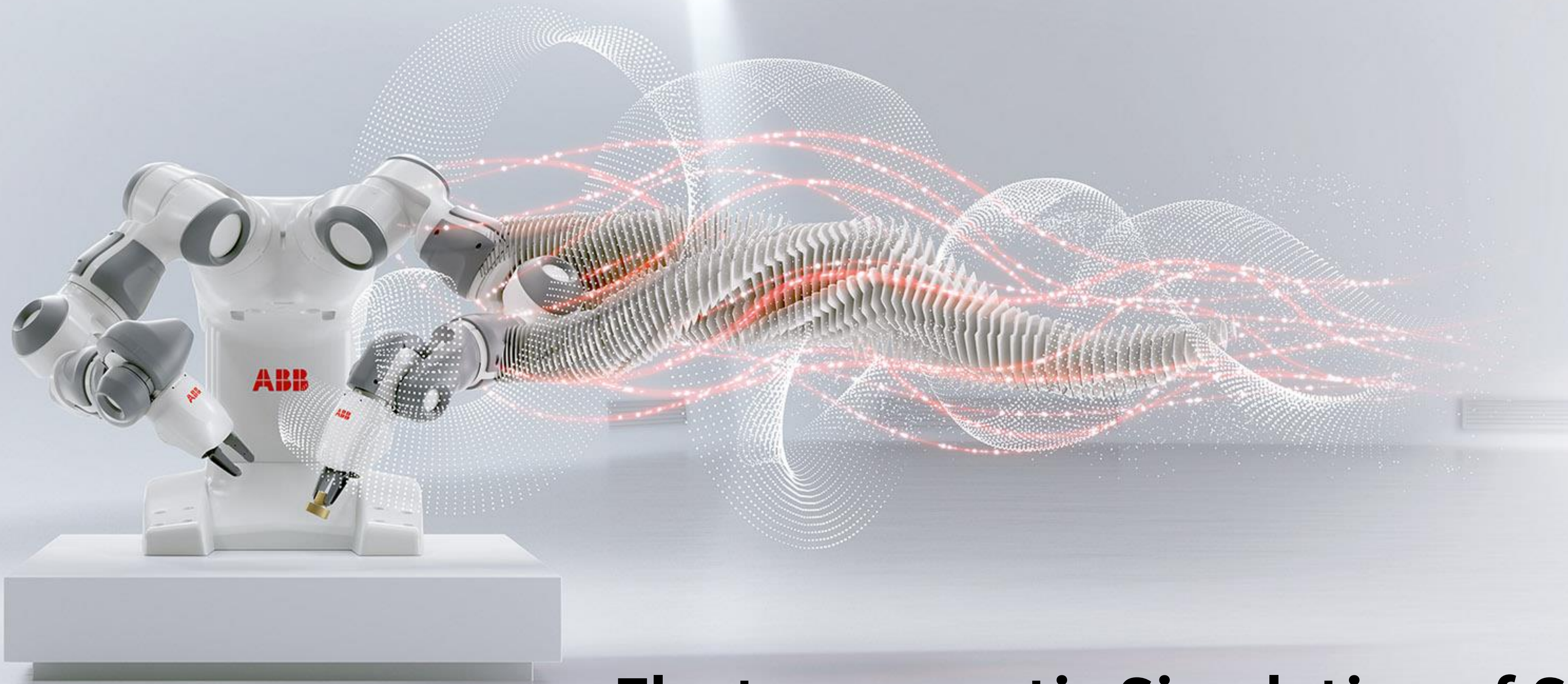

COMSOL CONFERENCE 2018 BOSTON

Electromagnetic Simulation of Split-Core Current Transformer for MV Applications

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R&D, Instrument Transformers & Distribution Components

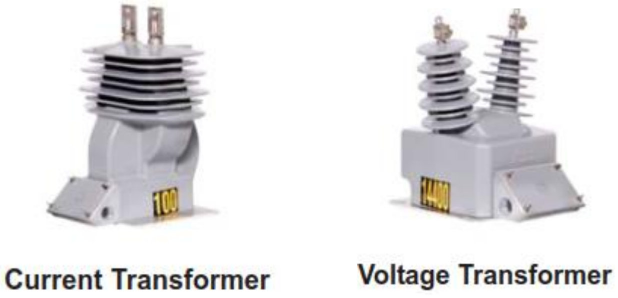
Pinetops, NC

ABB

Split Core Current Transformer (Sensor)

Background Information

- Instrument transformers: current transformers (CTs) & voltage transformers (VTs) are used for metering, monitoring, and protection and control application to measure current or voltage respectively.
- CTs & VTs convert high current and high voltage into a low measurable values so that it is safe to connect to the IED, controller, meters etc.
- CTs & VTs are installed during construction or need replacement.
- Preferred to replace the old unit without service disconnection.
- Clamp-on/Split-core type CT design can be installed without service disconnection.
- CTs are not safe due to the high open circuit voltages.
- Split-core CT (also called sensor) which convert the primary input current into measurable voltage signal is safe due to low output energy level.
- Industry is slowing transitioning to the sensor from CTs or VTs.



