



# Current Transformer Design That Combines Finite Element Analysis and Electric Circuit Simulation

Transient simulation of a transformer that makes use of a thermal-electromagnetic FE analysis integrated with an electrical circuit SPICE model is underpinning the development of sensor technology at ABB.

BY JENNIFER HAND

The design of sophisticated magnetic sensors and actuators demands a thorough understanding of their components and the electric and magnetic interaction they have with the environment. In electric current transformers and sensors, which are used to measure the electrical current in power distribution and control systems, the secondary winding is usually operated at close to short-circuit conditions to ensure small impedance, reduce electric current errors and avoid high voltages at the secondary side. However, in the real world there will always be deviations from ideal behavior because of material properties, design details, dynamic loading or other interactions.

“Finite element analysis (FEA) is a powerful means of investigating the way in which external electrical sources and loads interact with a magnetic subsystem like a transformer core. FEA illustrates the transient behavior of these cores and

the generated flux density distributions. It also elucidates the self-heating and effects of temperature-dependent material properties that need to be taken into account,” comments Dr. Rolf Disselnkötter, Senior Principal Scientist specializing in Industrial Sensor Technology at the ABB Corporate Research Centre in Ladenburg, Germany. “It is particularly important if the shape of



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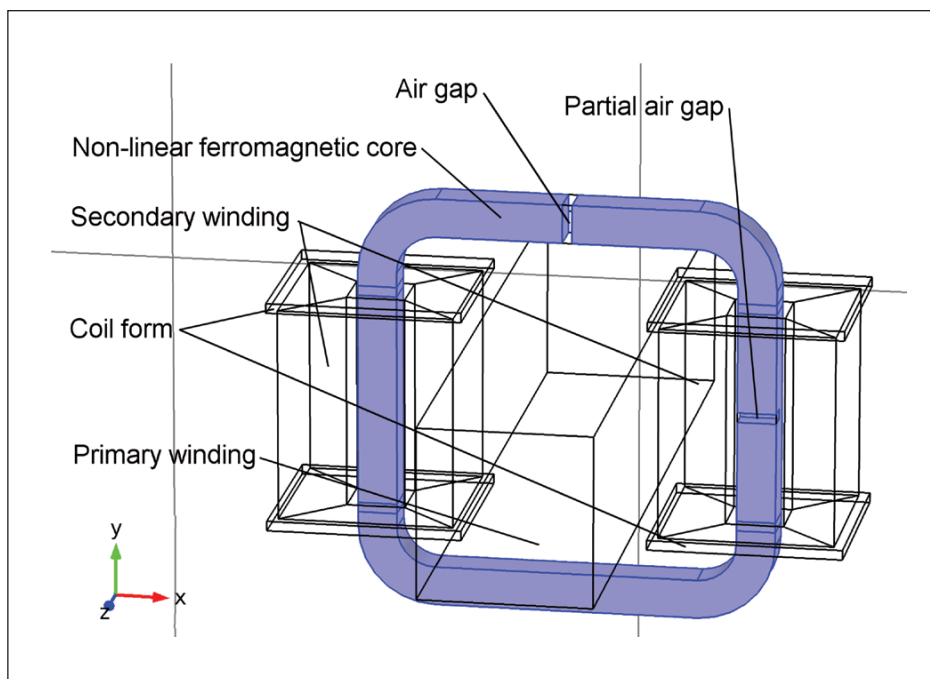


Figure 1: Geometry of the 3D transformer model with the ferromagnetic core in blue.



a component is complex and its behavior cannot easily be foreseen.”

Dr. Disselnkötter is working with engineers from the University of Dresden, and they have been using COMSOL Multiphysics for the past three years to develop modeling techniques for use in different applications. “We are looking at how various design parameters influence performance. From this, we are building up knowledge that ABB can apply to the future development of magnetic sensors, actuators and other magnetic components.”

