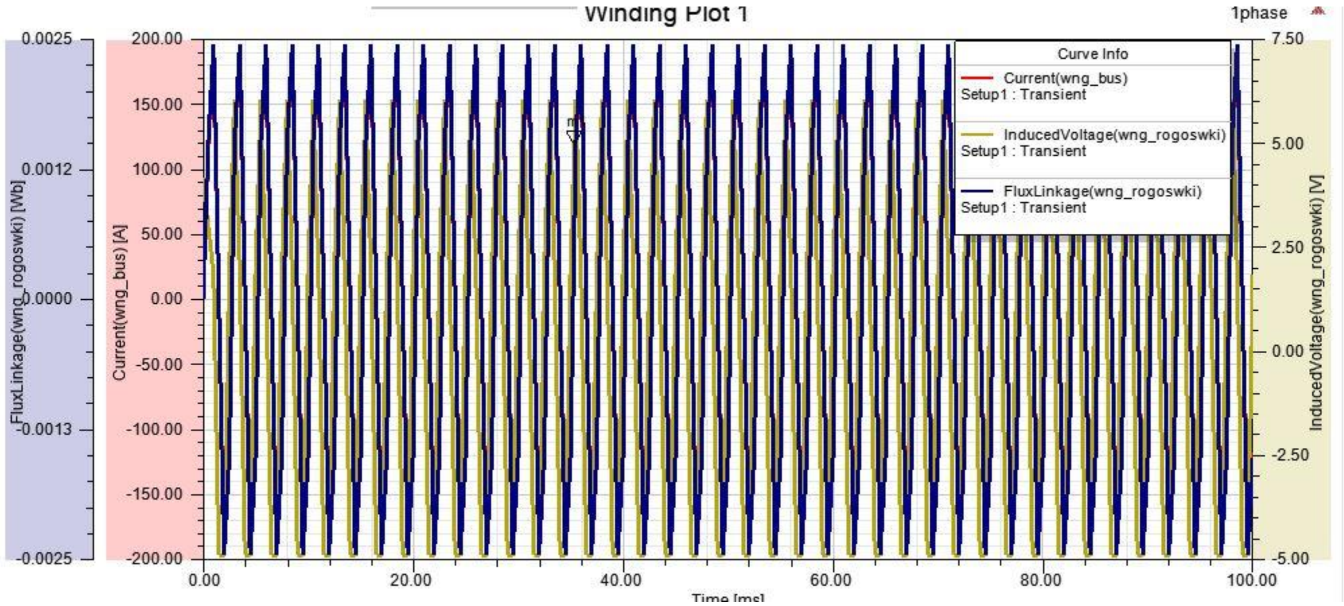


Fig 21; Transient current and Induced voltage at 400Hz

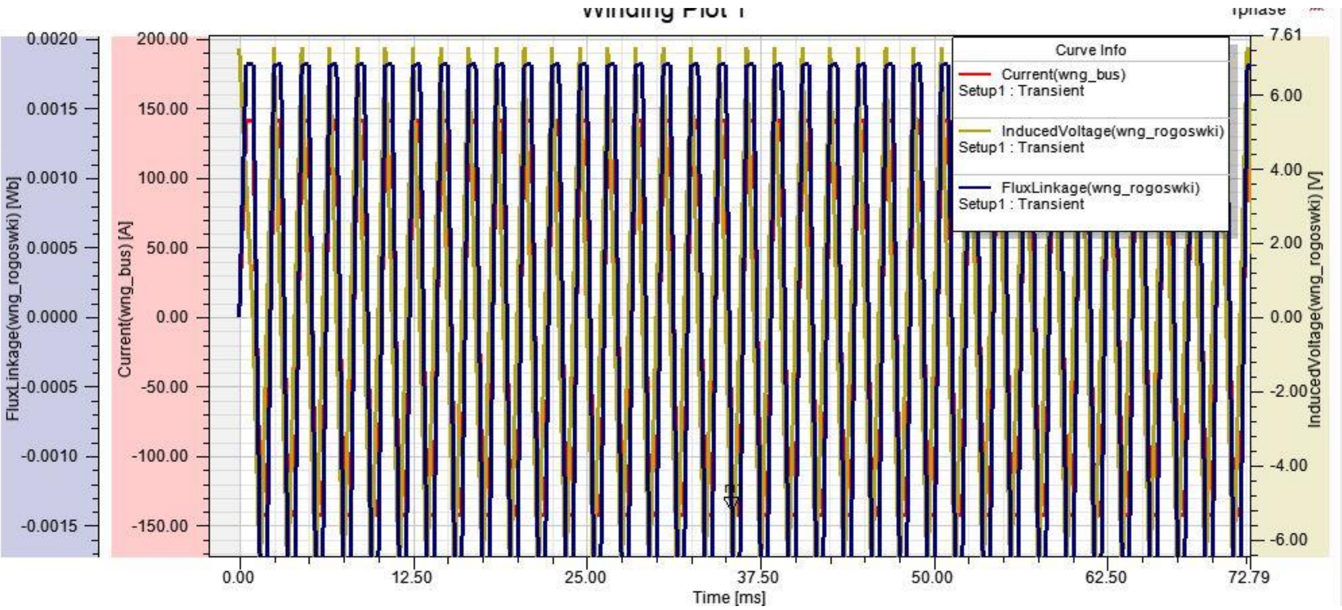


Fig 22; Transient current and Induced voltage at 500Hz

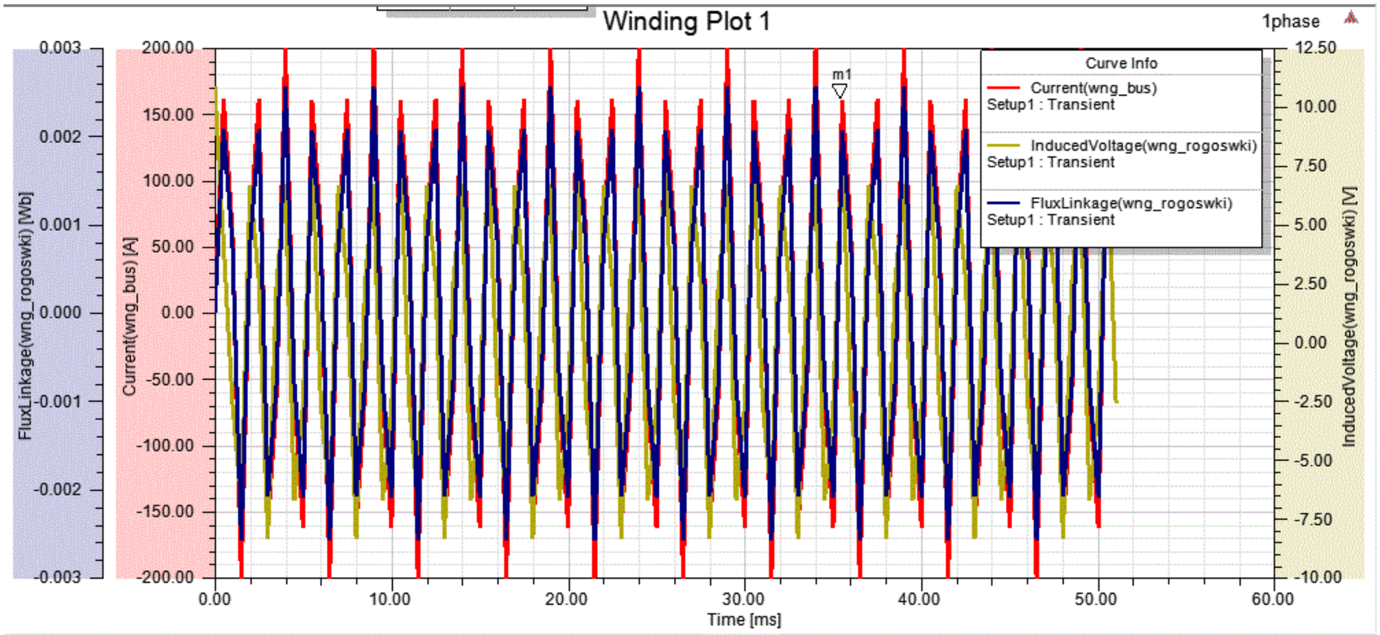


Fig23; Transient current and Induced voltage at 600Hz

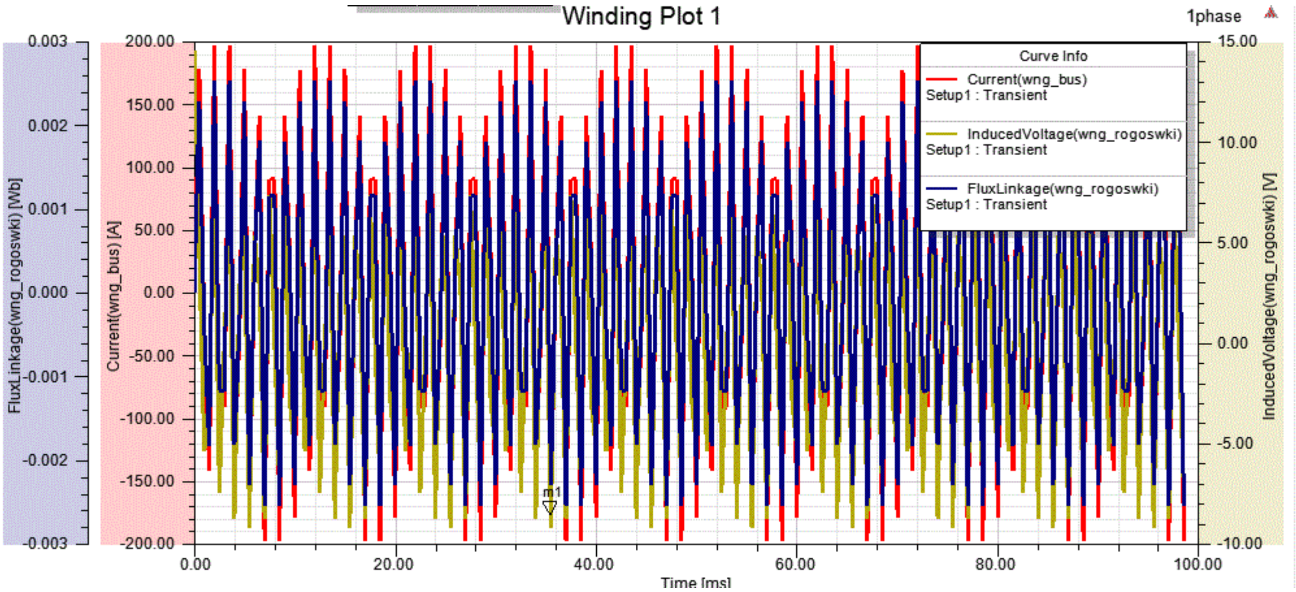


Fig 24; Transient current and Induced voltage at 700Hz

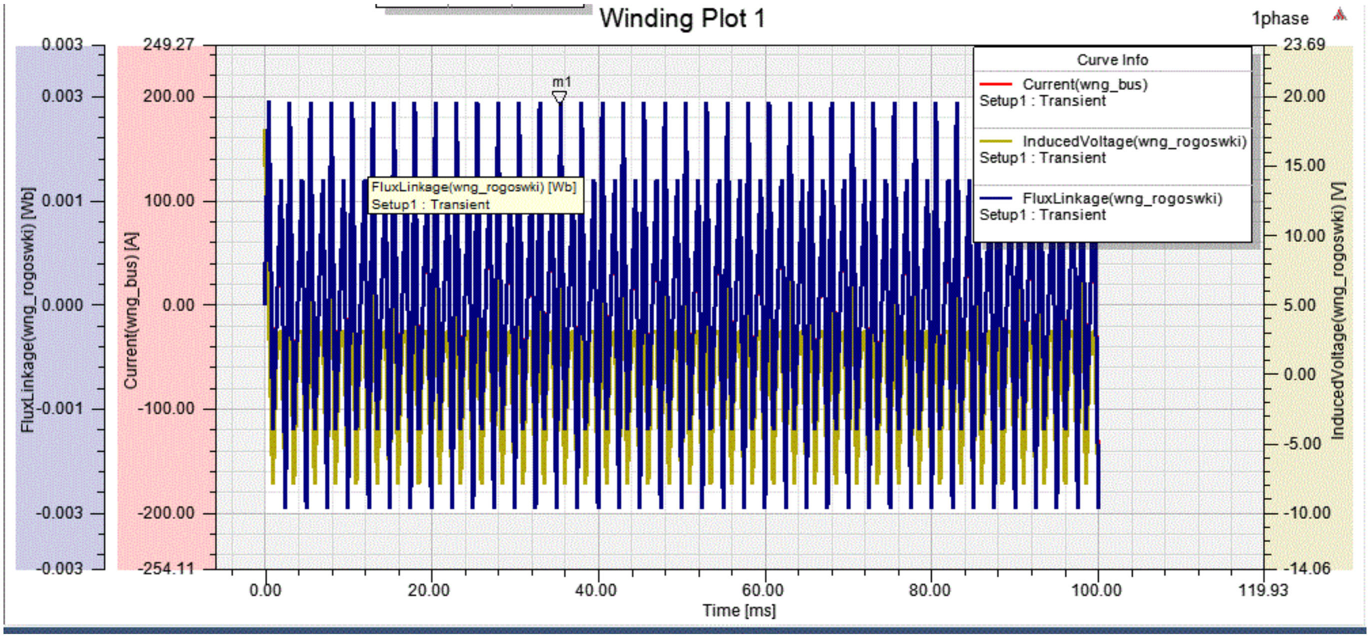


Fig 25; Transient current and Induced voltage at 800Hz

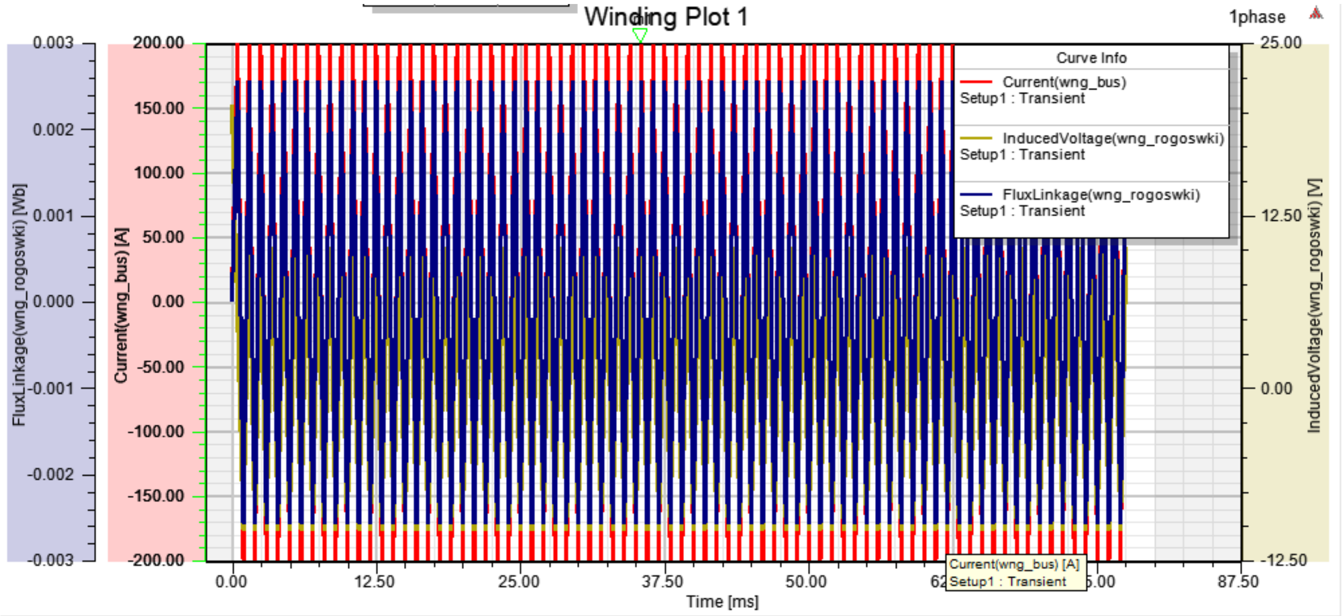


Fig 26; Transient current and Induced voltage at 1000Hz

3.5:Three phase system of Rogowski coil:

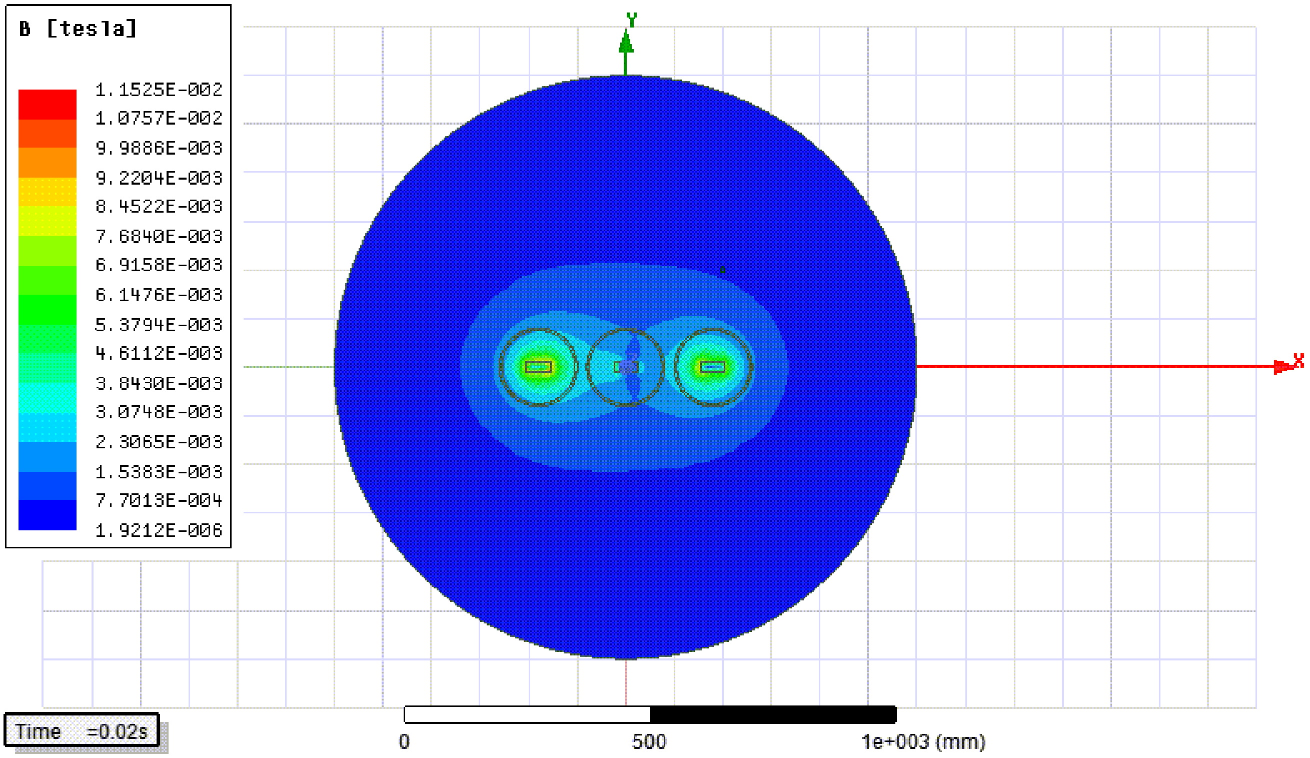


Fig 27; Three phase system of rogowski coil

Table 5: Changing the phase shift 3phase Rogowski coil

Current(A)	Frequency(Hz)
200	100
200	200
200	300
200	400
200	500
200	1000

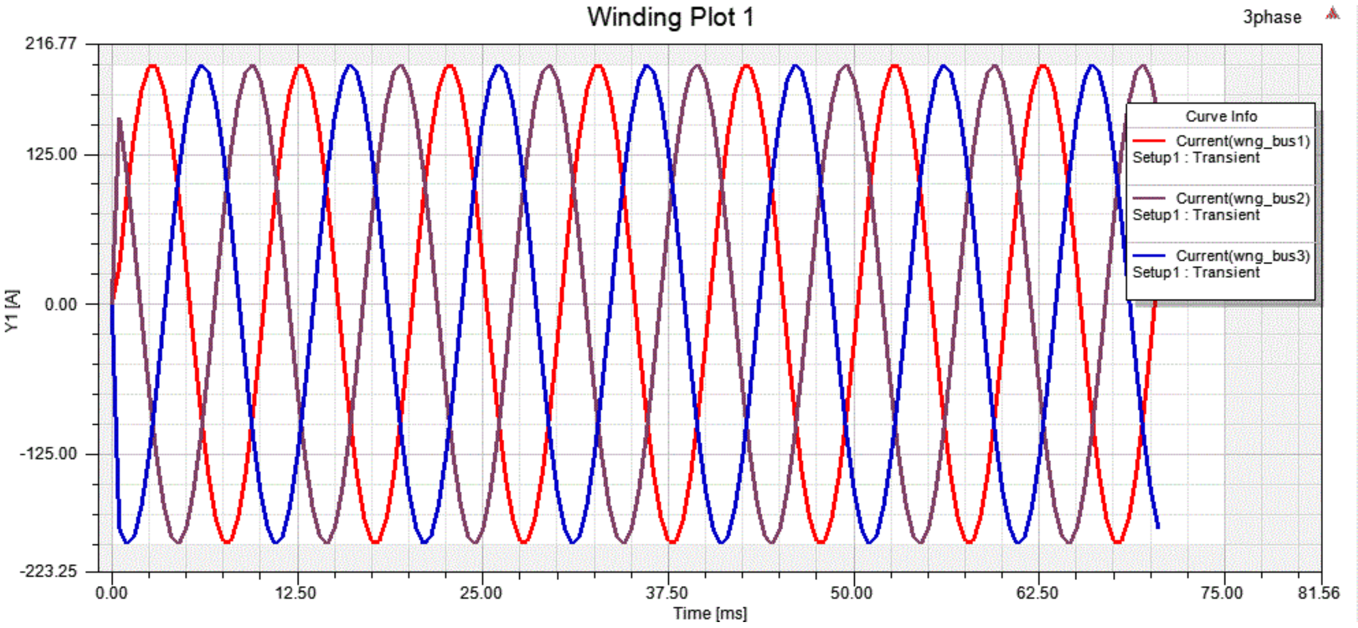


Fig 28; Current in bus 1,2 and 3 at 100Hz

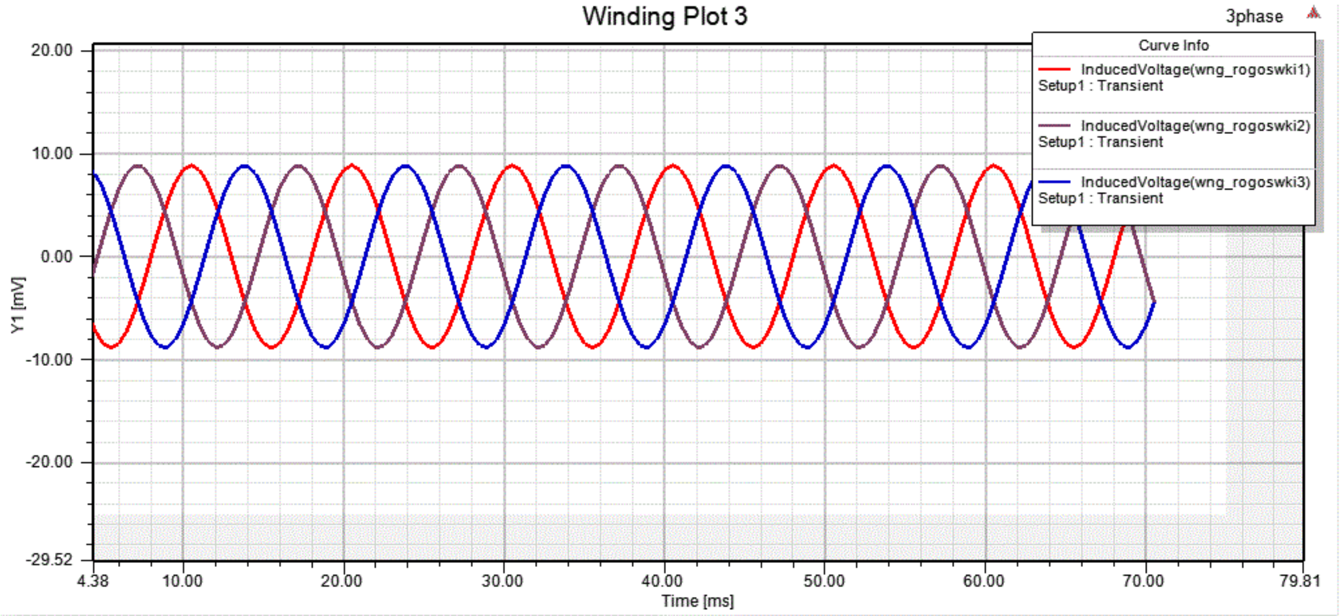


Fig 29; Induced voltage of Rogowski coil 1,2 and 3 at 100Hz

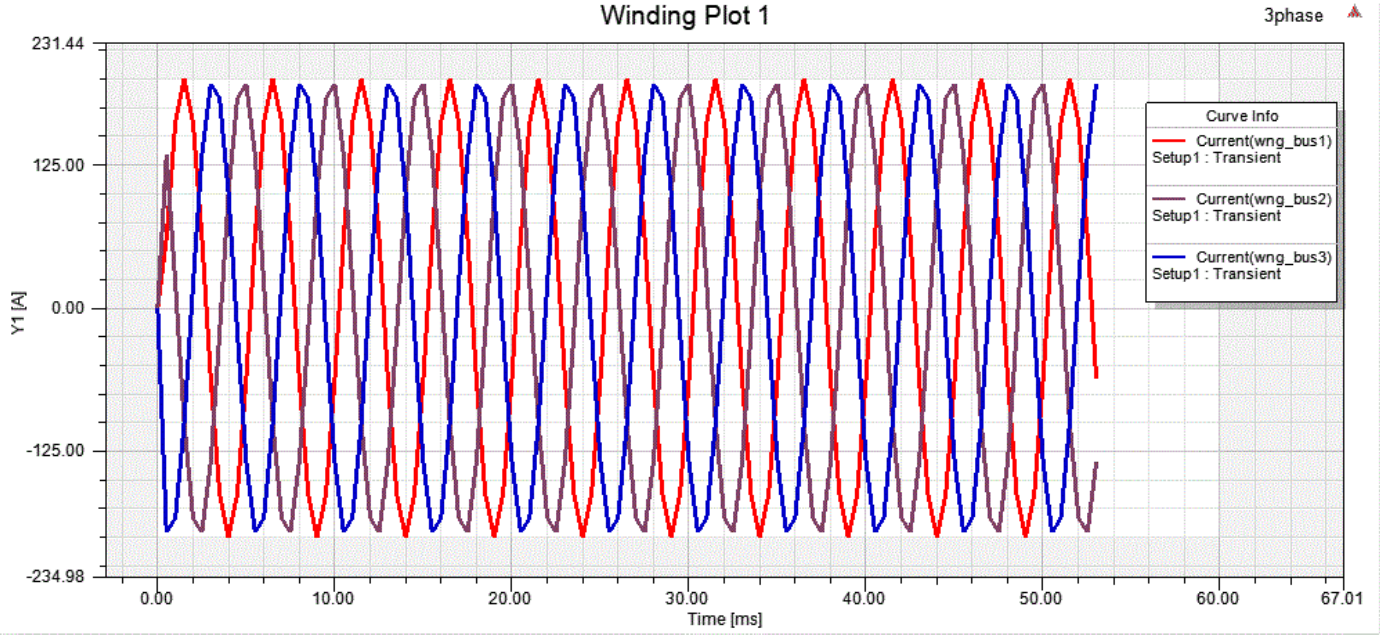


Fig 30; Current in bus 1,2 and 3 at 200Hz

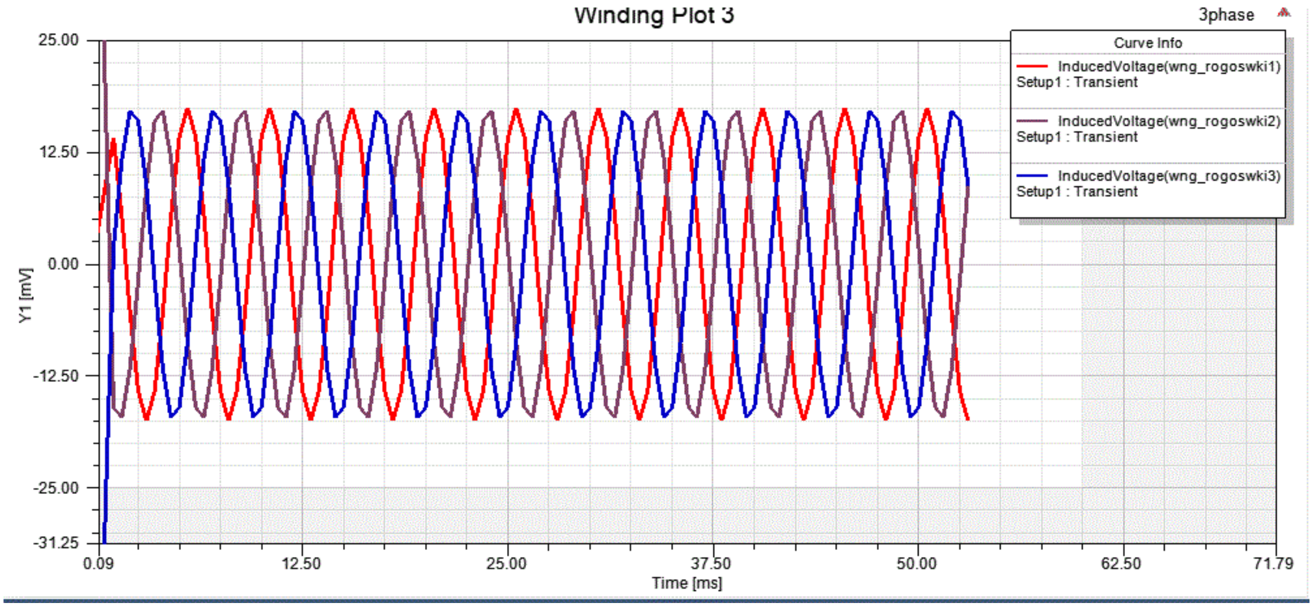


Fig 31: Induced voltage of Rogowski coil 1,2 and 3 at 200Hz

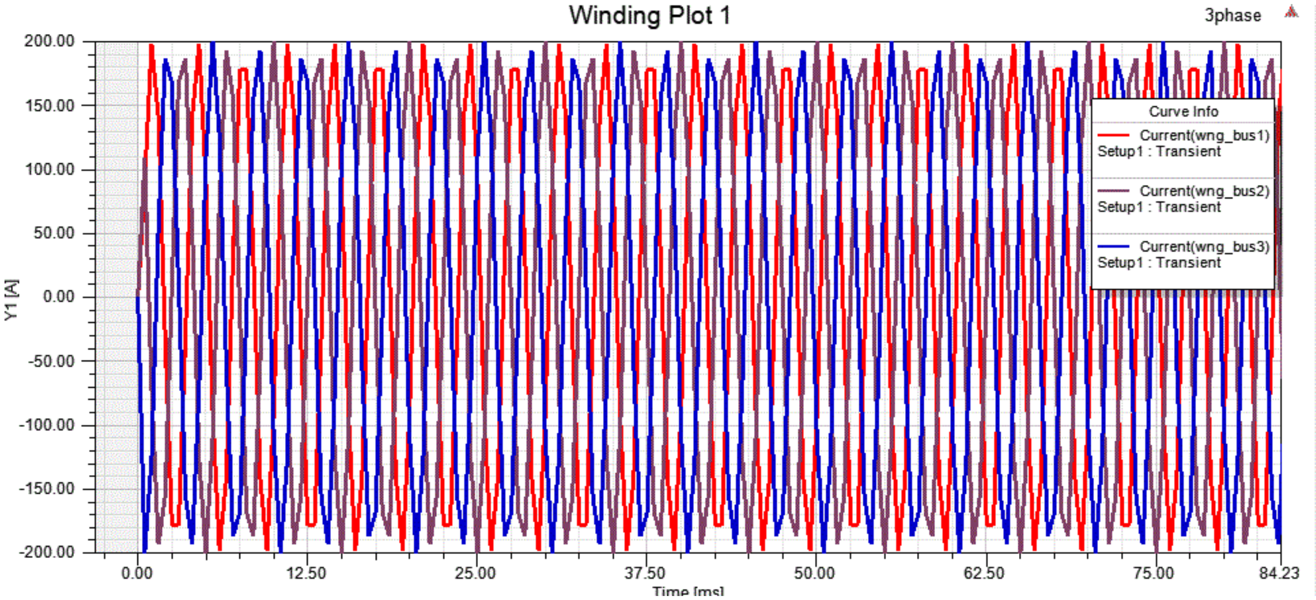


Fig 32: Current in bus 1,2 and 3 at 300Hz

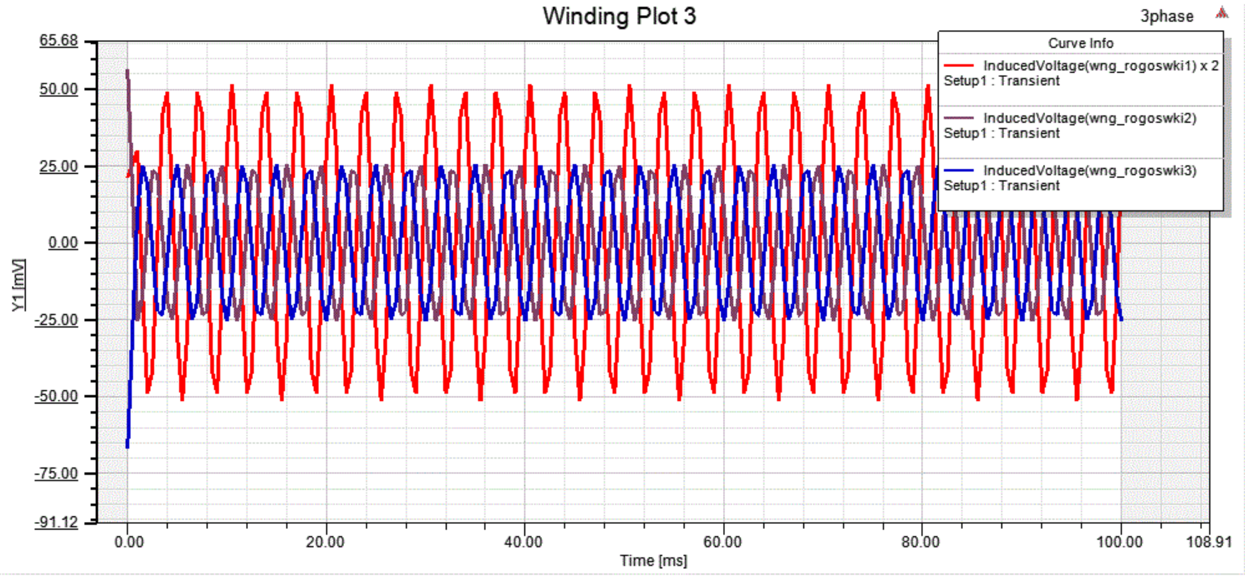


Fig 33: Induced voltage of Rogowski coil 1,2 and 3 at 300Hz

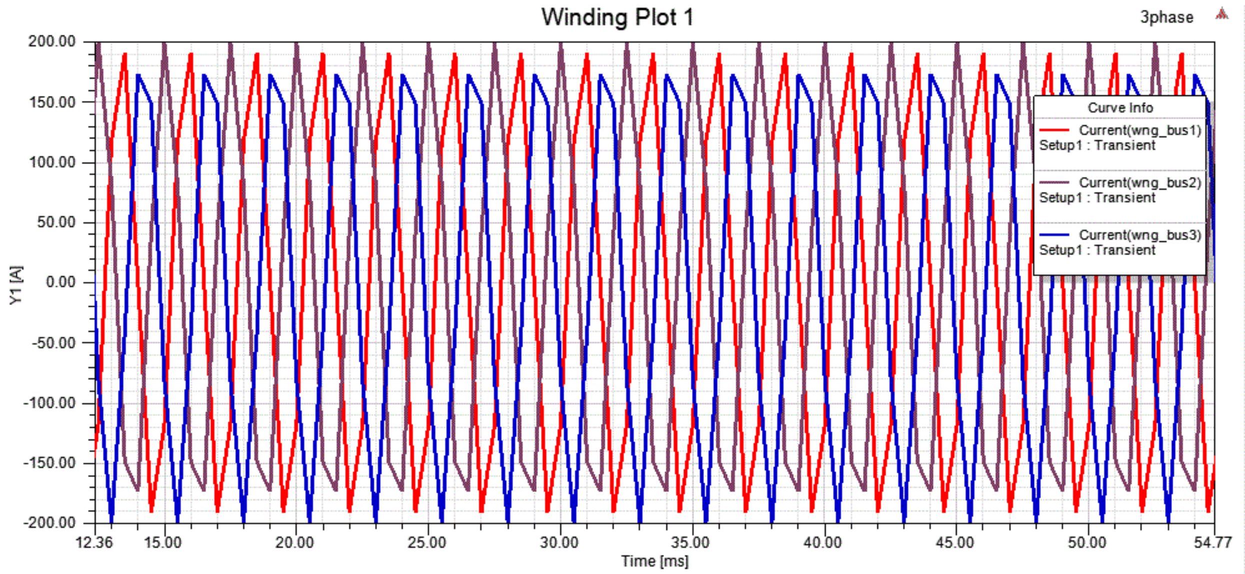


Fig 34; Current in bus 1,2 and 3 at 400Hz