Current Transformers


Split-core CT/sensor

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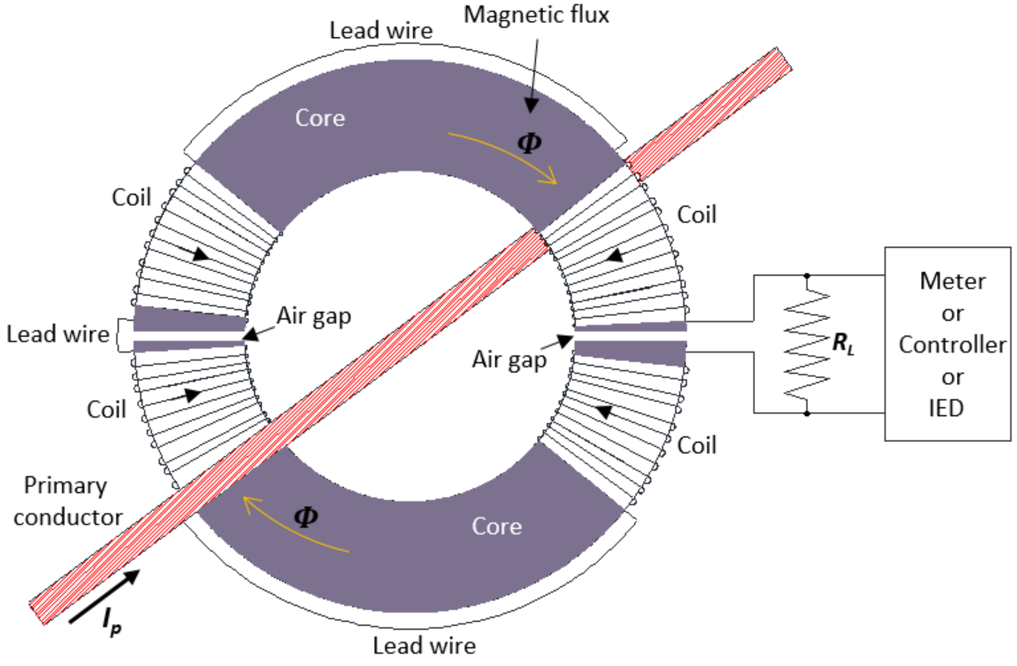
Split Core Current Transformer (Sensor)

Introduction & Working Principle

- The time-varying AC current through the primary conductor produces an AC magnetic fields around it.
- The magnetic core provide a easy path for this flux and enhance it.
- When this AC magnetic flux is passing through the core, the voltage is induced in the secondary coils (wrap around the core) due to the Faraday's law of electromagnetic induction.
- The split core design is used with a small air-gaps on two places.
- All secondary coils are connected in series with the load resistor. The meter is connected across the R_L.
- The primary current is converted into appropriate voltage signal in the secondary load resistor (600A: 10VAC).
- Design for metering application with accuracy > 1%.
- For submersible underground vault application.



Split Core Current Transformer (Sensor)

Design Objectives & Challenges

- To design and manufacture a submersible CT that will be operational in the vaults for current measurement in protection applications.
- Developing a reliable device to measure current in a harsh environment, requiring to be submerged up to 2m deep of water.
- Obtain 1% accuracy performance.
- Sensor should be easily installed without any tools & service interruption.

- Test Performed:
  - EMC testing,
  - Vibration testing
  - IP testing.

** Standards used for type testing were both IEC and IEEE because an IEEE sensor standard does not exist.

Design Challenges:

- Determining shape, size, weight, and winding turns
- Determining core shape, size etc.
- Split Core adds challenges to the design.
- Accuracy
  - Primary cable centering
  - Cross Talk (three phase orientations, conductor size, sensor positioning etc.)
- Submersible/water proof design for 2m deep vaults
- Pass all related industry standard tests.
  - BIL , STC, EMC, IP, Vibration, Accuracy etc.

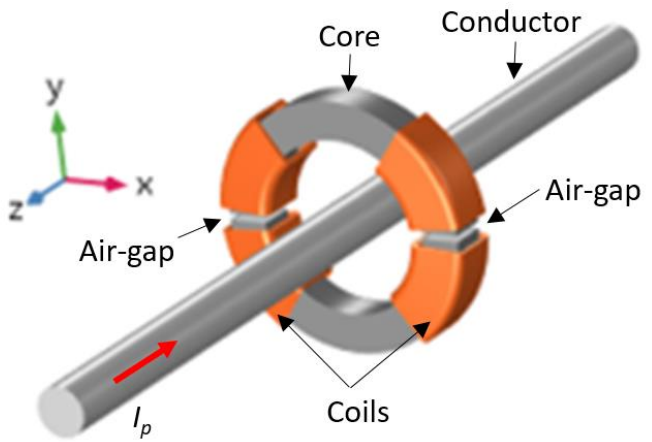
Single Sensor Simulation

Induced Voltage vs Number of Turns

- The simulation of a single sensor is perform to find the number of turns in the secondary coil that gives around 10V across the load resistor.
- When the number of turns increased in the secondary, the open circuit voltage increased accordingly
- When the load resistor is connected across the secondary, based on the load resistor connected, the output voltage can sometime decreased.
- In this particular situation, the load resistor is comparable with the secondary coil internal resistance.
- This results demonstrates the importance of FEA & Electrical Circuit co-simulation in product design.
- The result was used to prototype the sample and fine tuning for 10V output was done through load resistor modification.
- In this simulation, the impedance of the meter/controller is also considered.

Simulation results of voltages (V) while varying the number of turns in secondary coil with and without R_L.