The coupling of different physics is one of the fundamental challenges in the models, which already combine 3D geometry, magnetic non-linearity and transient analysis. “We are working towards advanced models that will combine several of these characteristics.”

### Understanding the Interactions

Figure 1 shows the geometry of the team’s most recent test model, which allows transient FE analysis of transformers that are integrated with models of external circuitry. Dr. Disselnkötter explains: “We are interested in how

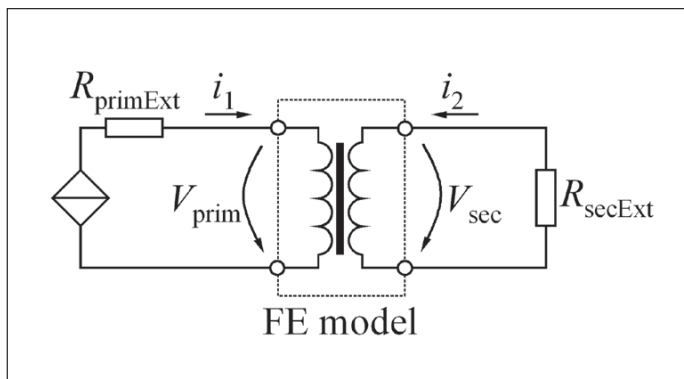


Figure 2: Primary and secondary circuits coupled to the FE model of the transformer.

geometrical design variations, material properties, primary current distribution, temperature and the electric circuitry will impact the accuracy of the electric current measurement. In order to allow for easy modifications and subsequent optimization procedures, we use parameter-based 3D model geometries. Because we want to highlight potential problems we made this model transformer intentionally ‘bad’. It therefore has small air gaps so that we can understand the effects these have.”

Apart from the deliberate air gaps on the right and at the top, this is a typical transformer with the primary winding made up of one turn (a bulk bus bar)

and the secondary winding consisting of multiple turns that are arranged on two coil bobbins. The magnetic system is described by Ampère’s circuital law and by Faraday’s law of induction. For the core material a nonlinear relationship between the flux density  $B$  and the magnetic field  $H$  of the type  $H = f(|B|) \cdot B/|B|$  is assumed. Because of this, precise modelling of the electrical signals requires a time-dependent

simulation. Further, the air gaps lead to an asymmetrical geometry and cause an imperfect coupling between the primary and secondary windings.

### Integrating with SPICE Components

Figure 2 shows how the FE model of the transformer was integrated with a circuit model and coupled to a sinusoidal current source at the primary side and an external load resistor at the secondary side. “We built the circuitry from the predefined components provided with COMSOL Multiphysics rather than importing it as a SPICE netlist,” comments Dr. Disselnkötter. “The cou-

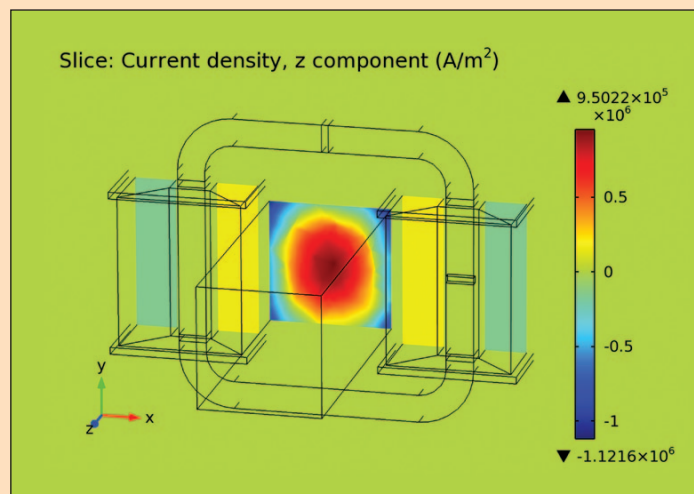


Figure 3: Simulated z-component of the total current density in the current carrying domains with skin effect in the primary conductor ( $i_{1peak} = 1000$  A,  $R_{secExt} = 20 \Omega$ ,  $t = 0.23$  s).