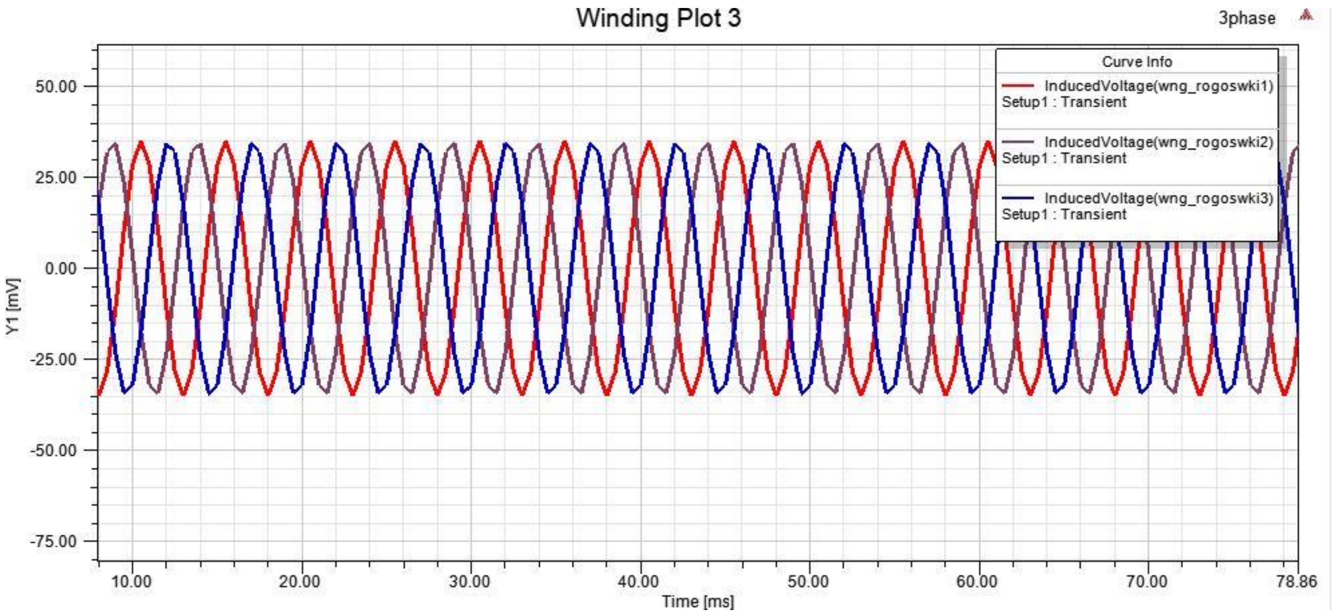


Fig 35; Induced voltage of Rogowski coil 1,2 and 3 at 400Hz

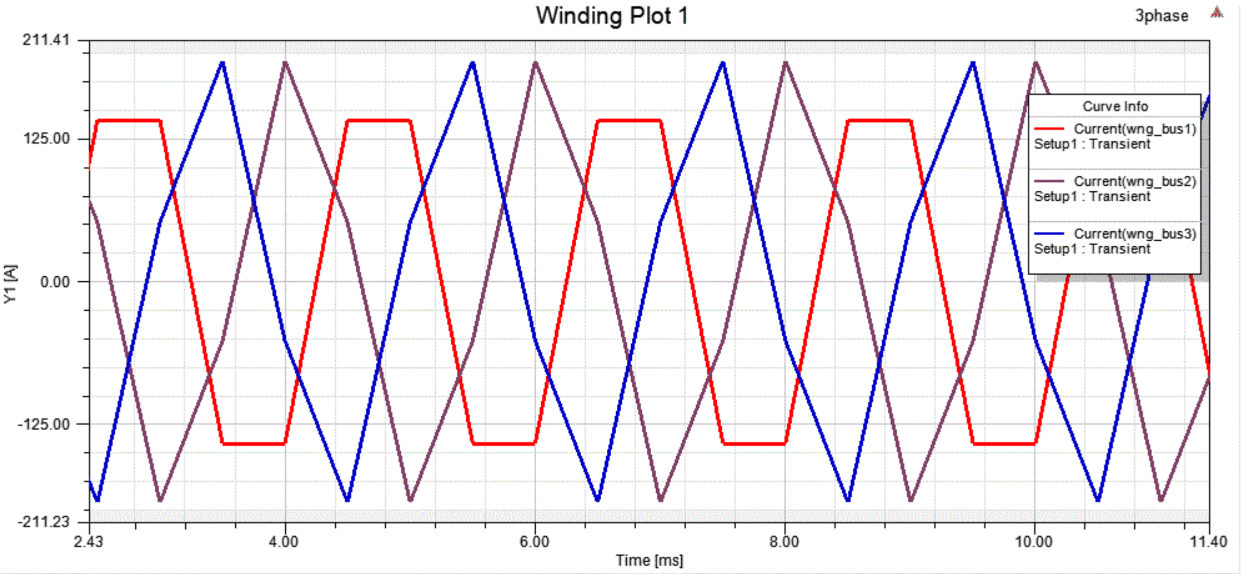


Fig 36; Current in bus 1,2 and 3 at 500Hz

Fig 37:Flux leakage at 500 hz

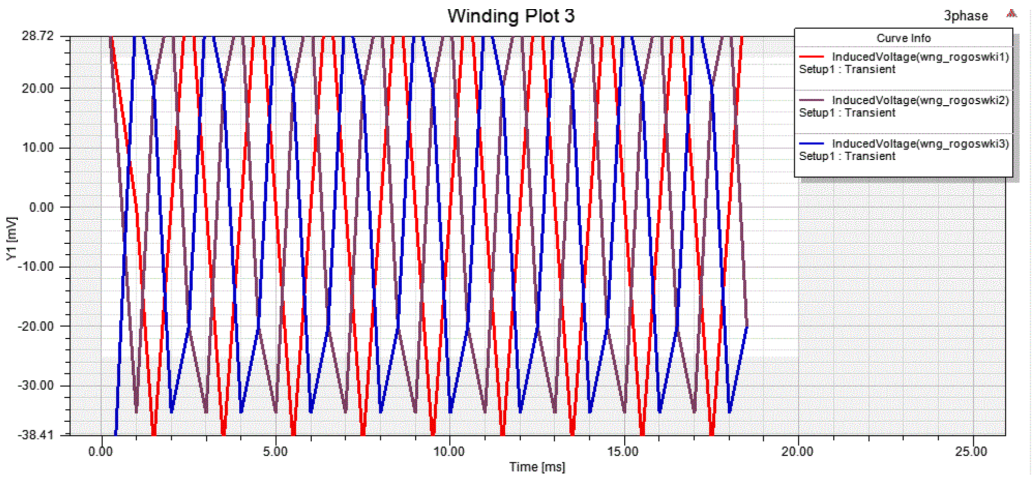


Fig 38; Induced voltage of Rogowski coil 1,2 and 3 at 500Hz

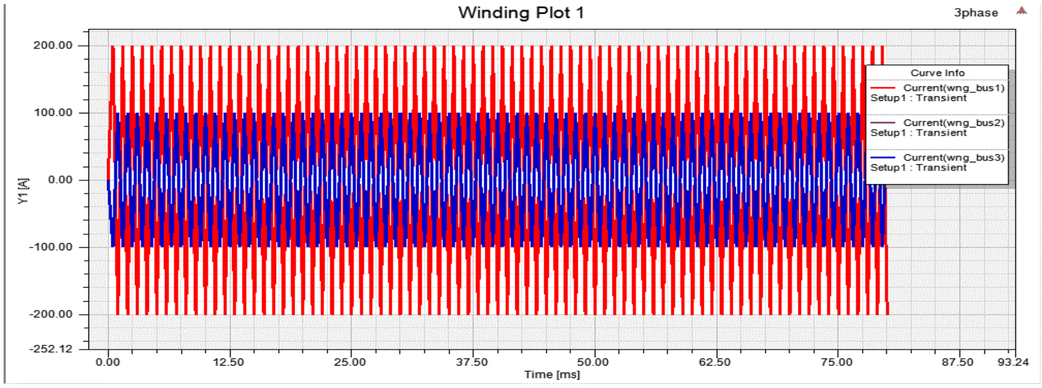


Fig 39; Current in bus 1,2 and 3 at 1000Hz

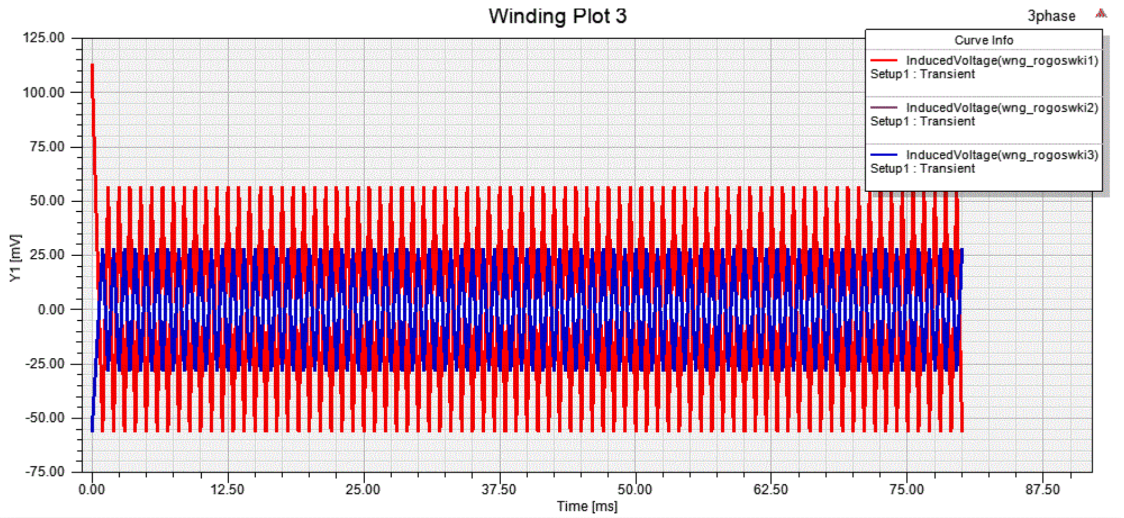


Fig40; Induced voltage of Rogowski coil 1,2 and 3 at 1000Hz

3.6:3D Model of Rogowski Coil:

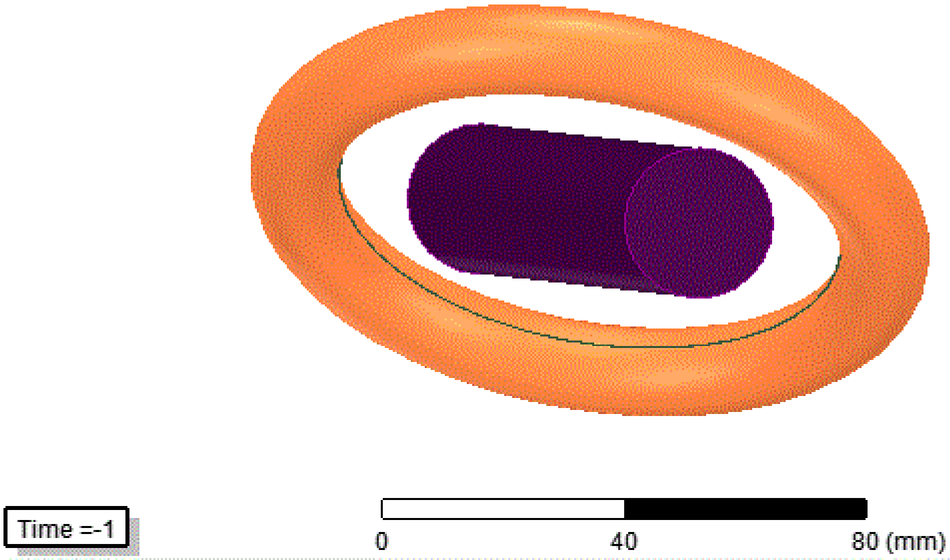


Fig 41:Rogowski coil at 60mm

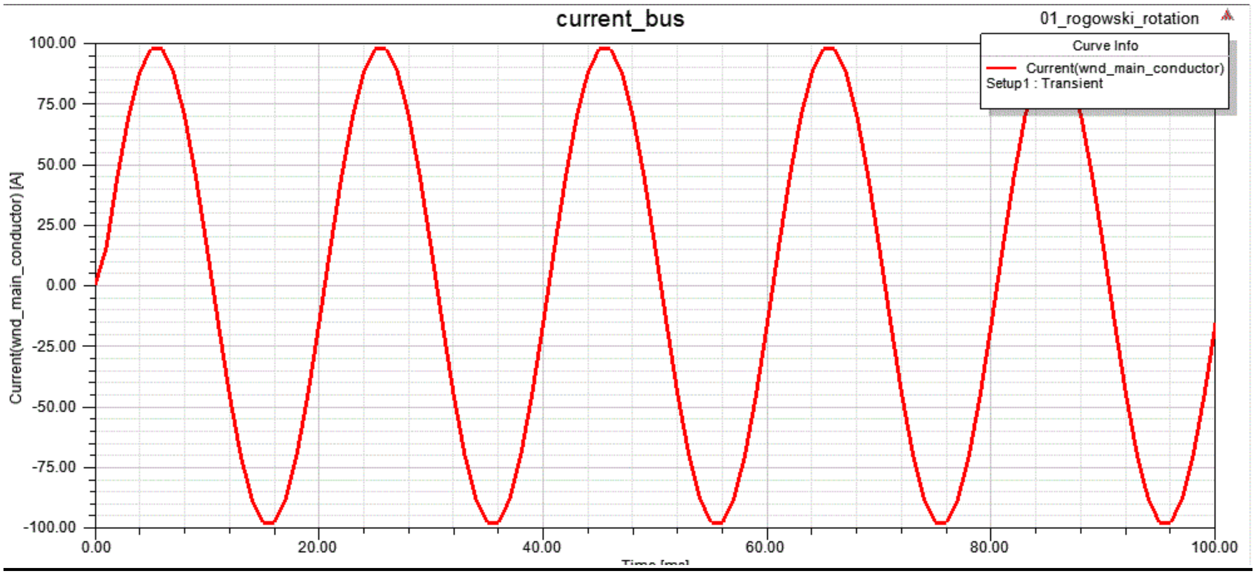


Fig 42 :Current main conductor

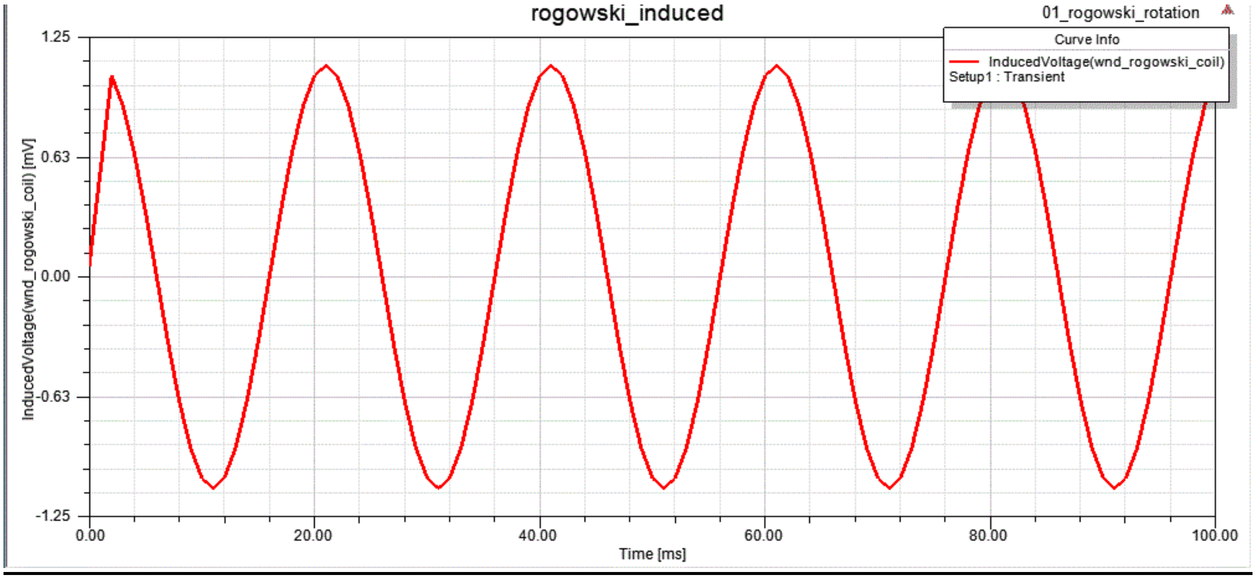


Fig 43:Induced voltage at rogowski coil

Fig 44::induced voltage and current at rogowki coil and main conductor

