Multiphysics modelling using COMSOL

A Case study from Electron One Consulting Ltd

This case study explains the work we undertook where we modelled an Induction heating system in COMSOL Multiphysics simulation software to correlate the simulation results with actual measurements.

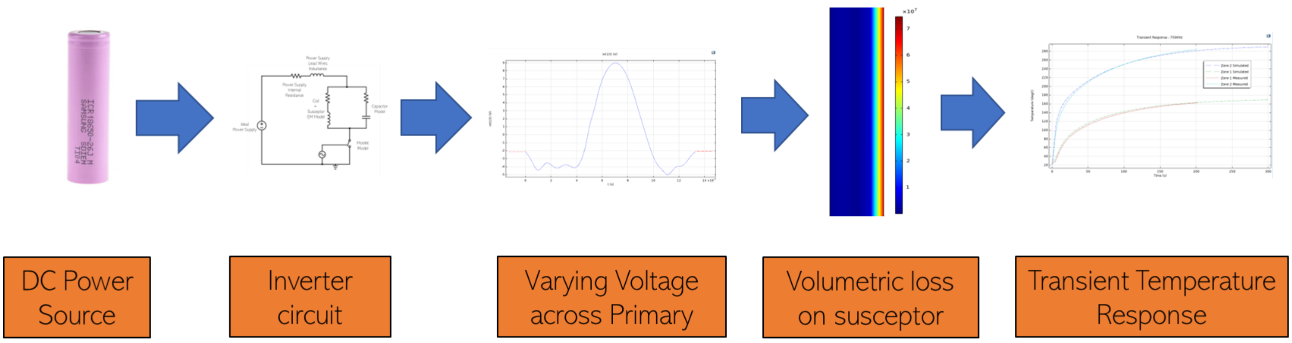
The simulated results were cross checked with several different measurement scenarios, and they correlated quite well over an open loop 200 second measurement period.

System Description

The system modelled is a handheld induction heating appliance. It runs off a DC battery which is the main power source. An inverter circuit converts the DC voltage into varying voltage to aid electromagnetic induction across the coil to a metal susceptor.

The metal susceptor is a single piece of ferromagnetic material which acts as a single turn secondary, and the induced eddy current is converted to heat thereby resulting in Induced heating of the susceptor.

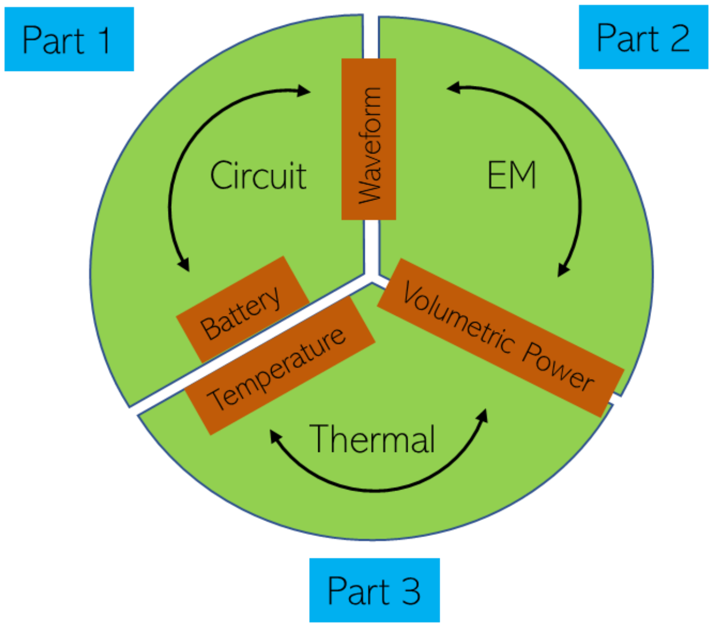
In the actual product there are thermocouples welded on the susceptor to monitor and control the amount of voltage presented on the primary coils thereby providing a control mechanism via device firmware for the heat generated on the susceptor.



Modelling this system is complex and although COMSOL Multiphysics simulator allows us to model all the parts in one tool, due to certain application specific quirks we encountered, multiple different tools had to be used to achieve correlation.

