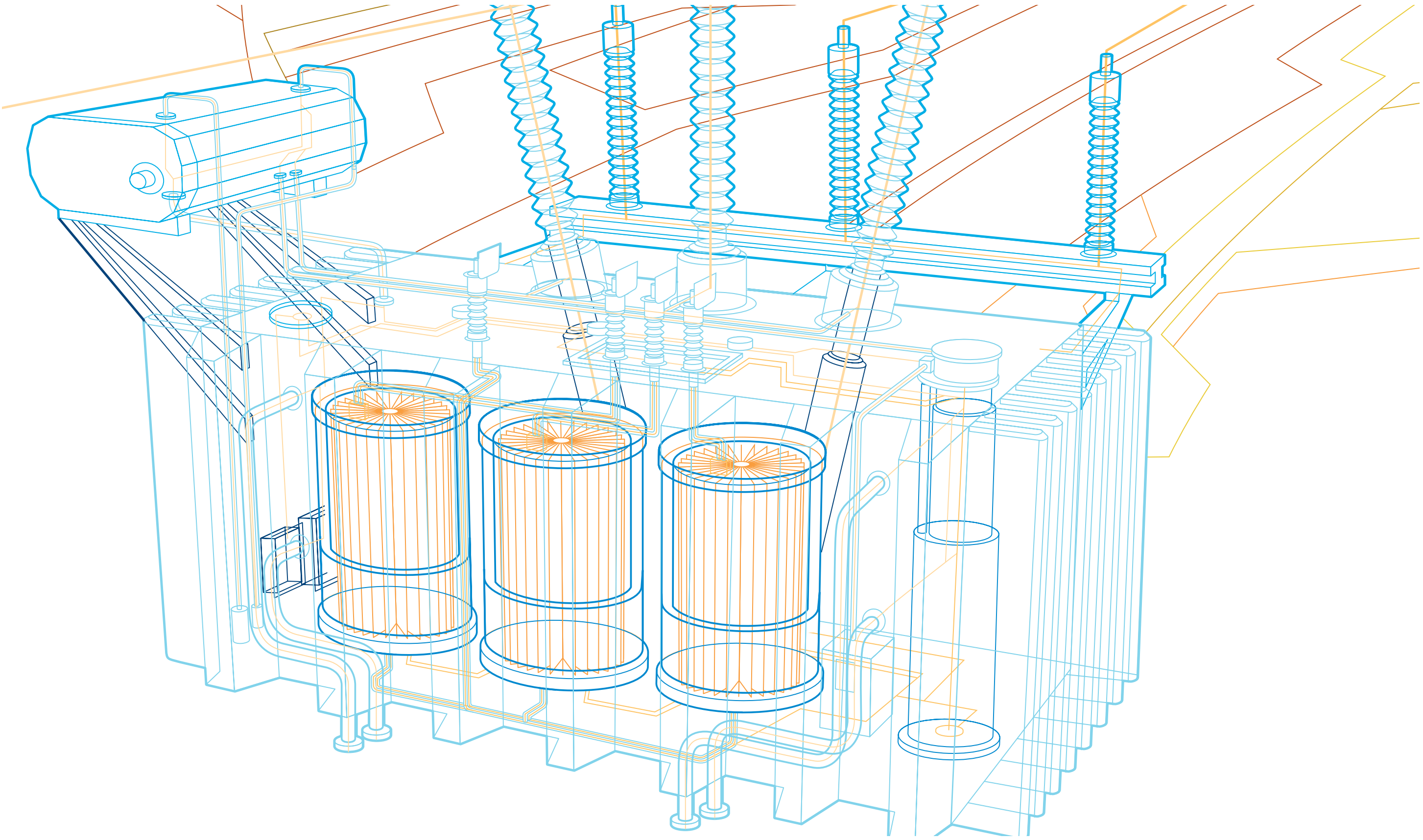
White paper

3D Modeling in transformer design



Introduction

For power system operators, asset management has always been a critical part of their business. Now with an aging infrastructure facing ever-increasing demand as well as profitability pressures and greater regulatory scrutiny, it is more important than ever. This is particularly true in the case of transformers, which are arguably the most important components on the power grid. They are also the most costly.

The interruption of power supply from a power transformer can have dire implications for utility customers, but it also represents the potential for catastrophic loss of revenue for plant and/or network owners. Accordingly, utilities take great care in procuring transformers. For example, utilities often look to reduce first costs by specifying more demanding service conditions (eg, overload, overvoltage, short circuit duty) in order to standardize assets, increase utilization or build in more contingency.