Number of turns	Voltage drop in coil resistance	Voltage across R_L	Open circuit voltage
4000	19.138	15.337	130.5
4500	19.486	13.774	146.99
5000	19.771	12.482	163.36
5500	20.015	11.402	179.7
6000	20.237	10.489	196.17



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Single Sensor Simulation in COMSOL Multiphysics

Physics Equations & Geometry

- Maxwell-Ampere's law including the displacement current as:

$$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t} = \sigma\mathbf{E} + \mathbf{J_e} + \frac{\partial \mathbf{D}}{\partial t} \qquad (1)$$

- For time-harmonic fields, the magnetic flux density, **B** and electric field **E** are defined as in terms of the magnetic vector potential, **A** as

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

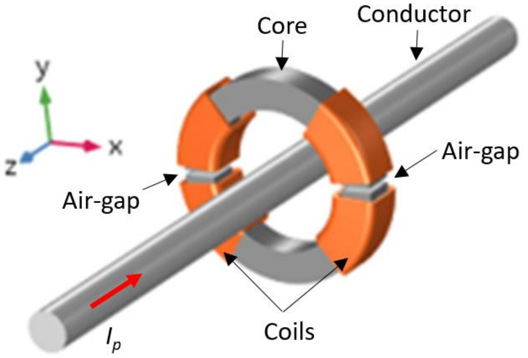
$$\mathbf{E} = -j\omega\mathbf{A} \qquad (3)$$

- Now, combining the above two equations with the constitutive relationships $\mathbf{B} = \mu_0(\mathbf{H} + \mathbf{M})$ & $\mathbf{D} = \epsilon_0\mathbf{E}$
- the Ampere's law for time-harmonic applications becomes

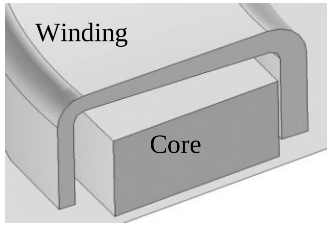
$$(j\omega\sigma - \omega^2\epsilon_0)\mathbf{A} + \nabla \times (\mu_0^{-1}\nabla\mathbf{A} - \mathbf{M}) = \mathbf{J_e} \qquad (4)$$

- This is the governing equation that is being solved when ***Magnetic Fields*** physics is used in ***Frequency Domain*** in COMSOL Multiphysics.
- To obtain a unique solution, the explicit gauge called *Coulomb gauge*

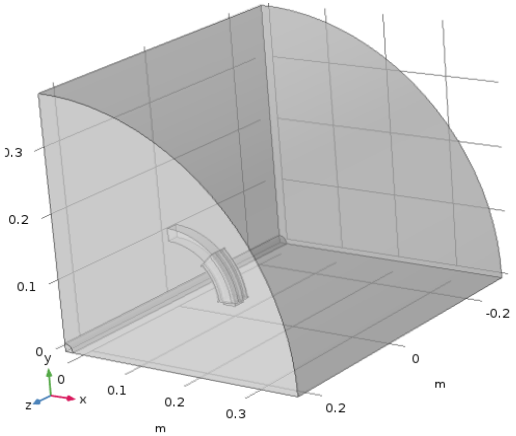
$$\nabla \cdot \mathbf{A} = 0 \qquad (5)$$



Geometry of a single sensor setup.



Uneven wire distributed winding around a toroidal air-gaped core

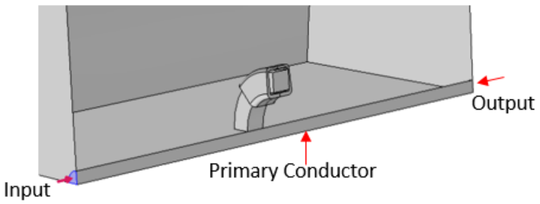


Quarter geometry of a single sensor setup.

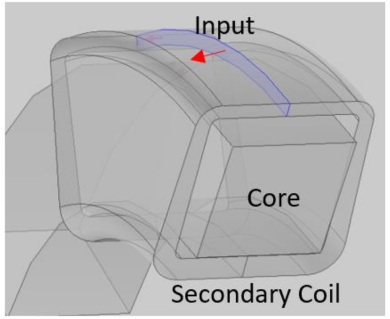
Single Sensor Simulation in COMSOL Multiphysics

Physics Setup & Boundary Conditions

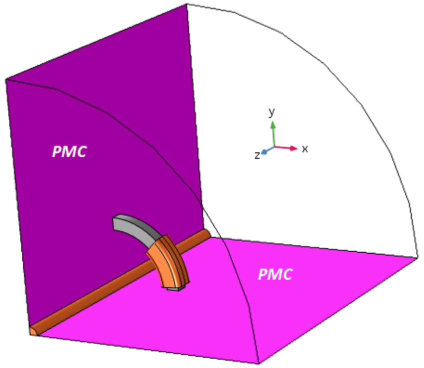
- The *Primary Conductor* is modeled as a *Solid conductor* using a **Coil** feature. The sector feature is used, cross-section area factor, F_A =4. Input and Output features are applied on two ends of conductor. Excited using the current feature (I = 60A to 600A).
- The *Secondary Coil* is modeled as a *Homogenized multi-turn coil* using a **Coil** feature. Input and Output features are applied on two ends of conductor. Excited using the *External Circuit*, connected load circuit and meter/controller.
- The *Perfect Magnetic Conductor* boundary condition $\mathbf{n}\times\mathbf{H}=0$ is imposed where the tangential component of magnetic field and also the surface current density is zero.
- This condition is used on the exterior boundaries to specify the symmetry condition for electric fields and electric currents.
- The rest of the external boundaries is default *Magnetic Insulation* boundary condition.



Geometry of a single sensor setup.



Uneven wire distributed winding around a toroidal air-gaped core



Quarter geometry of a single sensor setup.