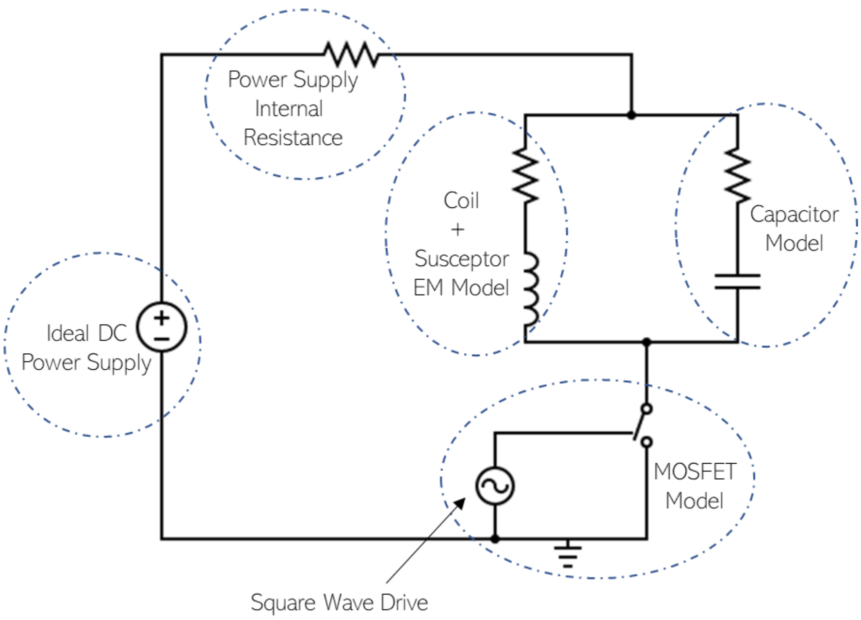
This Multiphysics measurement – simulation correlation activity can be divided into 3 distinct parts.

1. Circuit level correlation, involving exact modelling of the inverter drive circuit.
2. Electromagnetic energy transfer, which is a result of inductive coupling.
3. Thermal energy generation on the secondary side on the susceptor.

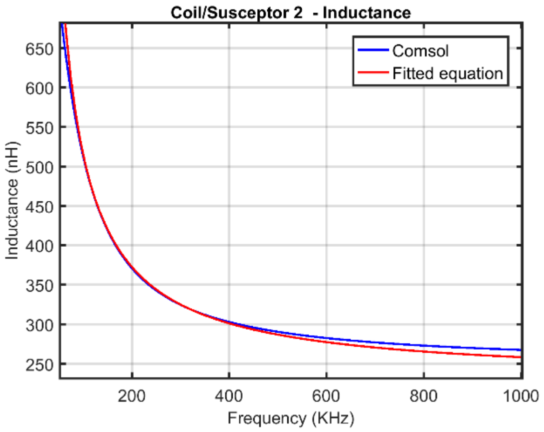


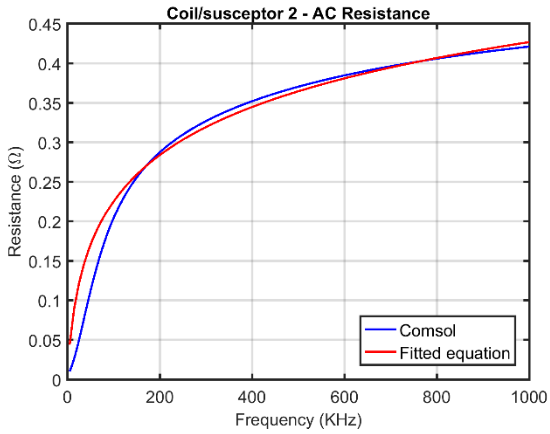
Part 1: Electrical modelling

Inverter circuits can be simple or complex depending on efficiency, cost, and PCB space requirements. In our exercise, a simple unipolar inverter circuit with Parallel LC was employed and that was modelled in Spice as shown below.