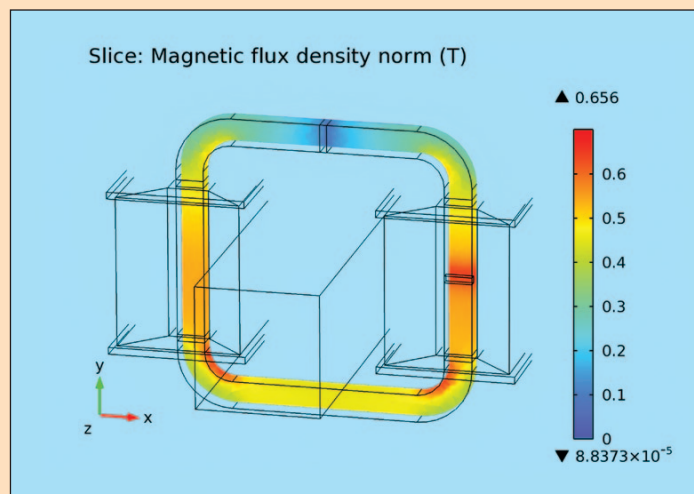


Figure 4: Simulated norm of the magnetic flux density in the center plane of the ferromagnetic transformer core ( $i_{1peak} = 1000$  A,  $R_{secExt} = 20 \Omega$ ,  $t = 0.23$  s).



pling with the magnetic model was then implemented with equations for the currents and voltages on the two sides of the transformer.”

### Eddy Currents

Both the electrical losses and the magnetic field distribution will depend on the current density distribution in the conductors. As an electric current alternating at high frequency will induce a changing magnetic field, and in turn an electrical field, the team wanted to model the eddy currents that would arise and therefore modify the current distribution in the conductors. “Modeling this is a bit tricky,” comments Dr. Disselnkötter, “as it is not the external current but the resulting total current that needs to be coupled to the circuit. In bulk conductors, like the primary bus bar of our model, the total current will be much lower due to the counteracting eddy currents. We therefore used a global equation approach to ensure that the total primary current follows the prescribed sinusoidal time course.”

In this way, the model computes the space and time-dependent eddy current density in the primary conductor, and the resulting flux density distribution in the magnetic core (Figures 3 and 4). “This is important for a precise calculation of the current error and the losses incurred by our non-ideal transformer.” (See Figure 5)

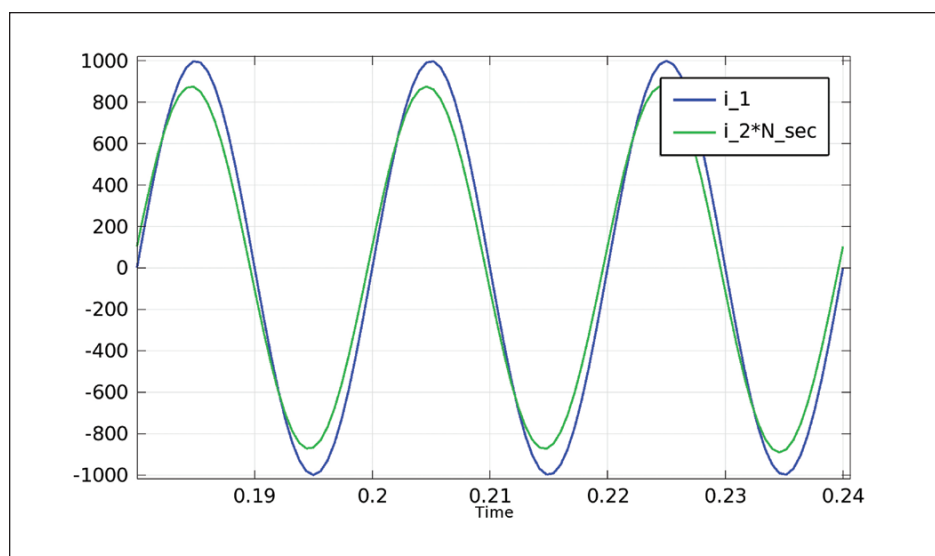


Figure 5: Simulated primary current  $i_1$  and secondary current  $i_2 \times N_2$  show an imperfect transformer coupling due to the air gaps in the core ( $i_{1peak} = 1000 \text{ A}$ ,  $R_{secExt} = 25 \Omega$ )