Nonlinear Magnetic Core

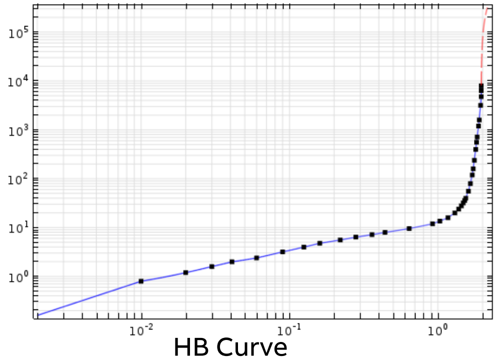
Simplification

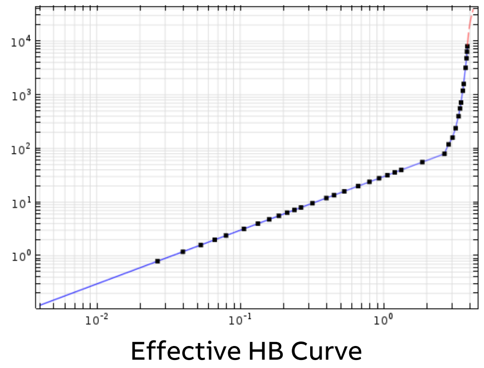
- The nonlinear magnetic BH curve (DC magnetization) converted to equivalent AC effective HB Curve using the Effective Nonlinear Magnetic Curves Calculator App from COMSOL Application Library.
- This effective HB curve is then used in modeling the magnetic core.
- It was found that the magnetic permeability is almost linear in the entire core due to low magnetic flux density.
- Homogenized anisotropic conductivity and permeability is used.

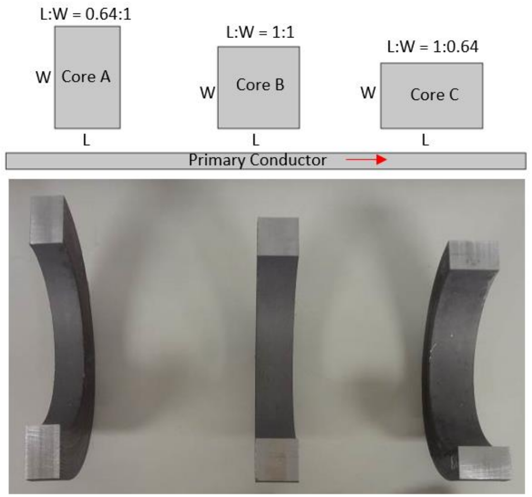
$$\begin{bmatrix} \sigma_r & & \\ & \sigma_\emptyset & \\ & & \sigma_z \end{bmatrix} = \begin{bmatrix} \frac{\sigma_c}{1000} & & \\ & \sigma_c & \\ & & \sigma_c \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} \mu_r & & \\ & \mu_\emptyset & \\ & & \mu_z \end{bmatrix} = \begin{bmatrix} \frac{\mu_c}{1000} & & \\ & \mu_c & \\ & & \mu_c \end{bmatrix} \quad (2)$$

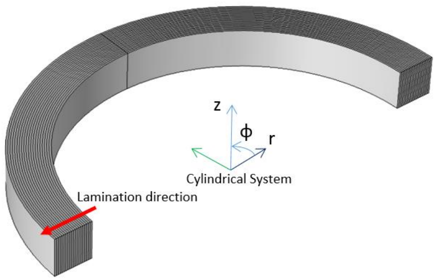
where, $\sigma_c = 1.9608\ [S.m^{-1}]$ is the core electrical conductivity and $\mu_c = 26400$ is the relative permeability of the linearized effective BH curve of M4 steel core.