On the supplier side, transformer manufacturers seek to optimize their designs to reduce cost and preserve margins, while delivering reliable performance. It is therefore vital that utility service conditions and system requirements are translated into a design that will meet or exceed requirements. Managing risk and uncertainty across the lifecycle of a transformer—which is measured in decades—starts with the design, so the ability to model various elements and operating scenarios is essential.

This paper explores how advances in modeling tools have ushered in a new level of sophistication in transformer design. Specifically, 3D modeling now allows manufacturers to apply a range of techniques in the design stage that benefit the utility over the life of the equipment.

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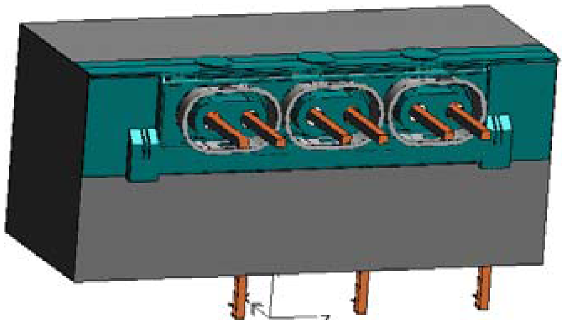

Figure 1: 3D Simplified transformer model used for finite element magnetic and thermal analysis

High current and stray flux control

The currents in the low voltage side of generator step-up transformers, static var compensator transformers and the tertiary windings of autotransformers can be extremely high. If they are not controlled properly, these currents can cause excessive tank heating (hotspots) in the vicinity of the low-voltage and tertiary bushings and leads. This, in turn, can cause leaks requiring costly on-site repairs. High temperature gaskets (eg, Viton) are therefore recommended, but the transformer's design also plays a role in reducing risks associated with high currents.

For example, non-magnetic and copper shielding helps avoid hotspots and keep the temperature of the tank walls and cover within specified limits. Traditionally, the area and position of this shielding was based on empirical formulas and 2D simulations, but the limits of this approach meant that the shielding used might be more or less than necessary.

Modeling in 3D allows non-magnetic and copper shielding to be optimized. The 3D design software allows different definitions of the transformer materials (eg, linear or nonlinear, isotropic or anisotropic, with or without specified losses). The result is a much more accurate design.

Figure 4 gives both the calculated and actual measured results from a finished unit. During testing, the transformer was scanned with an infrared camera to detect any abnormally hot areas. The results were normal with no area above 100 °C.

From figure 4 we can see that the measured results are very similar to those predicted and all within the limits of the standards.

However, the tested condition is not a true reflection of the temperatures that may be observed in service. The main reason is that during testing, the iso-phase bus duct (doghouse) and shorting bars are not connected. These components have a considerable impact on the current flow and interaction of the transformer's own tank heating. Figure 5 shows the temperatures observed during service. High temperatures are clearly visible at the interface of the low voltage bushings and the bus duct.

Interestingly, standards do not state who (manufacturer or customer) is responsible for the cost of any rework that arises from abnormal temperatures observed during operation. It is therefore essential that both test and service conditions are modeled at the design stage. Fixing the problem on-site after the fact is very costly and requires that the transformer be taken out of service.

Other eddy losses and tank shunt optimization.

All transformers produce both no-load and load losses, and a utility usually specifies the $/kW associated with each of these components. Generator transformers are almost always loaded to their full rating, so accurate calculation of load loss is very important for the manufacturer, in particular when the $/kW is very high. Too high a guarantee could make the transformer uncompetitive at the quotation stage when considering the total ownership cost (TOC), which includes the cost of the transformer plus the cost of the losses (no-load, load and auxiliary).

Also, since losses generate heat, it is important to have an accurate calculation of their magnitude so that the cooling equipment is sized appropriately. If the measured losses are significantly higher than expected, there could be localized overheating (hotspots) and even gassing.