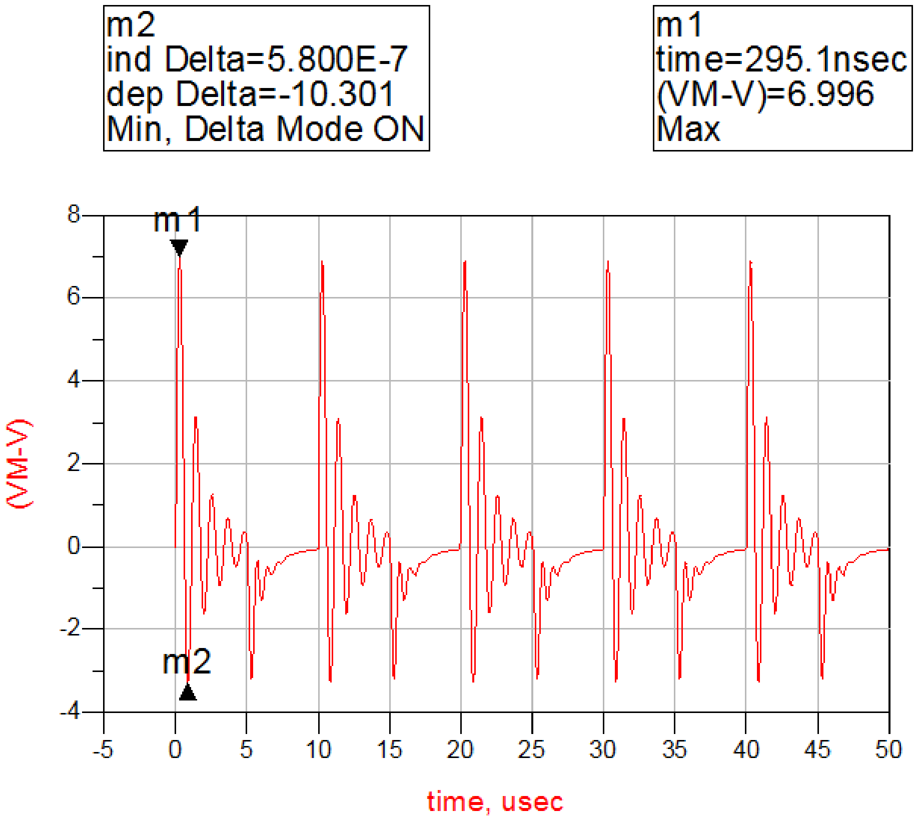


It should be noted that when a susceptor is included in the model as a load, inductance and AC resistance vary over frequency and this needs to be captured and fed back into the model. Example of varying Inductance and AC resistance shown below.





Based on this modelling, we were able to achieve the below shown waveform across the terminals of the inductor, which acts as primary winding for Electromagnetic induction into the susceptor, which acts as a load.



The same set-up was measured and below is the measurement waveform across the terminals of the inductor.

As can be seen, the simulated and measured waveforms match very closely indicating the accuracy of the modelling (including parasitic inductance and capacitance).

It must be explained that details like lead inductance (required for feeding power in to a measurement set-up, for instance) need to be captured to ensure all variables in the system are modelled properly.

Commentary on Unipolar drive Inverter systems

The curious thing with unipolar drive inverter systems is that even though we drive the MOSFET using a fixed 100 kHz signal, because of the way it's architected, multiple harmonics of the fundamental frequency get generated.

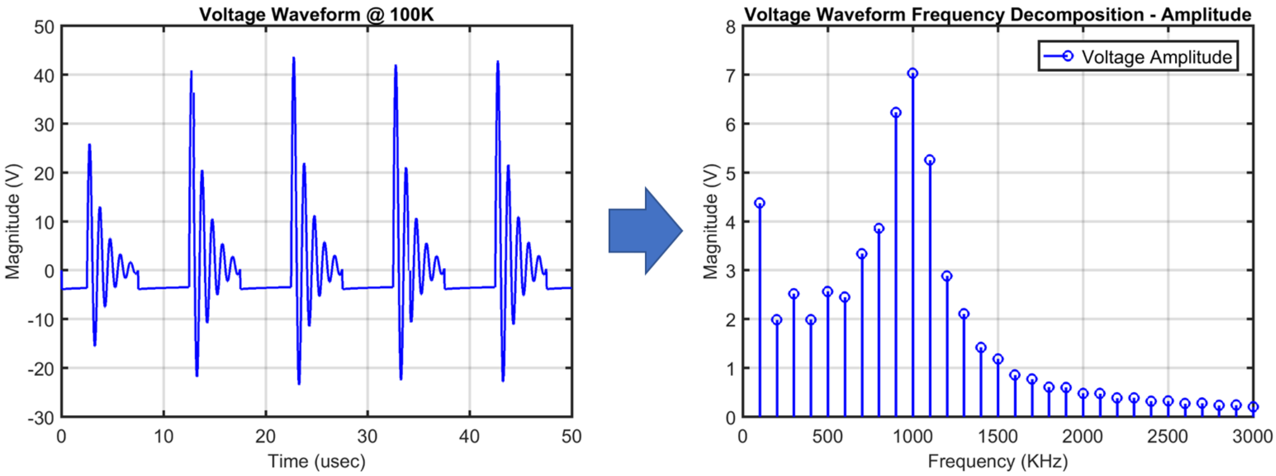
The exact amplitudes of these signals can be seen by decomposing the time domain signals into frequency domain using Fourier decomposition.

