# High Voltage High Frequency Pulse Transformer, A Design Analysis

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**Special purpose, high voltage, pulse transformers frequently have exceptionally high requirements associated with their design. Such is the case for the prototype 1:25 kV step-up pulse transformer being developed for the klystron modulator system at the European Spallation Source. An insulation requirement of 150 kV as well as strict specification regarding the voltage transformation that the system performs, makes the construction of the device highly challenging. Evaluation of the electromagnetic, electrostatic and geometric design of the transformer therefore provides a much needed insight into vital parameters of the device.**

## I. Core of the Analysis

At the center of the performed transformer analysis lie two main models; high frequency adjusted equivalent circuit model and finite element based electrostatic model.

The equivalent circuit model condenses magnetic and electric qualities of the transformer to a set of circuit components in such way, that when voltage is applied to the circuit, it exhibits qualities similar to those of the real transformer. The equivalent circuit is seen below in figure 1.

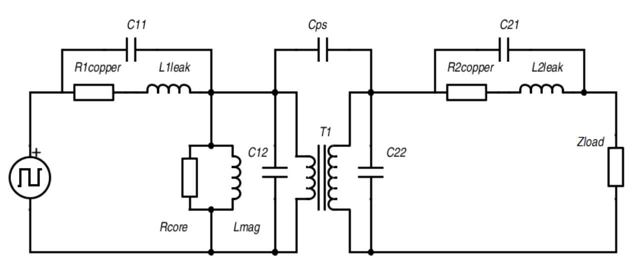


Fig. 1. Equivalent scheme of the pulse transformer

The component values are estimated using analytic, measurement and finite element based methods. Analytic models are used in order to acquire rough estimation of the parameters using mathematical expressions, while finite element simulation provides a more precise estimation. Finally, the measurements on the pulse transformer are performed through short-circuit and no-load tests. The results of the three methods are compared in order to verify their credibility.

In figures 2 and 3 the no-load and short-circuit conditions are displayed in finite element program FEMM. Among other parameters $L_{mag}$, $L_{1leak}$ and $L_{2leak}$ are obtained through the simulations.

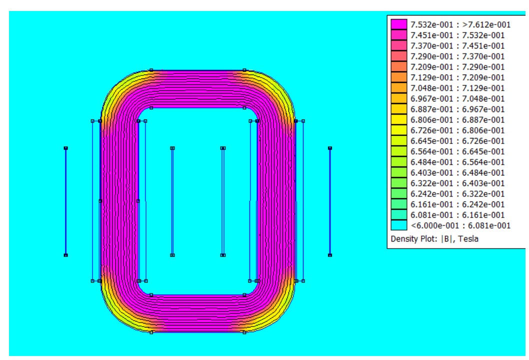

Fig. 2. Open circuit FEMM simulation

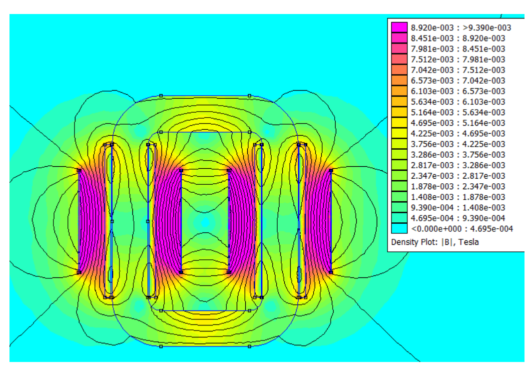

Fig. 3. Short-circuit FEMM simulation

Both plots display magnetic field lines, in addition to magnetic flux density, which is shown in color across the simulation region.

The results of equivalent circuit simulations all point toward two main results. Primarily, the values of leakage inductances, $L_{1leak}$ and $L_{2leak}$ are of great importance due to large portion of the voltage expected to fall over the load falling over these parasitic elements instead. In the figure 4 importance of reducing the leakage inductance is shown.

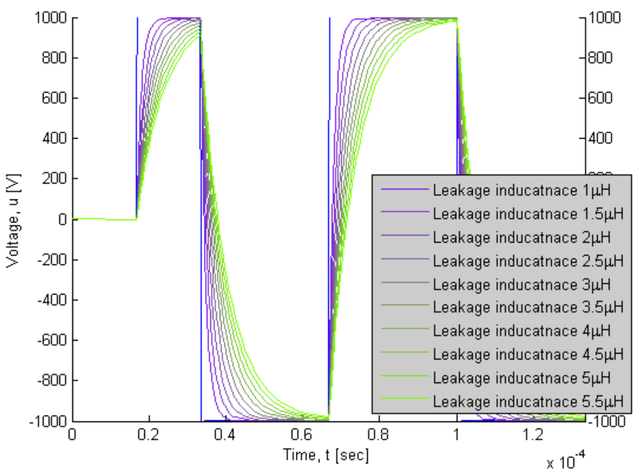


Fig. 4. Influence of leakage inductance on output waveform

As is apparent, the voltage over the load does only reach its intended top value during each half period if the leakage inductance is low enough. For the prototype pulse transformer the leakage inductance is expected to be around 4.5 $\mu$H, which threatens the voltage capability of the system at nominal load. Different estimation methods predict a output voltage between 18.3 kV and 22.4 kV for the transformer, with 19.2 kV being the minimal allowable value at nominal load of 1 k$\Omega$.