4. External Influence of Rogowski coil:

As well known, the behavior of the Rogowski coil is significantly affected by the presence of external fields having components along the coil axis (z-axis), as those generated by conductors which lay in the same plane of the device. As an example, Fig. 9 well clarifies how the flux generated by the external conductor links the entire coil circumference inducing an additional electromotive force. The final effect is an uncorrected indication of the current value to be measured. In order to quantify this discrepancy,a unitary current is considered, which flows in the conductor posed in the coil plane, at a distance D from the coil centre, when the same current is assumed in the main conductor

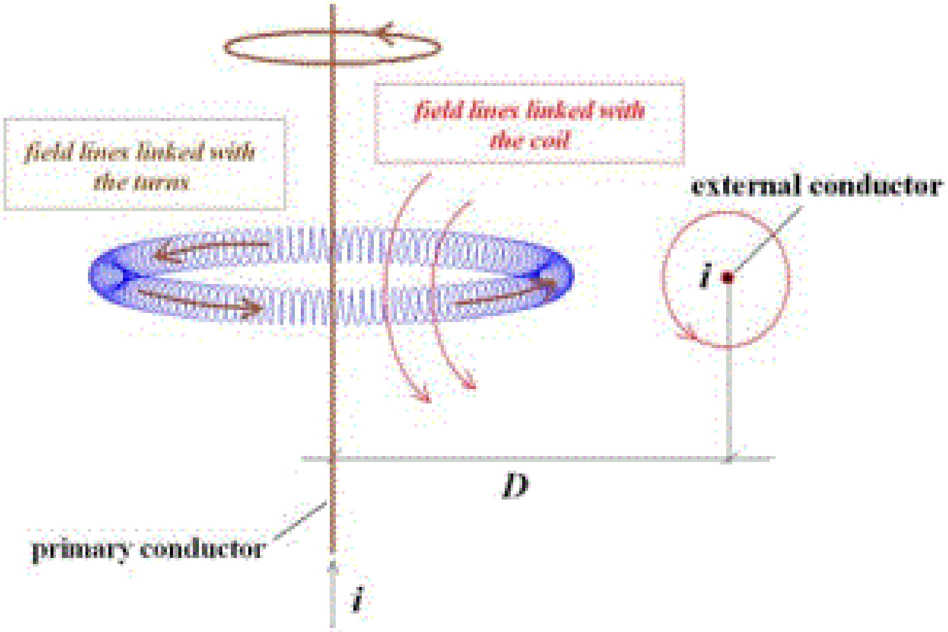


Fig.45: Influence of an external conductor on the coil measurement.