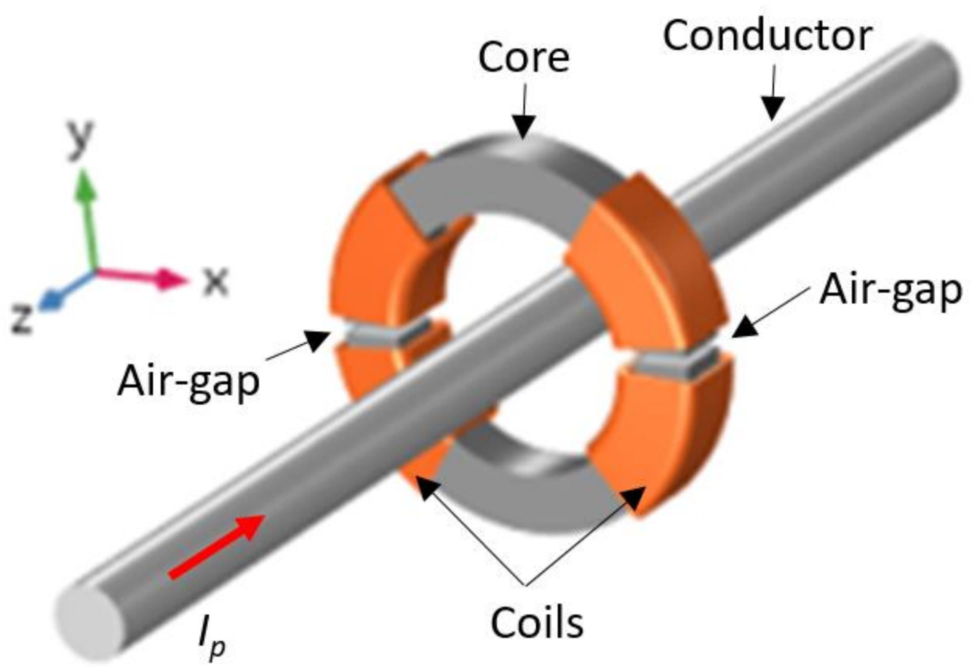


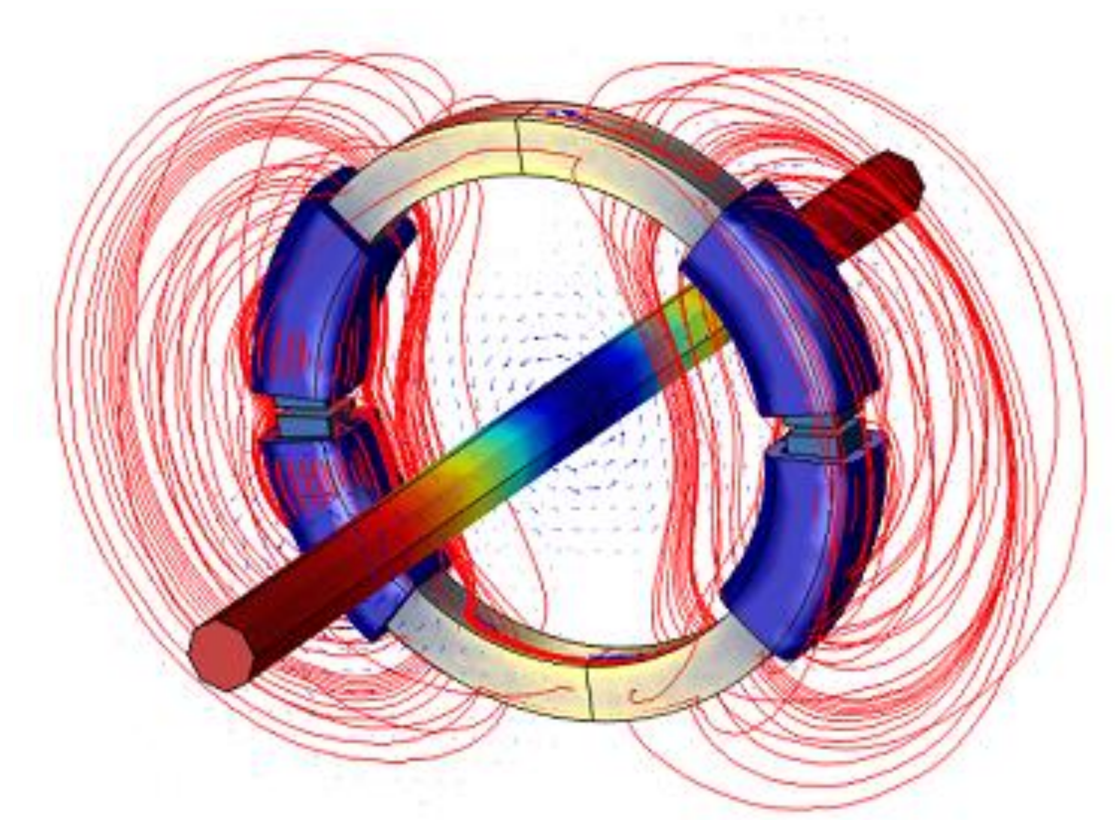
Three different cross-sections of cores.



Split Core Current Transformer (Sensor)