Secondarily, saturation tendencies are observed in the core throughout the simulations. This is supported by measurements performed on the prototype. Mild saturation behavior can be observed in figures 5 and 6. First one represents oscilloscope measurement at no load while second one displays simulation results in Simulink under same conditions.

As seen in the figures, current waveform values start to rise significantly toward end of each half period. If the saturation of the core is allowed to reach critical values, very high current spikes are to be expected in the input current, threatening to damage the device and destabilize its output. High saturation levels can be

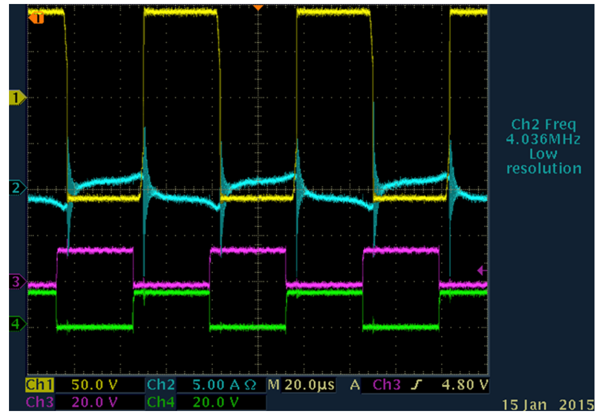


Fig. 5. Current waveform measured using oscilloscope

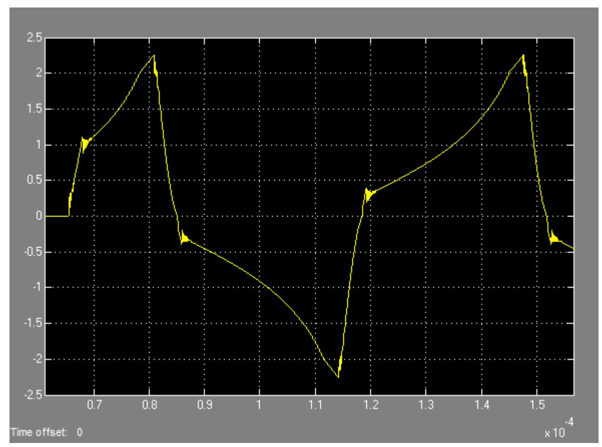


Fig. 6. Current waveform acquired through nonlinear Simulink simulation

reached through asymmetry of the excitation waveform, lower operation frequency or higher input voltage.

Electrostatic analysis of the system offers another point of view on its functionality. Namely, high voltage devices are prone to develop corona effect and electrical arcing if need for sufficient creepage and clearance distances as well as avoidance of sharp edges in the design are overlooked. A clear indication of such effects can be found through electrostatic model of the device. Corresponding model for the transformer is seen in figure 7.

The simulation shows that no electrical arcing is expected when the transformer resides in oil with dielectric strength around 12 MV/m. Notably, if pockets or bubbles of air are present in the submerged transformer the risk of arcing increases due to dielectric strength of air being 3 MV/m. Corona effect, which occurs at lower field strengths can however be present in the design, resulting in modest power losses and possibly solid dielectric degradation.

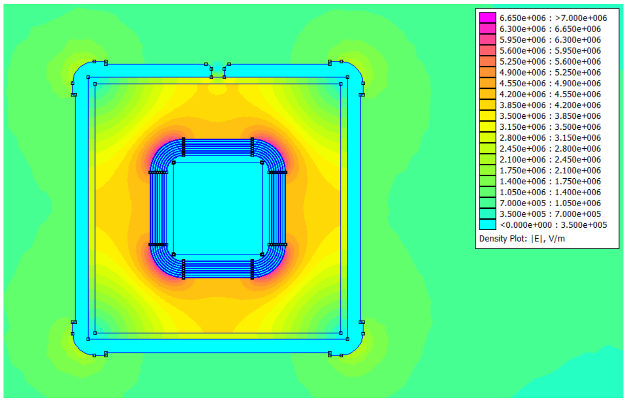


Fig. 7. Electrostatic simulation of transformer cross section in Finite Element Method Magnetics

## II. Conclusions of the analysis

Following the evaluation of the transformer prototype a conclusion is drawn that the design is functional in all aspects, however, room for improvement and safety margins is present.

Primarily the leakage inductance is to be minimized by introducing measures which reduce the leakage flux. Such measures include reducing number of transformer turns on each winding, increasing the length of both primary and secondary winding and decreasing the area between the two. This way reduction of voltage drop can be achieved for the whole design.

While altering the construction, it is important to remember that change of one parameter can unintentionally compromise other aspects of the design. This results in need of a fine balance between sufficient clearance between the windings and saturation of the core on one side and reduction of leakage inductance on the other.

A viable approach to the matter is to reduce the saturation levels through increase in the core cross section by use of an additional magnetic core. This way number of turns and thereby leakage inductance can also be reduced.

Among other improvements use of low permittivity insulators in order to decrease the parasitic capacitance is advised for the primary winding. Another alteration is to increase the radius of the anti-corona devices, which not only reduces corona effect but also decreases the chances of potentially very hazardous electrical arcing.

While the performed analysis revolves around a prototype transformer, the extracted results can be applied to a wide range of similar devices.