It must be noted that all these frequencies get inductively coupled into the susceptor and have an impact on the thermal response on the susceptor.

Part 2: EM modelling

To accurately capture the thermal response on the susceptor, we need to decompose the simulated / measured time domain waveform into frequency domain components and then feed individual frequencies at the primary terminal to look at the magnetic field induced by each frequency on the susceptor.

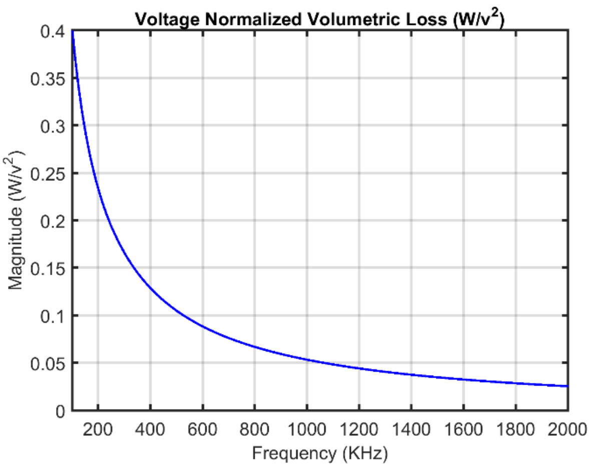
Below example shows the frequency decomposition involving various harmonics of a 100KHz unipolar drive. As can be noted, the fundamental's magnitude is lower than some of the harmonics generated by the inverter circuit.



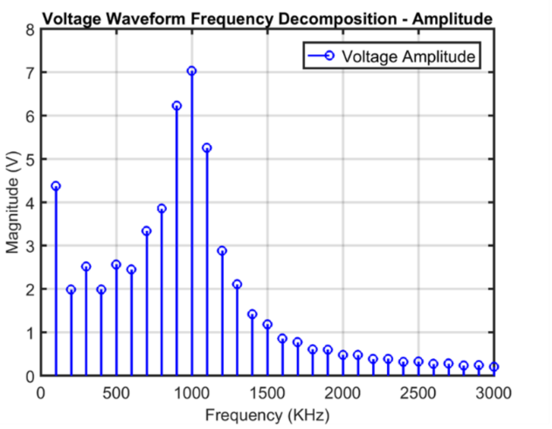
Although some of the harmonics are much higher in magnitude than the fundamental frequency the coil is driven with, it does not mean that those harmonics generate most magnetic field on the susceptor.

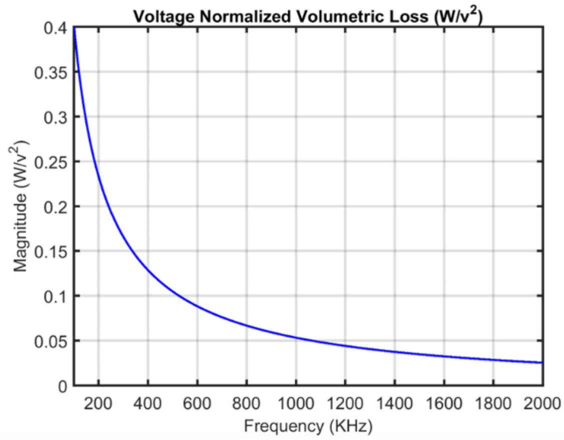
It's important to know that the magnitude of power transferred across the susceptor varies over frequency. So, for instance, 100 kHz 1V pk-pk signal at the primary winding would produce certain amount of power over the susceptor. On the other hand, a 1000 kHz 1V pk-pk signal at the primary winding would produce much different power.

Over multiple simulations we managed to normalise this and called it "Voltage normalised volumetric loss". This is the power transferred for 1V amplitude of a signal that is presented across the winding of the inductor.



So, the total coil power that's applied on the primary winding is nothing but a sum of the amplitude squared times the volumetric loss at that frequency. This power includes all the individual frequency components that are involved in the waveform which were broken down using Fourier decomposition.