Magnetic Flux and Current Density Plot

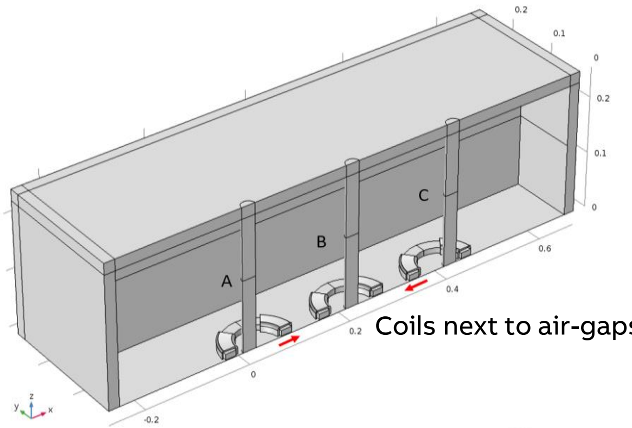




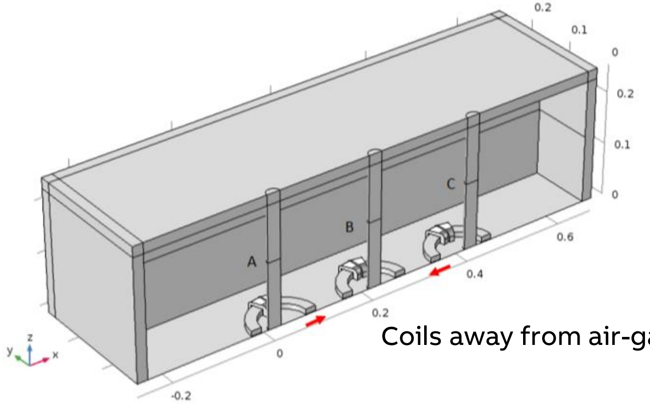
Three Phase Cross-Talk Simulation

Geometry & Mesh

Geometry

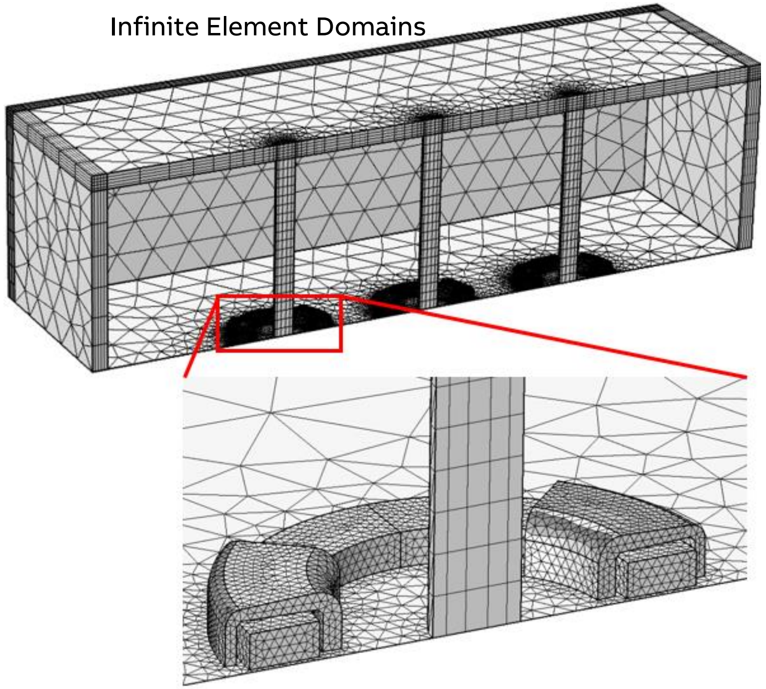


Coils next to air-gaps



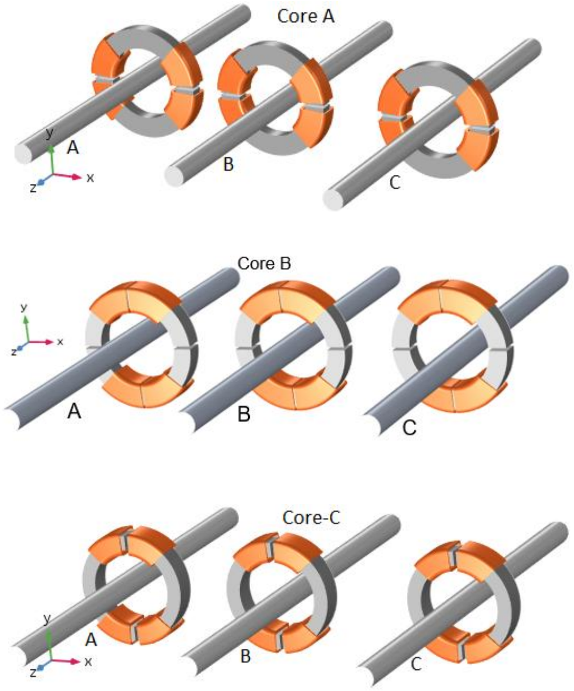
Coils away from air-gaps

Meshing



Zoom-in version of mesh in and around sensor.