If the current which flows in the primary and in the external conductor is equal to 1 A, the influence of the external source can be quantified by considering an equivalent current which, flowing in the primary conductor (in absence of the external one), should generate the same magnetic flux totally linked by the. A compensation turn, wound in the opposite direction with respect to the main coil, or a second winding, with the same number of turns wound in the opposite direction with respect to the main one are efficiently used for the compensation of the effects due to the external field having components along the coil axis (z-axis). Rogowski coils with a compensation turn and of a double coil with a counter-wound winding are illustrated, respectively, in Fig. 10a) and Fig. 10b).

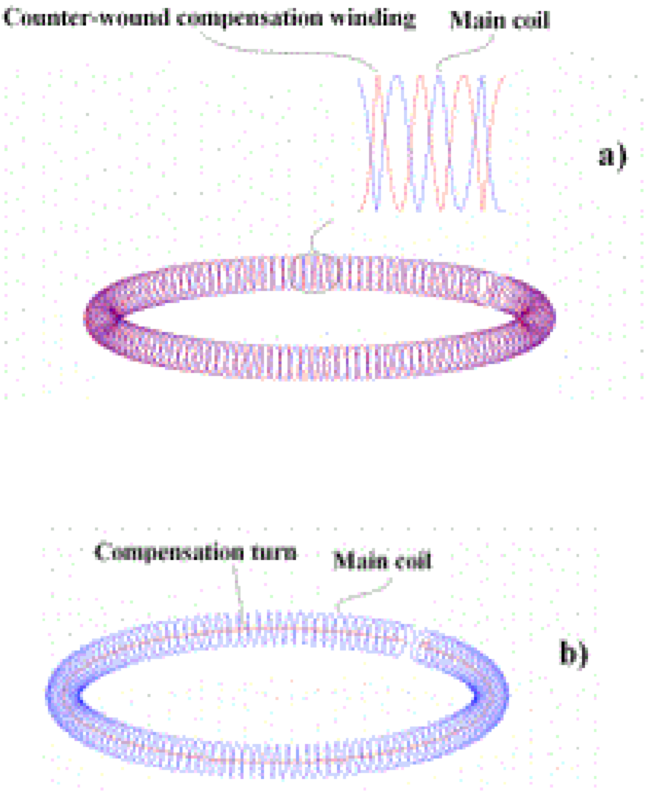


Fig.46: Plotting of the coil with a) a counter-wound winding, b) a compensation turn.

The effects of the non-orthogonal positioning of the primary conductor axis with respect to the coil plane are then investigated. The analysis is carried out by considering several values of the tilt angle α, for different coil gaps. Fig. 46 shows that an anti-symmetrical behavior occurs for positive and negative α values. This effect can be considerably reduced by adopting a counter-wound winding, because the magnetic field, generated by the tilted primary conductor, introduces also field components along the coil axis. By using the double coil, the influence of the angle † decreases of about one order of magnitude, as shown in Fig. 47. As last analysis, a primary conductor with a rectangular cross-section is considered, modelling the bulk conductor with a number of thin conductors suitably positioned and assuming the opening angle β=2°

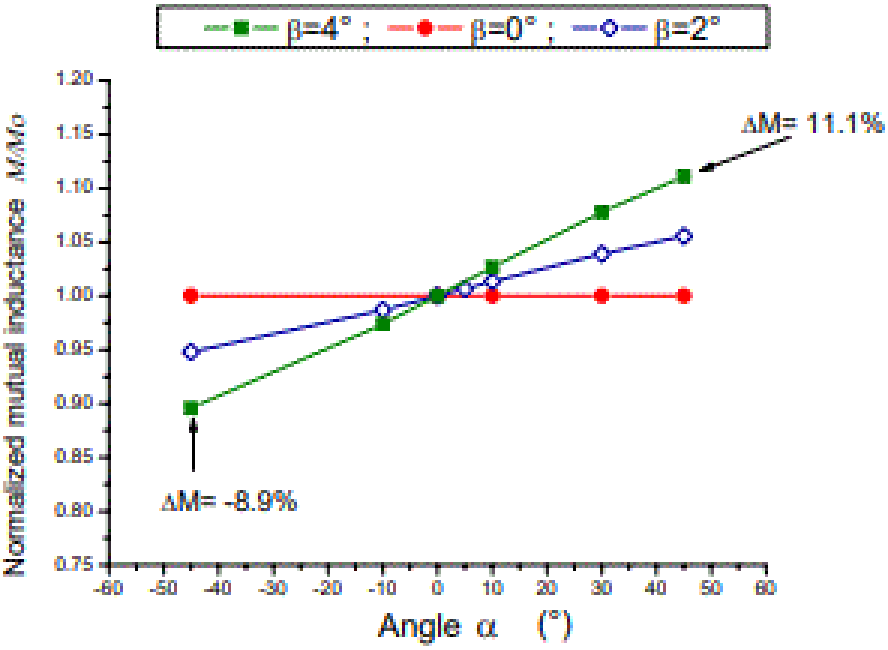


Fig: 47 Normalized mutual inductance behavior with nonorthogonal position of the primary conductor.

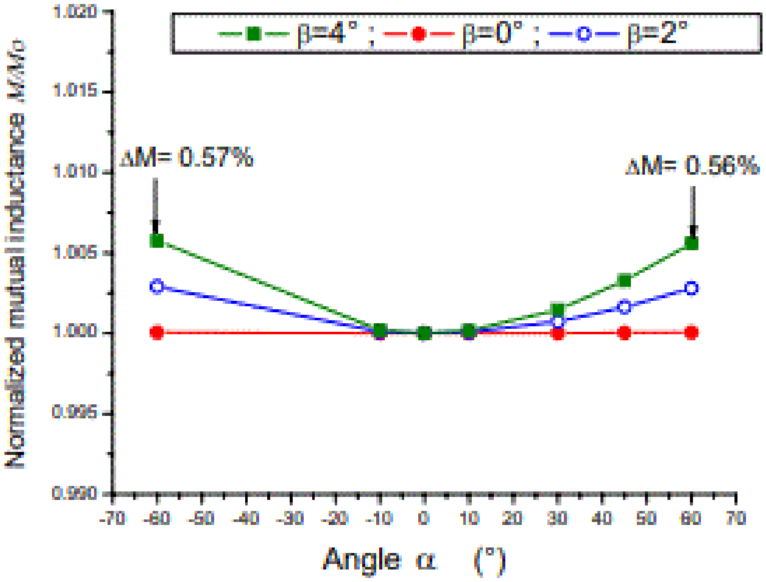


Fig 48: Normalized mutual inductance behavior in non-orthogonal conditions: effect of the addition of a second winding.[12]