COIL POWER = $\sum_{k=0}^{n}[A^2.V_l]$

Part 3 – Thermal modelling

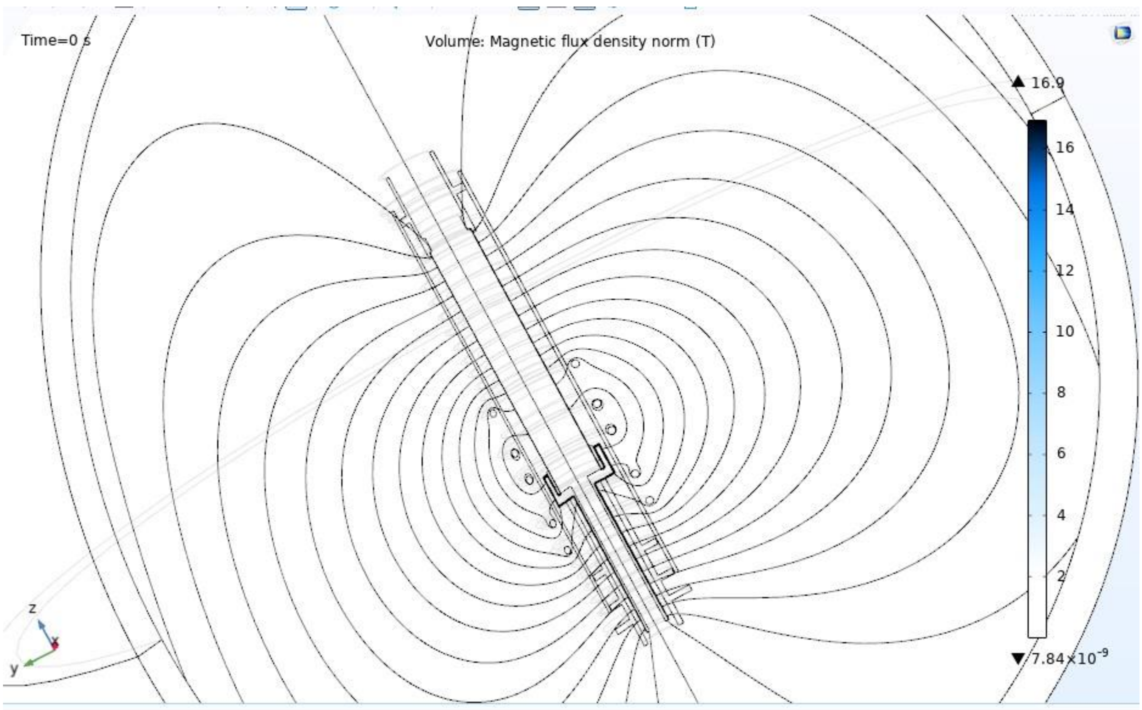
The calculation above provides the total coil power that is applied to the primary side across the Inductor. We could use this to simulate magnetic fields that would be generated when such power is applied across the terminals.

Then we could use the material properties of the materials used to see how these magnetic fields manifest themselves as heat.

Thermal modelling also involves carefully understanding and establishing conduction, convection, and radiation paths. The other key parameter to model is surface emissivity of each of the mechanical component used along with their thermal properties.