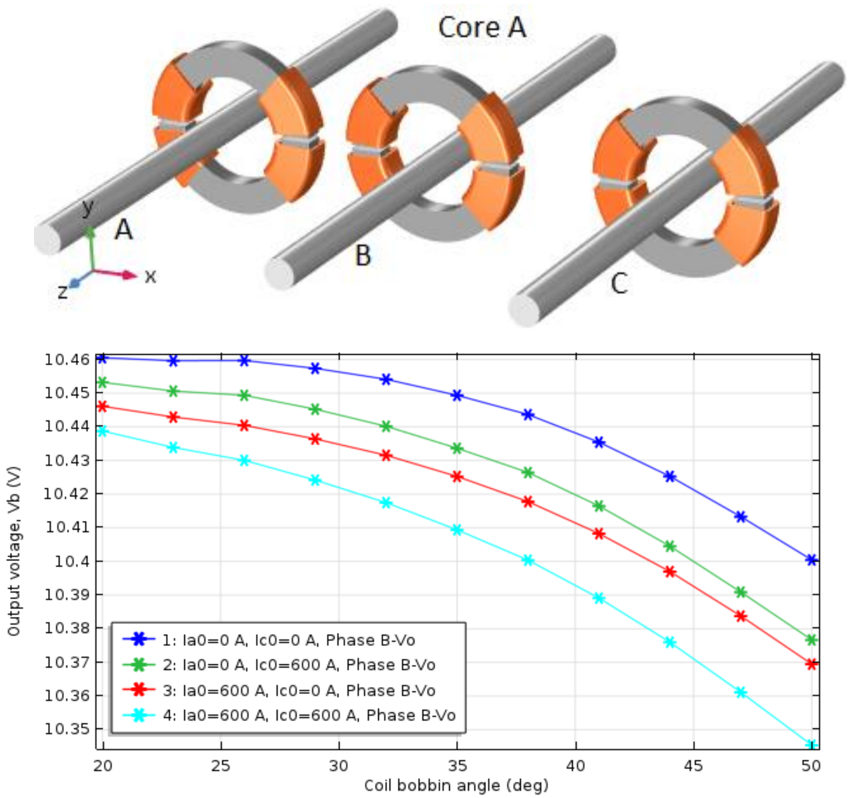
Configurations Studied



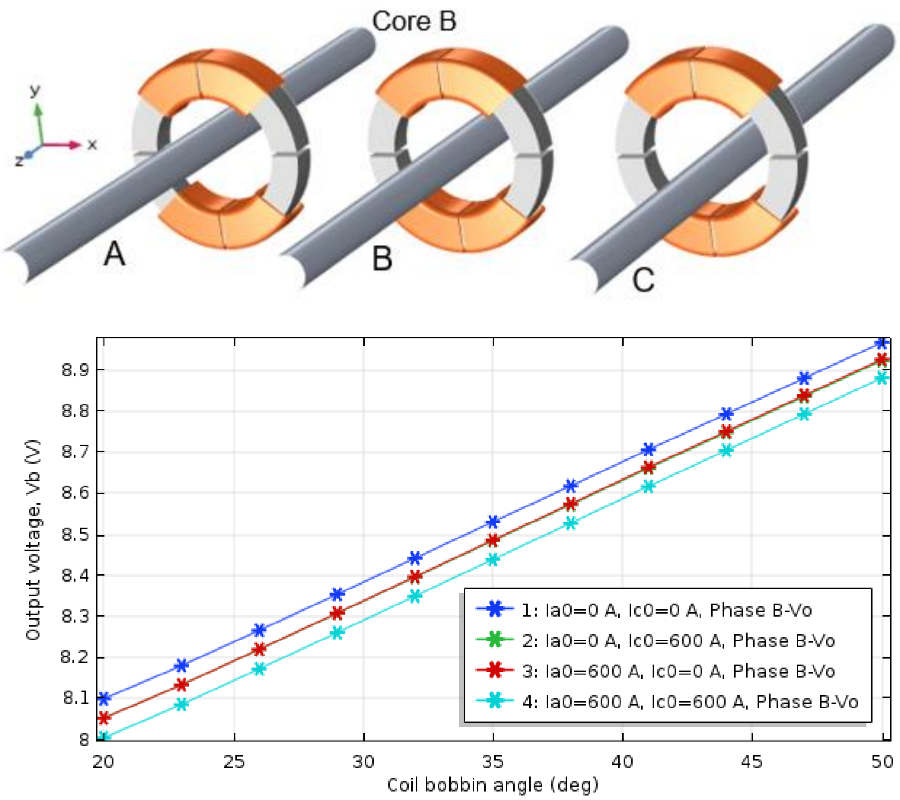
Configuration of few combination studied for cross-talk simulation for Core-A, Core-B and Core-C.

Three Phase Cross-Talk Simulation

Simulation Results: V_b vs Bobbin Angle



Output voltage of sensor placed in phase B with Core-B used and when the coils in secondary are placed next to the airgaps.



Output voltage of sensor placed in phase B with Core-B used and when the coils in secondary are placed away from the air-gaps.

Three Phase Cross-Talk Simulation

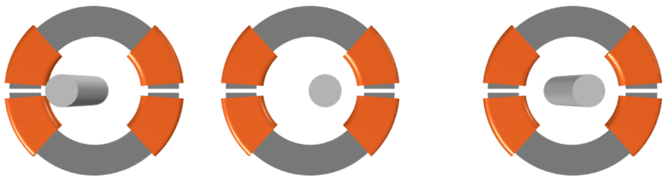
Results for few configurations

Vb	% Error	Ia	Ib	Ic
8.9595	0	0	600A	0
8.907	-0.585970199	600A	600A	0
8.9055	-0.602712205	0	600A	600A
8.852	**-1.199843741**	600A	600A	600A

Vb	% Error	Ia	Ib	Ic
8.8927	-0.74558	0	600A	0
8.8472	-1.25342	600A	600A	0
8.8448	-1.28021	0	600A	600A
8.7984	-1.79809	600A	600A	600A

Sensor offset of 0.5in.

Vb	% Error	Ia	Ib	Ic
10.5071	0	0	600A	0
10.4848	-0.212237439	600A	600A	0
10.4809	-0.249355198	0	600A	600A
10.458	-0.467303062	600A	600A	600A



Vb	% Error	Ia	Ib	Ic
10.468	-0.37213	0	600A	0
10.455	-0.49586	600A	600A	0
10.454	-0.50537	0	600A	600A
10.419	-0.83848	600A	600A	600A