4.1: Changing the position of external conductor

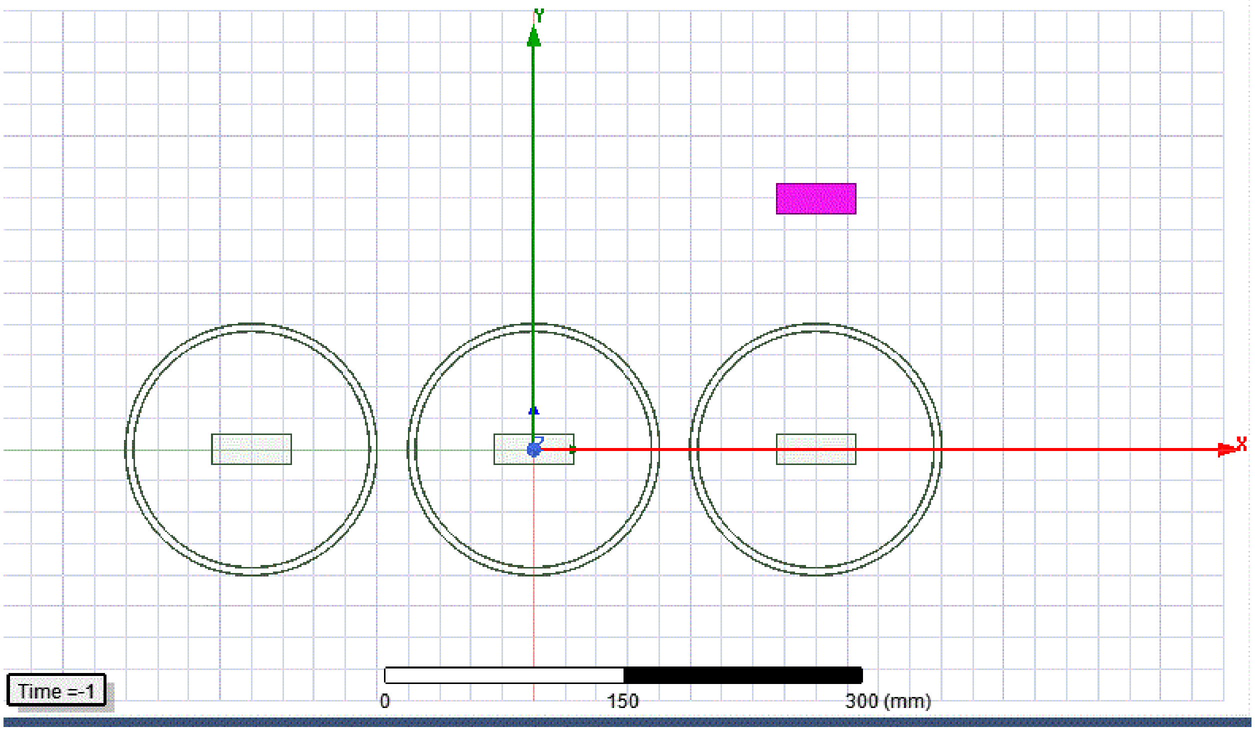


Fig 50: Using external conductor at Rogowski coil

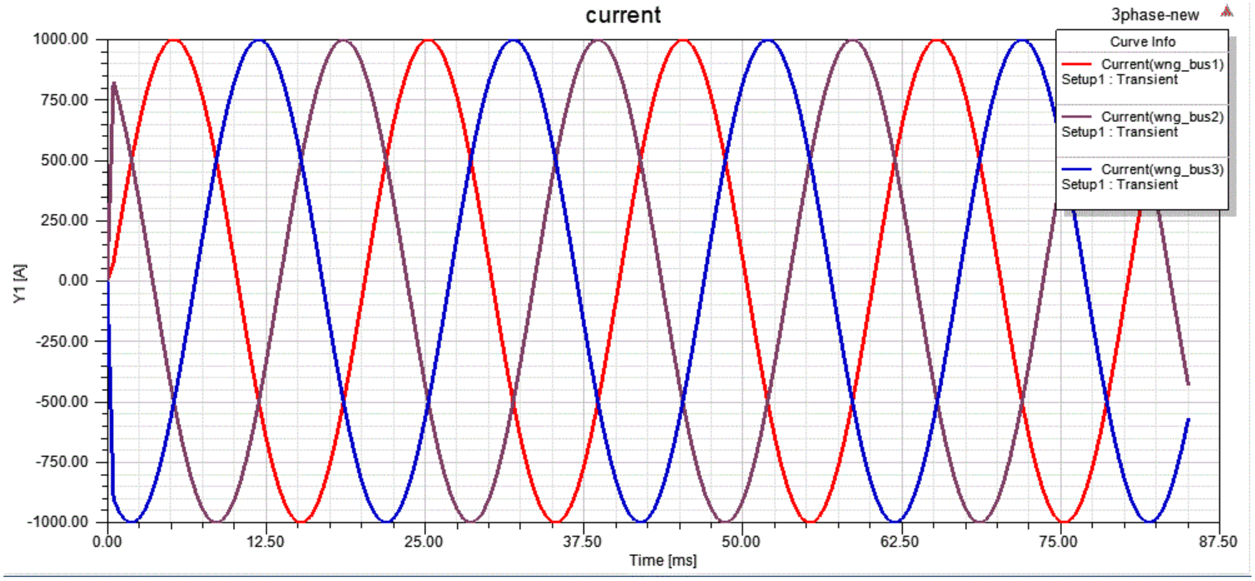


Fig 51:Current at Bus bar 1,2,3

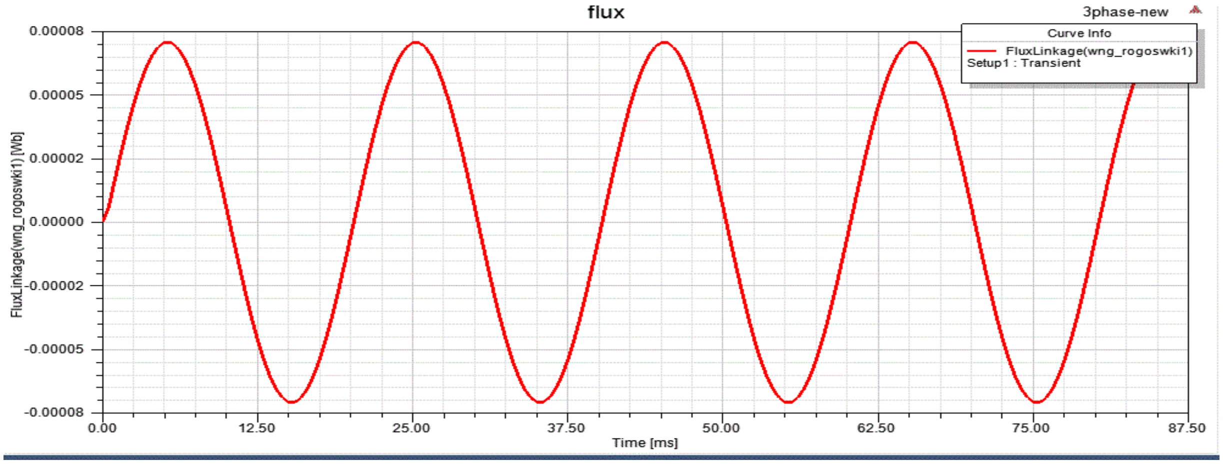


Fig 52:Flux leakage at rogowski coil

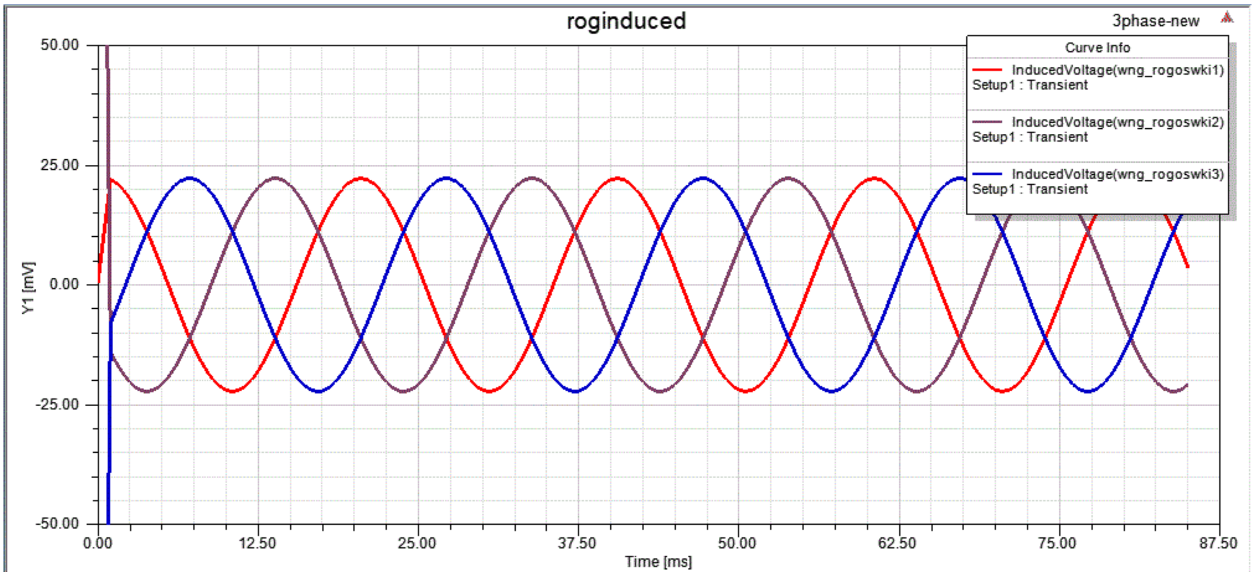


Fig 53:Induced voltage at Rogowski 1,2,3

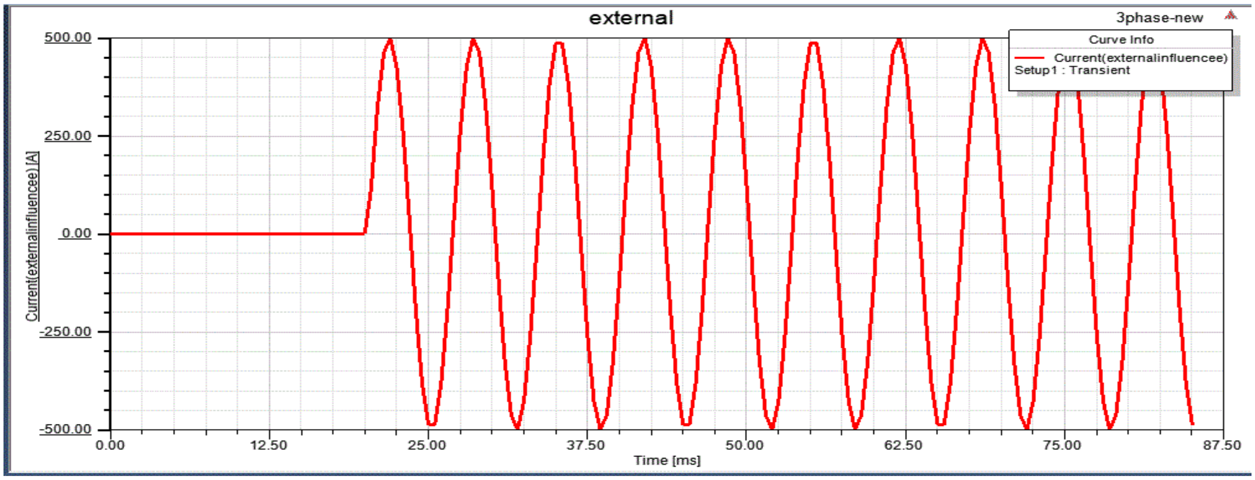


Fig 54:External Influence of Rogowski coil

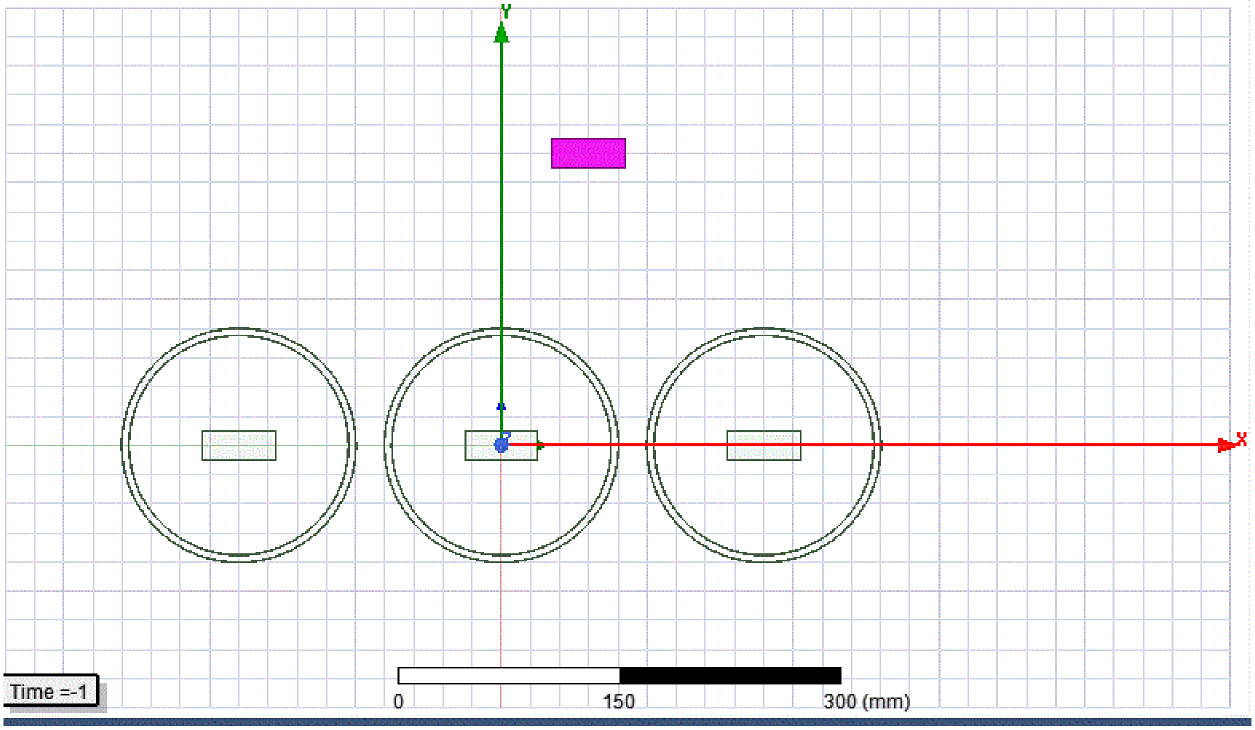


Fig 55: Changing position of external conductor at Rogowski coil

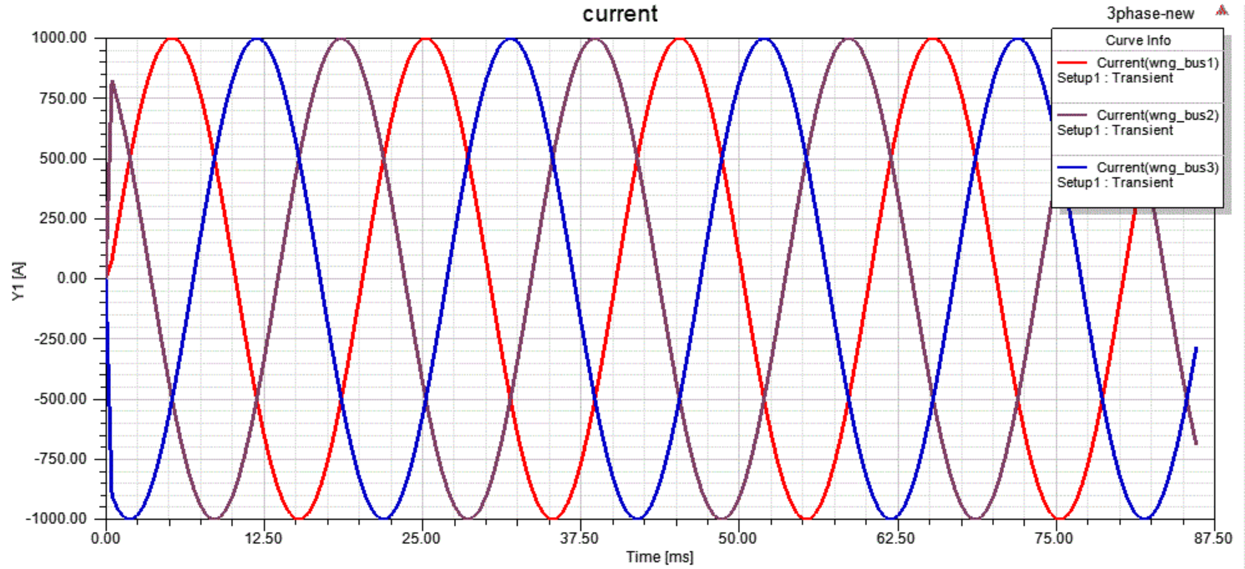


Fig 56:Current at Bus bar 1,2,3

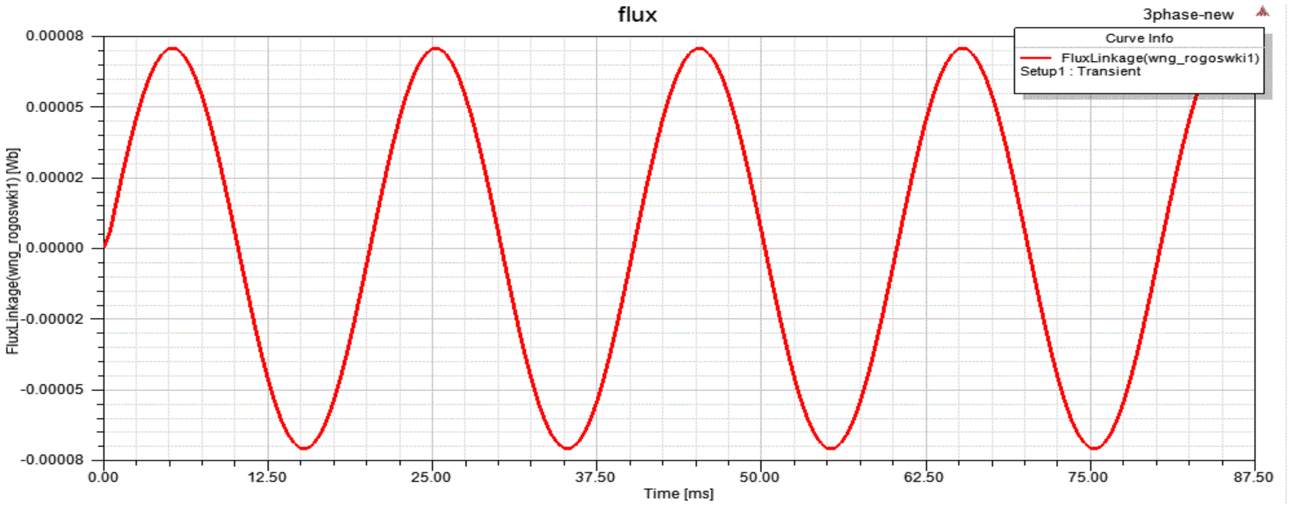


Fig 57:Flux leakage at rogowski coil

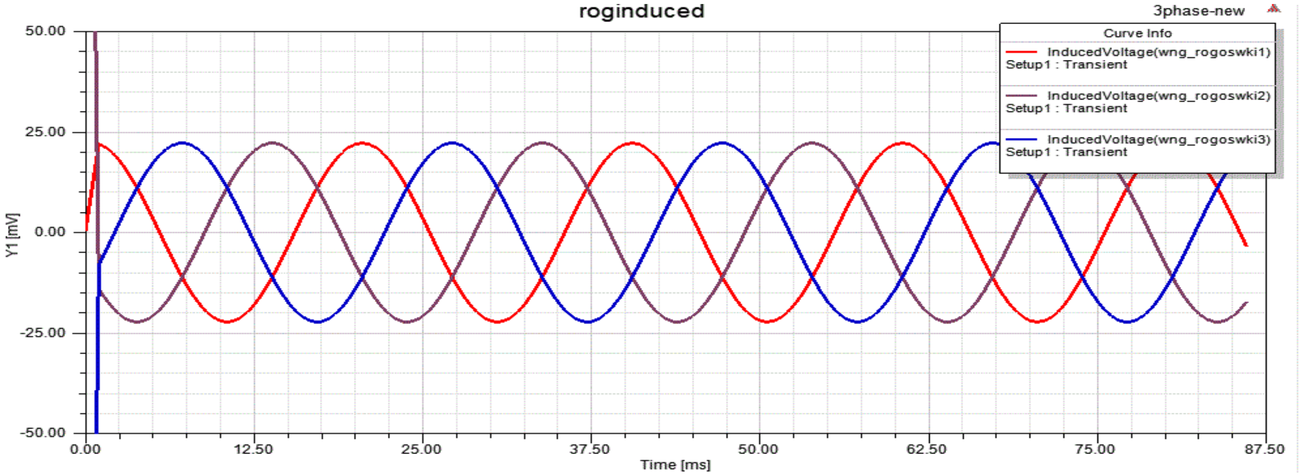


Fig 58:Induced voltage at Rogowski 1,2,3

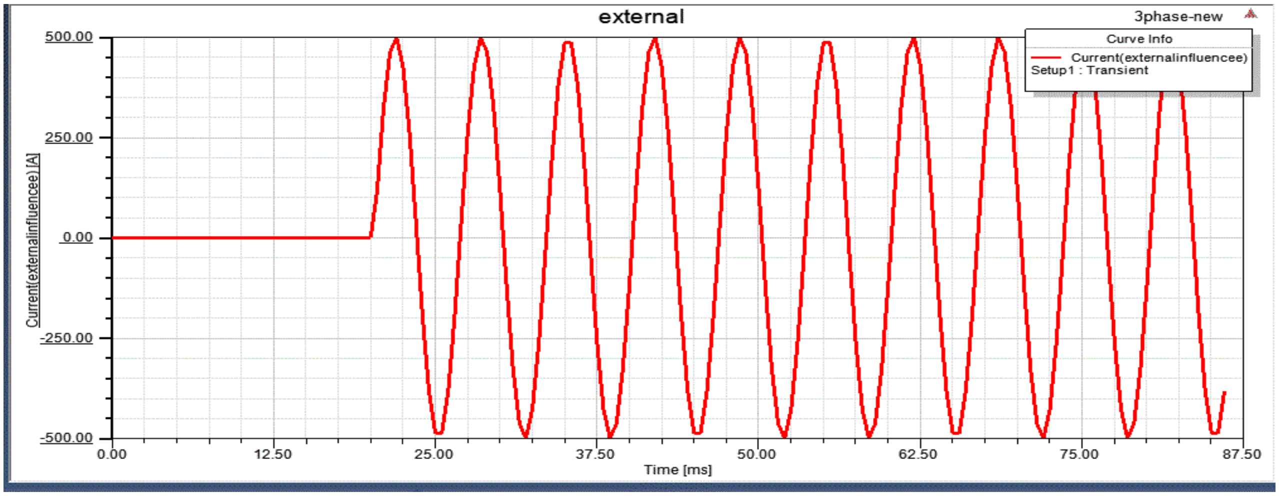


Fig 59:External Influence of Rogowski coil

5. Using External circuit at Rogowski coil:

When there is an external current outside the discrete RC, some errors will certainly occur in the measurement of the current encircled by the discrete RC. This is due to the error in the approximation Of Amperes law incomplete closed geometry of the discrete RC.In the actual measurement process the value of external current and the relative position of the external conductor leads to interference error.