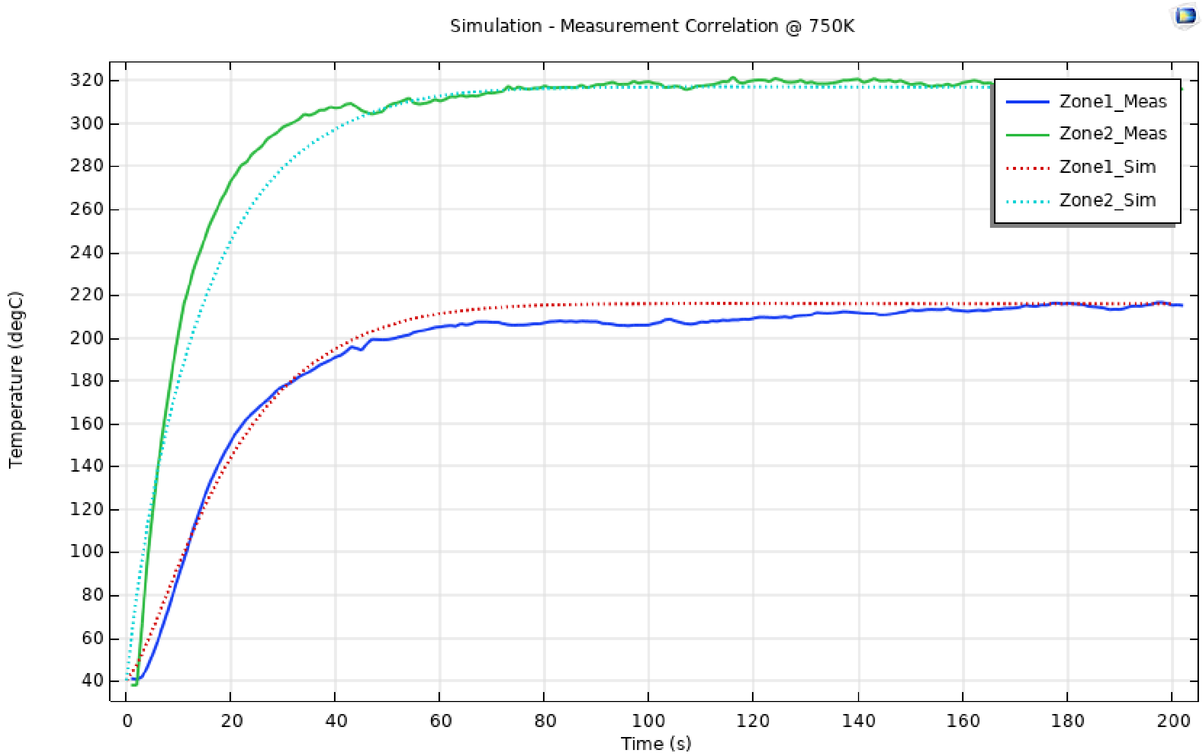
Once all of these are set-up, a Multiphysics simulator like COMSOL could simulate the fields produced in the system, as shown in the example below.

This field creates eddy currents on the susceptor surface resulting in heat.



The simulator allows to add temperature probes on the susceptor surface – to emulate the real-life temperature probes welded on the susceptor.

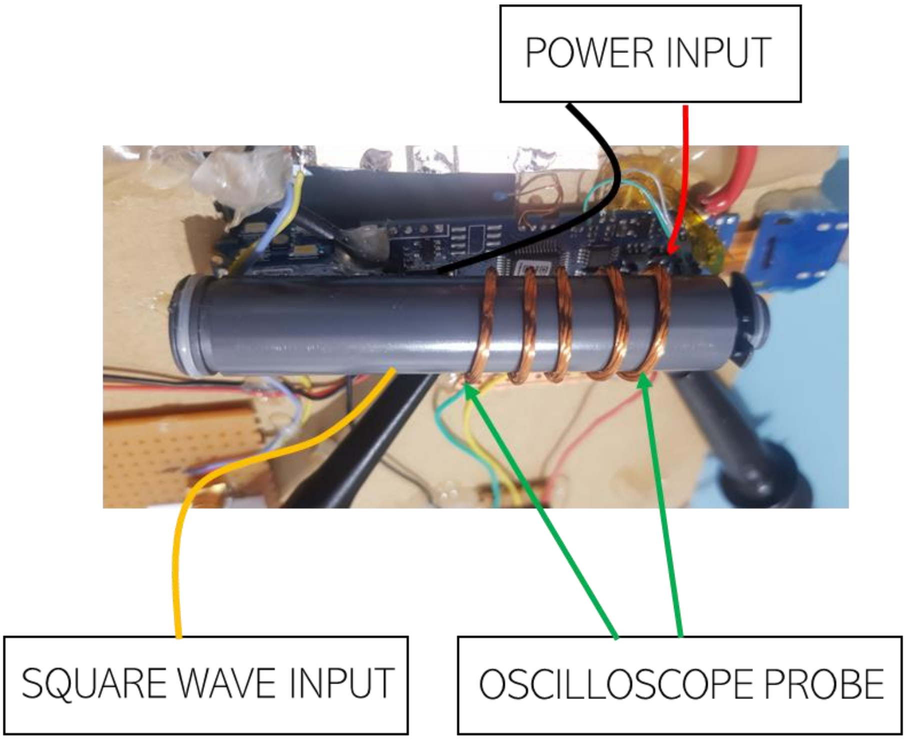
The simulation can be run over extended periods of time to see how well the correlate with the measurements taken.