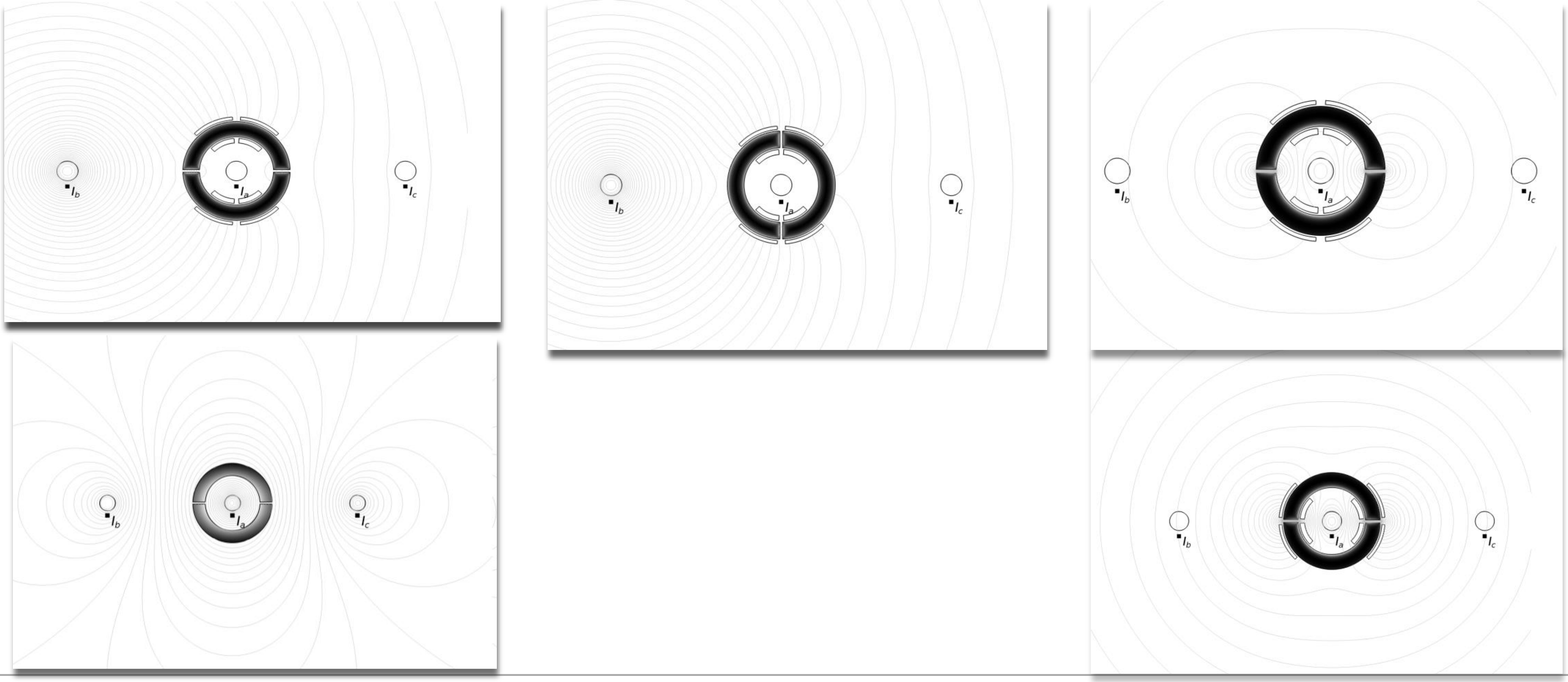
Sensor offset of 0.5in.

Simulation and experimental results the cross-talk on different core cross-section design.

Features	Methods	Core A	Core B	Core C
Accuracy Spread/Range	Measurements	0.90%	0.60%	0.30%
	Simulations	0.8%	0.56%	0.42%
Cross-talk error (position & orientation)	Measurements	1.10%	0.80%	1.30%
	Simulations	1.20%	0.91%	1.25%

Three Phase Cross-Talk Simulation

Flux lines around conductor and sensor (2D View)



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Submersible Split Core Sensor

Final Product Specifications

Ratings for the split-core sensor (RSS-1).

Rated primary current	600 [A]
Rated extended primary current	1200 [A]
Rated secondary voltage	10 [V]
Accuracy class	1%
Insulation class	600 [V]
Maximum system voltage	0.66 [kV]
Rated frequency	60 [Hz]
Power frequency test voltage	4 [kV]
Lightning-impulse test voltage	10 [kV]
Rated continuous thermal current	1200 [A]
Rated short-time thermal current	12 [kA]
Duration of rated short-time thermal current	1 [s]
Rated dynamic current	32.4 [kA]
Dimensions	192x172x54
Weight	4.5 [kg]
Cable length of electronic transformer	22.9 [m]

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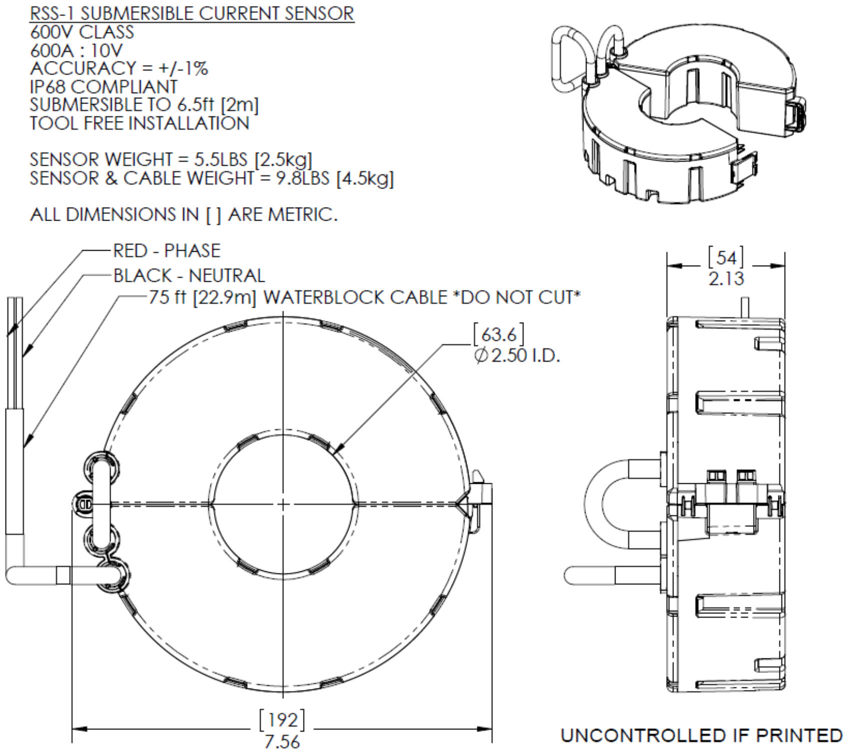

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