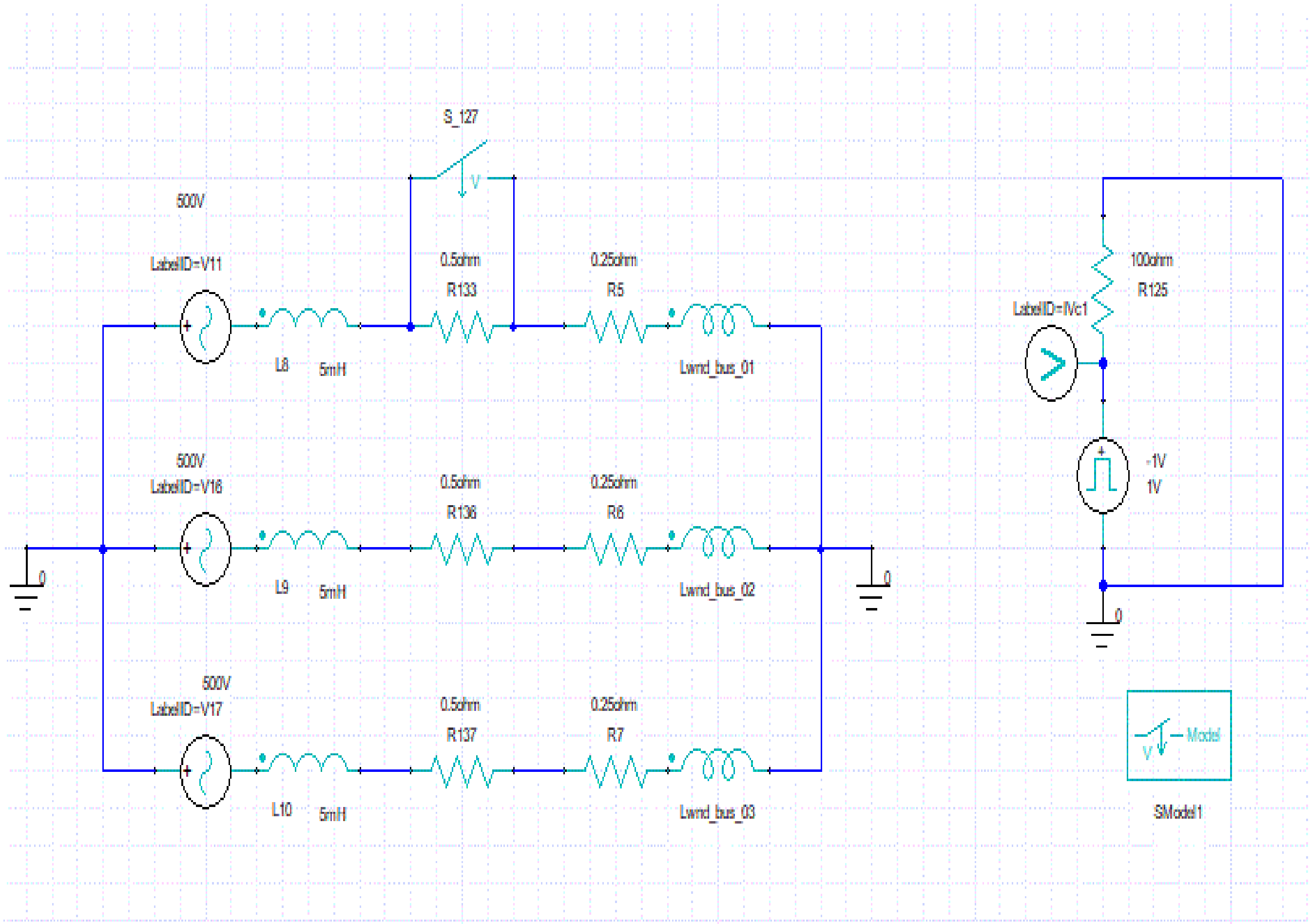


Fig 60;External influence circuit of Rogowski coil

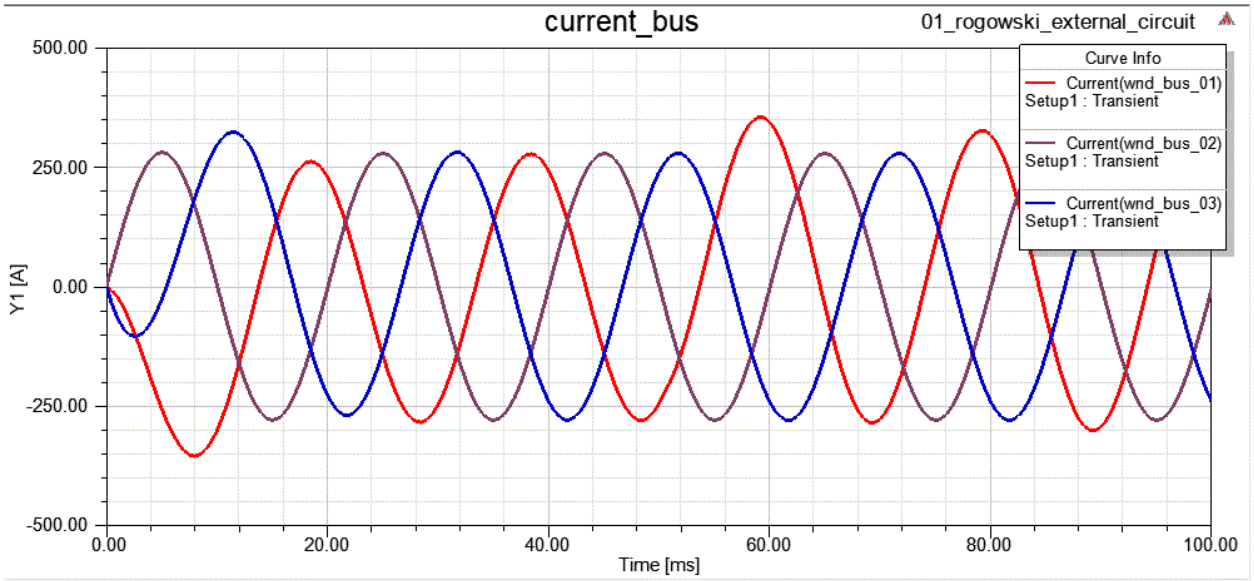


Fig 61:Current at Bus bar 1,2,3

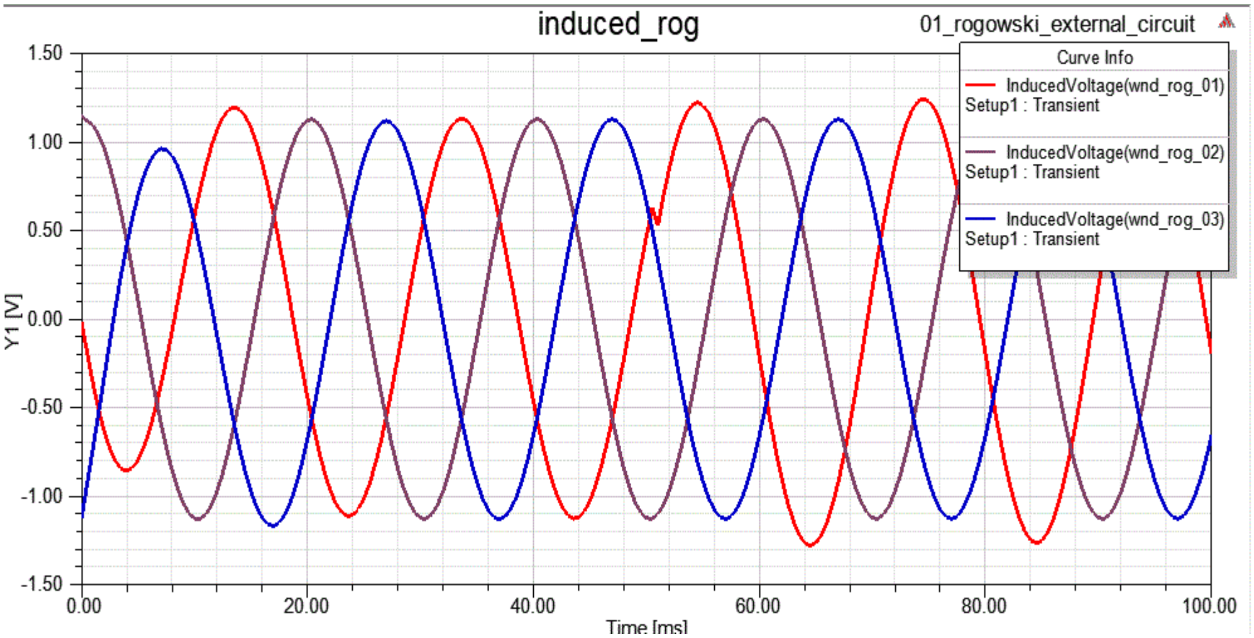


Fig 62:Induced voltage at Rogowski coil 1,2,3

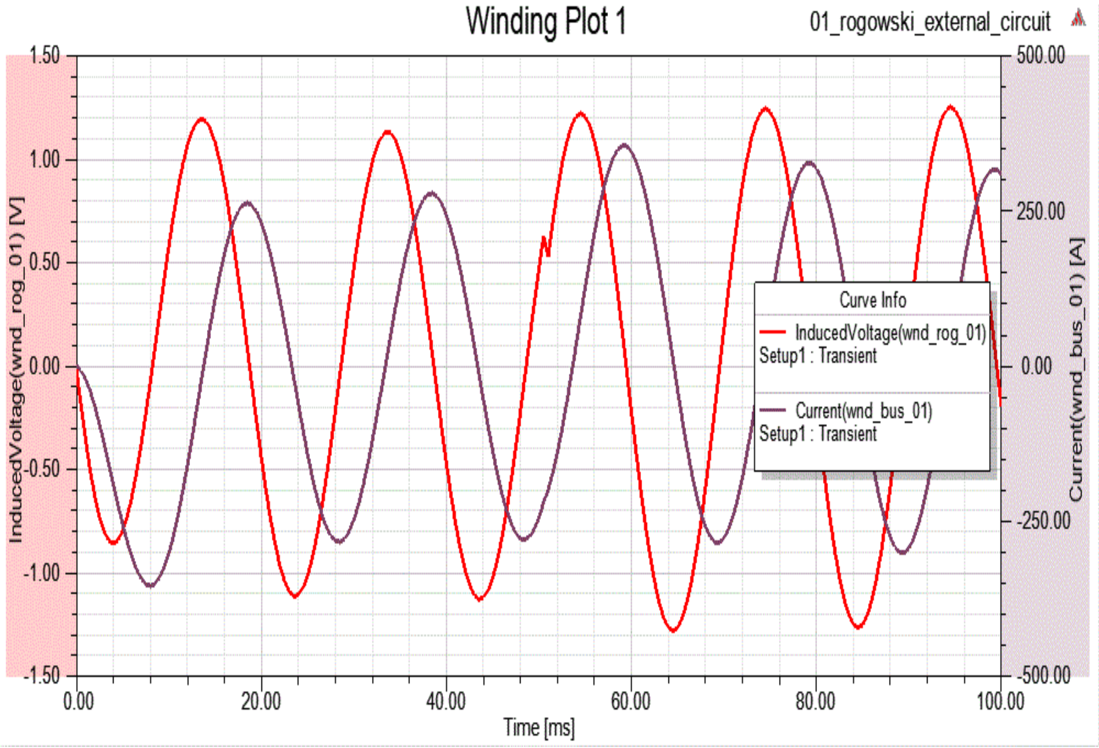


Fig 63:Induced voltage at Rogowski coil and Current togather

5.1. Additional source Using in External circuit at Rogowski coil:

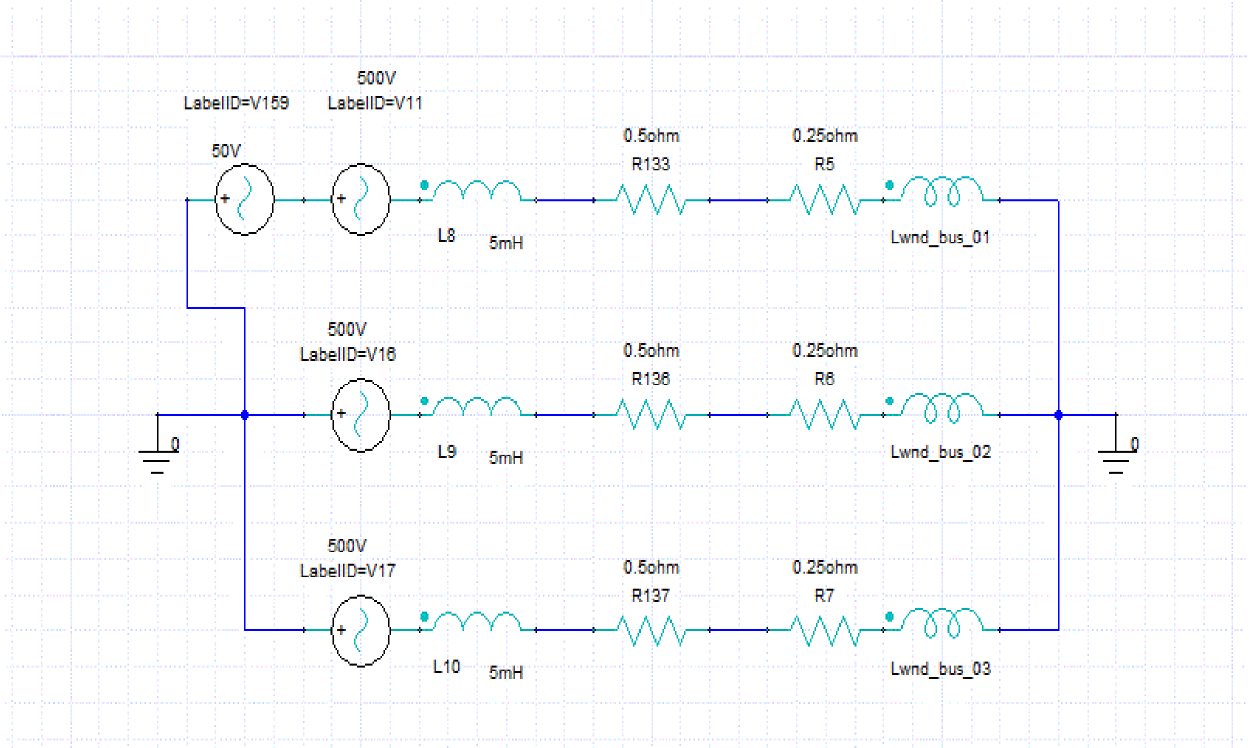


Fig 64;Additonal souce in External influence circuit at Rogowski coil

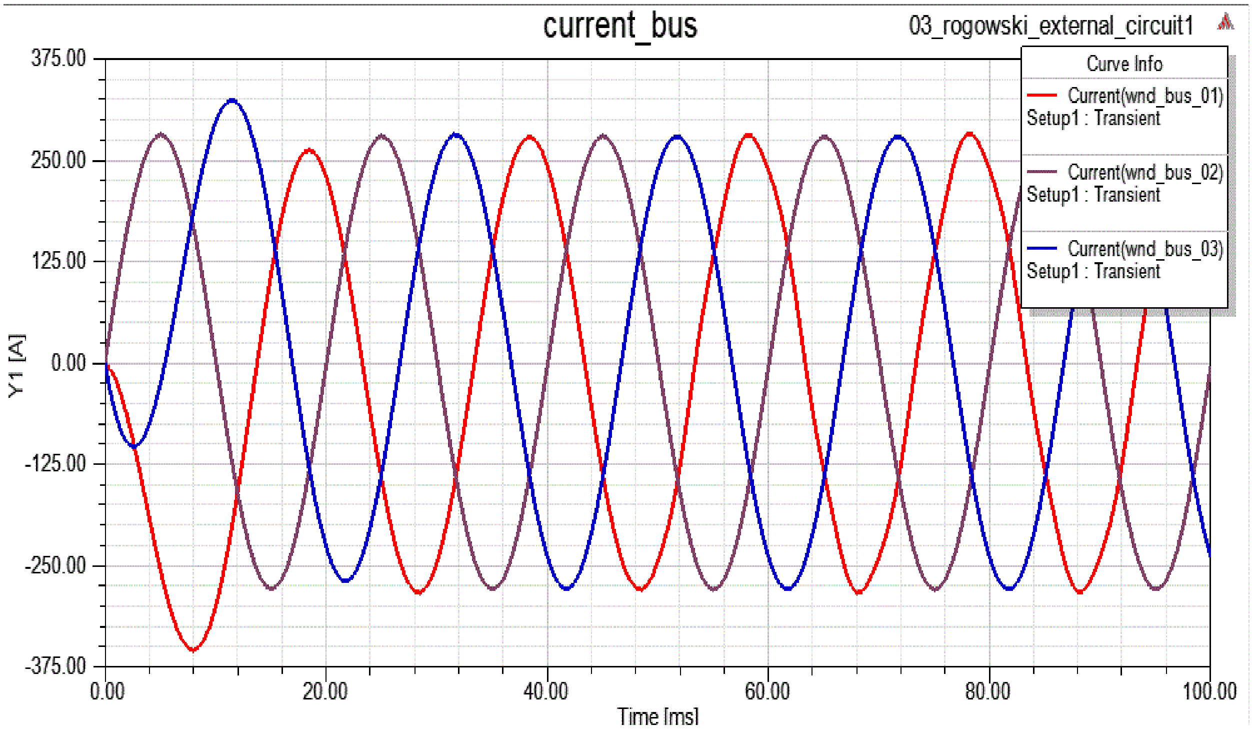


Fig 65:Current at Bus bar 1,2,3

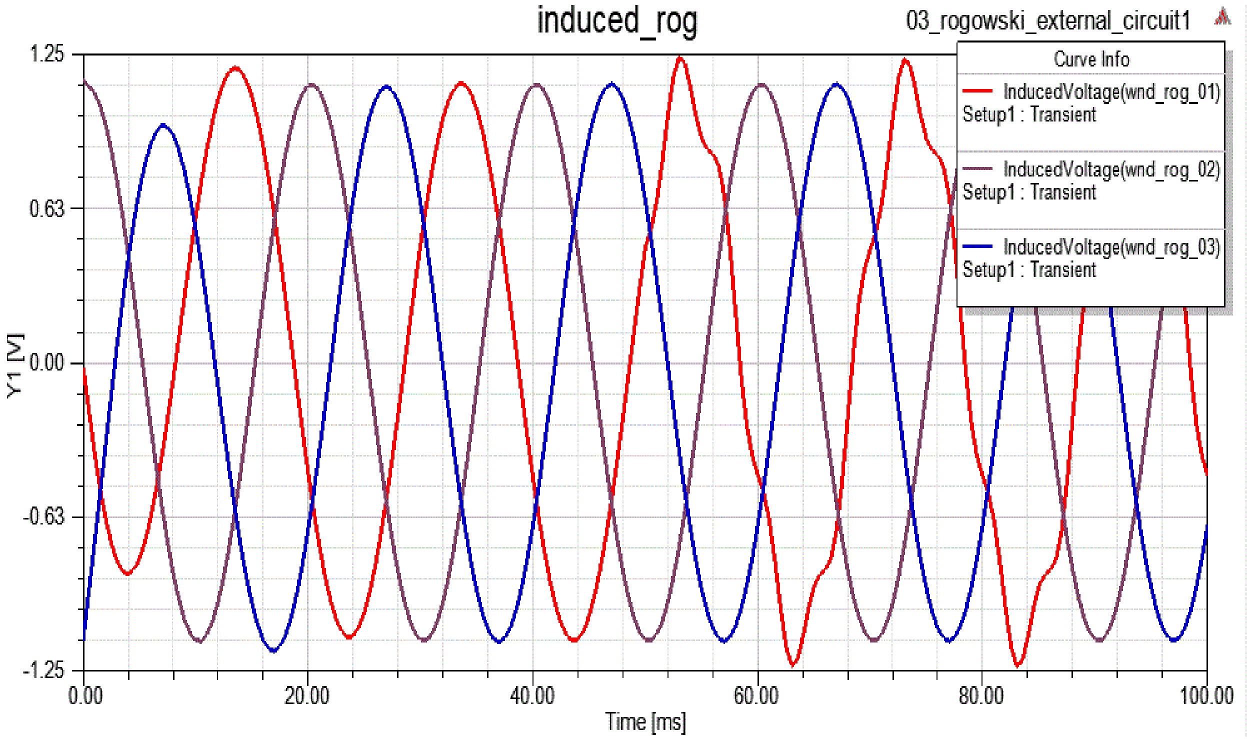


Fig 66:Induced voltage at Rogowski coil 1,2,3

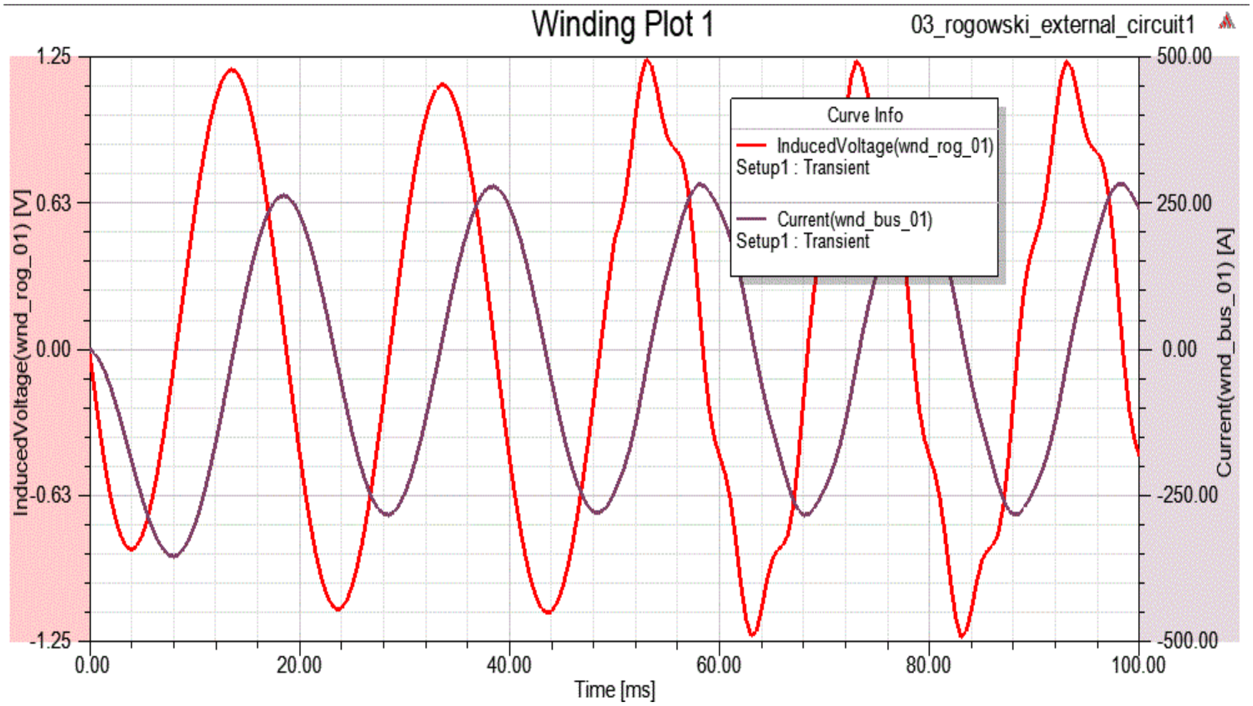


Fig 67:Induced voltage at Rogowski coil and Current togather

6. Final Conclution:

In this paper, different aspects of the Rogowski coil were presented. First, the history of the coil was brought up. Then,the basics of Rogowski coil is discussed and different methods about output integration also discussed. Afterwards, we wil use two models of the Rogowski coil firstly 2d model and secondly 3d model.In this thesis we will see many types of frequency responds.We also use external influence for changing the position of the external conductor but there will be show a very small error which we can be neglate it.and finally we will use the external circuit and additional external circuit at for changing the frequency at rogowski coil.

References:

[1] En.wikipedia.org. (2019). Rogowski coil. https://en.wikipedia.org/wiki/Rogowski_coil [Accessed 14 Jan. 2019].