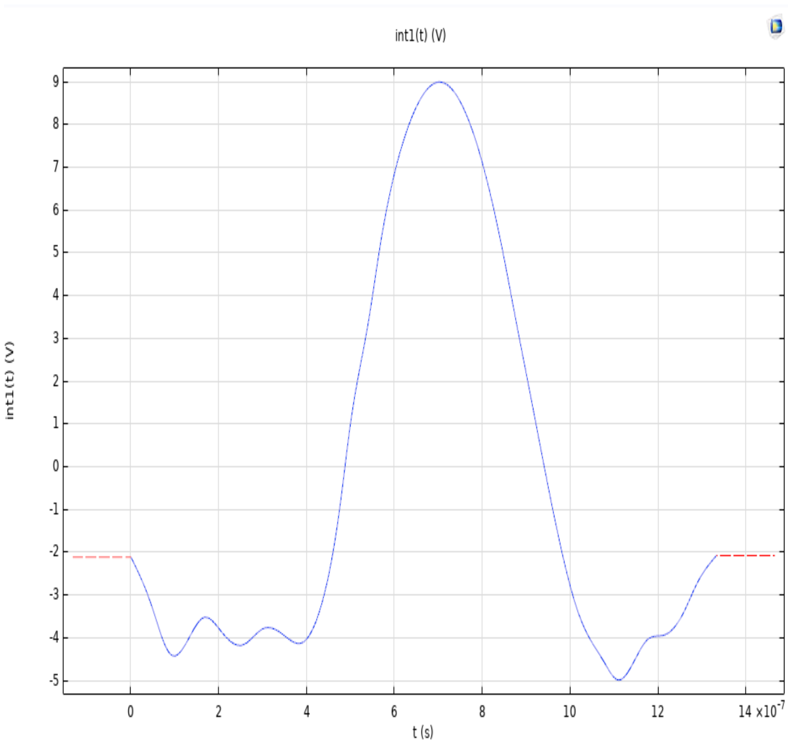
ELECTRON ONE CONSULTING

Real-life example

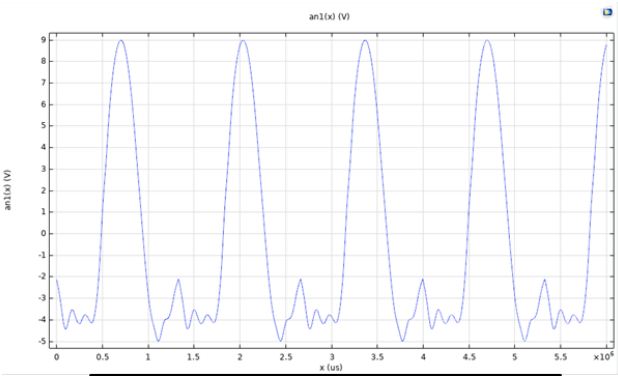
Below is a picture of a measurement set-up that was used to correlate measurements with Multiphysics simulations. Voltage waveforms measured across the coil (inductor) terminals which also act as the primary winding.



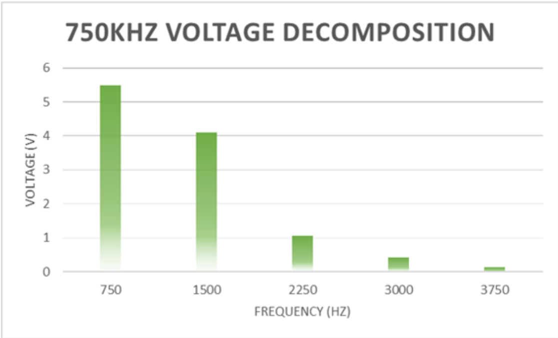
Below image is the voltage measured across the coil terminal.



To simplify the work, this measured waveform was fed directly into COMSOL as time domain input. To cross check, the same waveform was decomposed into frequency domain and coil power was calculated as explained earlier before feeding that coil power into COMSOL.