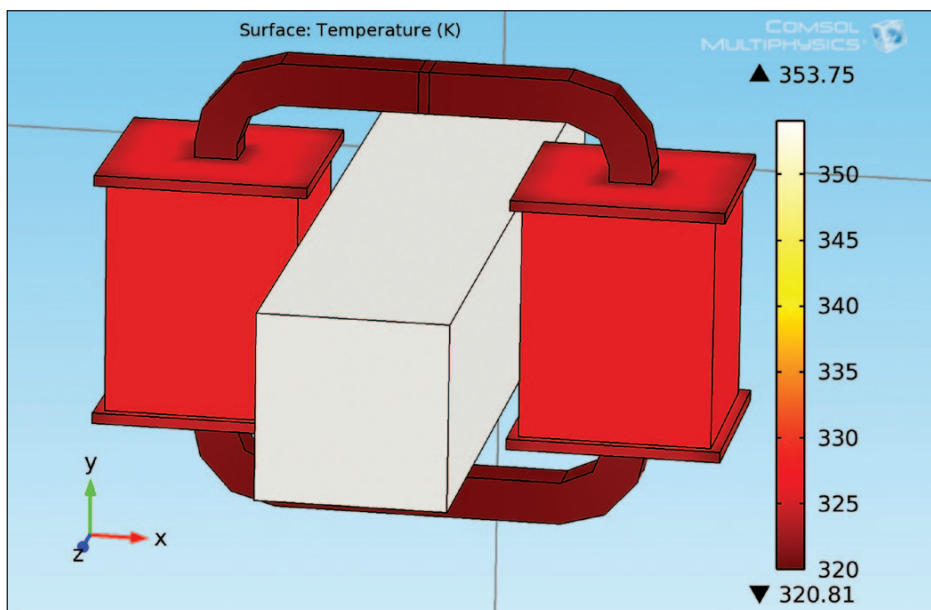


Figure 6: Simulated stationary temperature field at the surfaces of the solids ( $i_{1peak} = 1000 \text{ A}$ ,  $R_{secExt} = 20 \Omega$ ,  $T_{amb} = 300 \text{ K}$ ).

### Transient Thermal-Electromagnetic Simulation

COMSOL Multiphysics was also used to build the thermal model, which took into account both heat conduction in the participating solid materials as well as external convection on surfaces by means of convection coefficients.

In general, electrical and magnetic material properties are temperature-dependent, so the effects of self-heating also had to be considered. As a result the electromagnetic FE model was fully coupled to a thermal

FE model of the assembly. In most applications, however, the time scales of the electromagnetic and the thermal model are very different, so the team decided to iterate alternate solutions of the two models. The homogeneous temperature field was used as input for the first time-dependent study step of the electromagnetic model. After three or so simulated current periods the time-averaged local power loss density was obtained as a new input to the thermal model. In the following thermal simulation, the new temperature field was calculated and sent back to the electromagnetic model. The solutions converged within five iteration loops, leading to the temperature field shown in Figure 6. Also, the results shown in Figures 3 to 5 have been influenced by this temperature distribution.

The team is continuing this work. “We are looking for more accuracy and need to include further details, like the effects of the transformer core lamination and the anisotropic structure of the coils. In order to check the validity of the models, we plan to compare simulation results with accurate measurements on real magnetic components. Ultimately, we want to know that we can rely on our models and use them to optimize design processes.” ■

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