[2] Ieeexplore.ieee.org. (2019). The Rogowski Coil Principles and Applications: A Review - IEEE Journals & Magazine.https://ieeexplore.ieee.org/document/6922615 [Accessed 11 Feb. 2019].

[3]https://www.researchgate.net/publication/267641815_The_Rogowski_Coil_Principles_and_Applications_A_Review [Accessed 12 Feb. 2019].

[4]http://www.pespsrc.org/kb/published/reports/Practical%20Aspects%20of%20Rogowski%20Coil%20Applications%20to%20Relaying_Final.pdf [Accessed 15 Feb. 2019].

[5] How it works PEM.http://www.pemuk.com/how-it-works.aspx [Accessed 12 Mar. 2019].

[6] Rocoil.co.uk. (2019). [online] Available at: https://www.rocoil.co.uk/principle.htm [Accessed 22 Mar. 2019].

[7]http://www.pespsrc.org/kb/published/reports/Practical%20Aspects%20of%20Rogowski%20Coil%20Applications%20to%20Relaying_Final.pdf [Accessed 15 Feb. 2019].

[8] Fehlberg, V. (2019). How Rogowski Coils Work | Aimdynamics. [online] Aimdynamics.com. Available at: https://aimdynamics.com/rogowski-coils-work/ [Accessed 22 Mar. 2019].

[9] EEP - Electrical Engineering Portal. (2019). Rogowski Coil Construction. [online] Available at: https://electrical-engineering-portal.com/rogowski-coil-construction [Accessed 3 Apr. 2019].

[10] What is a Rogowski Coil Current Probe? .https://www.rs-online.com/designspark/what-is-a-rogowski-coil-current-probe [Accessed 25 Apr. 2019].

[11] http://www.imeko2009.it.pt/Papers/FP_676.pdf [Accessed 23 Apr. 2019].

[12]Analysis of Rogowski coil behavior under non ideal measurement_conditions. https://www.researchgate.net/publication/228435322_Analysis_of_Rogowski_coil_behavior_under_non_ideal_measurement_conditions [Accessed 19 Apr. 2019].