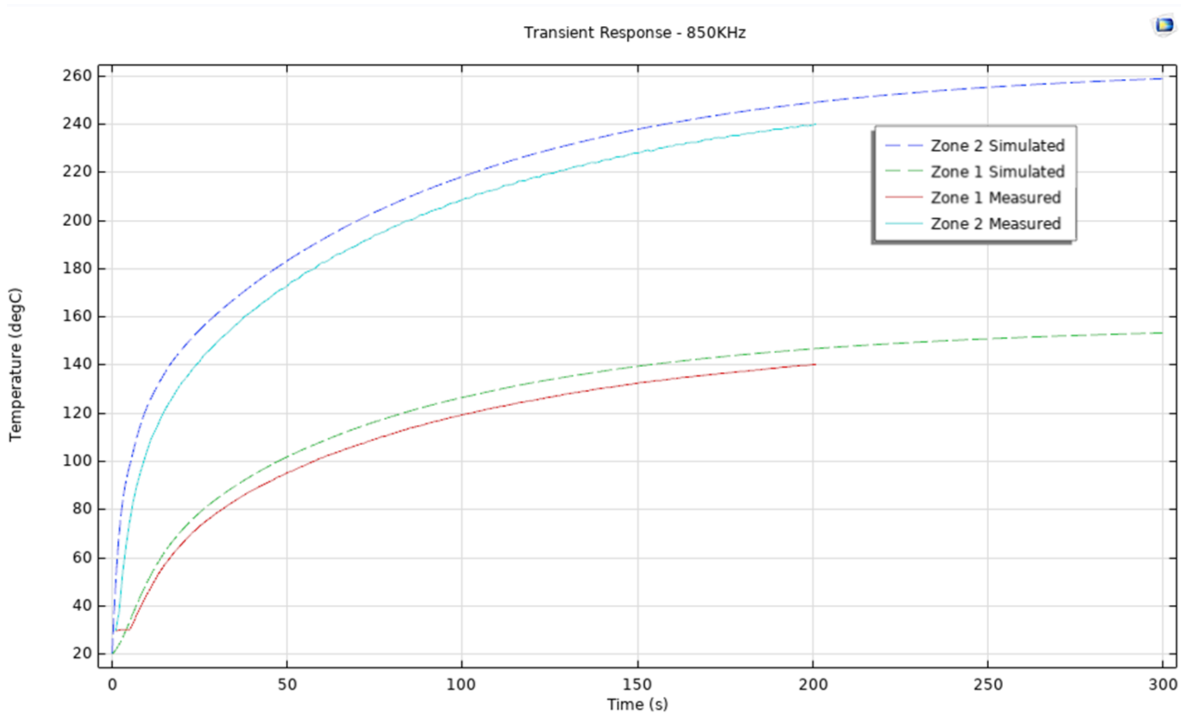


COMSOL Time domain input



COMSOL Frequency domain input

Both simulation and measurement results were captured and plotted in a single graph to see how well they correlate, as shown below.

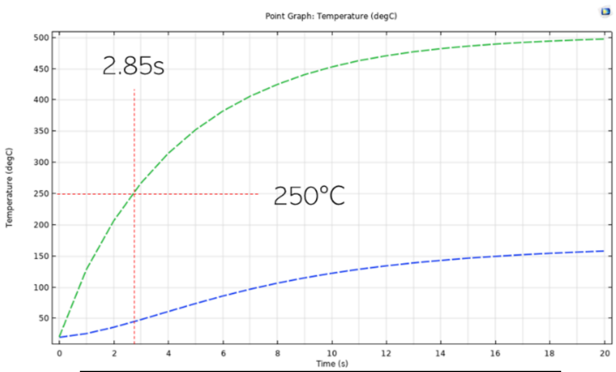


Summary

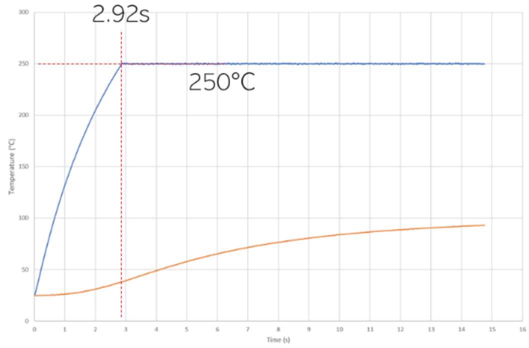
As can be seen, the simulated values are quite close to measured values over a very long period of time (200 seconds). The temperature rise is very gentle in these tests, mainly because the power input to the coil is quite low. This is intentional, so that we don't accidentally damage the test set-up due to overheating.

In reality, much more power is put in to the primary and a software control loop is employed to maintain the temperature at a setpoint.

To show case that this model is fit for the real world, a very short simulation with real life power values was conducted and the correlation results are shown below.



SIMULATED TEMPERATURE



MEASURED TEMPERATURE