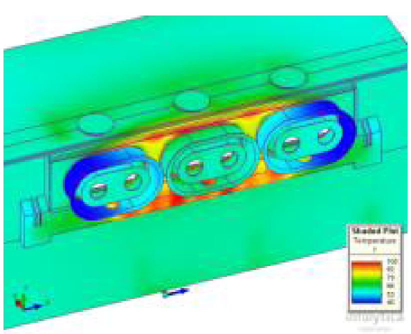

Figure 2: Temperature distribution predicted around the LV bushings for test conditions

Figure 3: Transformer during factory tests

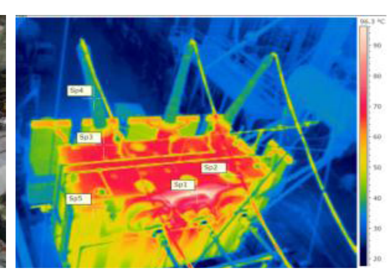

Figure 4: Thermal scans taken during temperature rise test

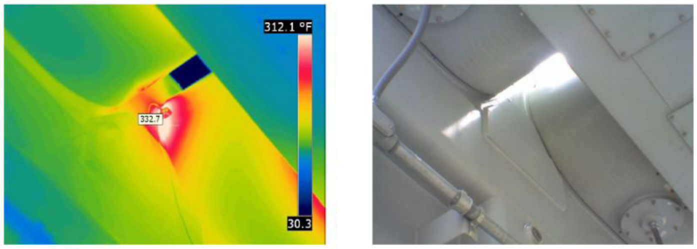

Figure 5: Temperatures observed during service

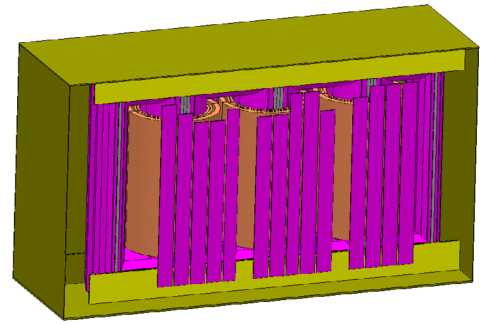

Figure 6: 3D Model of shunts

Load losses are made up of three components: resistive losses (in windings, leads and busbars), also known as DC losses; eddy losses (in windings resulting from eddy currents in conductors exposed to magnetic fields); and stray losses or “other eddy losses” (in the metallic parts of transformers exposed to magnetic fields). The resistive and winding eddy losses are calculated using finite element analysis. Since the other eddy losses cannot be directly measured, it is important to have a good idea of their value and optimize them. A 3D study can help using a suitable transformer model that contains the main components of the transformer, the metallic parts exposed to magnetic fields and the real geometric transformer dimensions.

Magnetic tanks shunts are used to reduce other eddy losses by attracting stray flux and thus reducing the flux that passes to the tank, core clamps, core tieplates, etc. Since the tank shunts attract flux and are made up of thin laminations of core steel, the manufacturer must ensure that they do not saturate during normal operation or any overloading conditions. Such saturation could create localized hotspots on the tank wall, allowing more flux to pass to the tank and other metallic parts. Utilities also may specify the maximum flux density in the tank shunts at different operating conditions.

Figure 7 shows the flux distribution in the tank shunts. From these results we can see that the flux density is very low, meaning that the number of tank shunts used can be reduced. In fact, for the unit shown here, the tank shunts were completely removed. The estimated load losses were very close to what was measured and were within guarantee. This gives confidence in the calculation of other eddy losses.

The use of the 3D modeling has the advantage that any case can be studied (eg, number of tank shunts, thickness of shunts, which walls will have tank shunts, etc.). This allows a better optimization of the tank shunts for all service conditions including overloads and over voltages.

Core and clamp temperatures

Due to the leakage flux from the transformer windings and any high current leads, the temperatures on the core clamps need to be calculated to ensure that they do not exceed the temperatures specified during all service conditions. Excessive heat may cause them to gas. The required magnetic clearance from the windings to the top and bottom core clamps is typically based on empirical formulas and 2D simulations. Here again, using the same 3D model as for other eddy losses and tank shunt optimization we can calculate the temperatures of the core clamps more accurately.

Dielectric or mechanical distances may require larger clearances. If the temperature of the core clamps is too high, there are methods to reduce them and they can be introduced directly into the 3D model and the resulting temperatures calculated. The 3D simulation for calculating core clamp temperatures has been verified by the installation of thermocouples and fiber optics on the core clamps and comparing the results. One method that should be considered only as a last resort is increasing the clearance from the windings to the clamps. This will increase the height of the tank which potentially could create a problem in transportation.

Since this leakage flux is also attracted by the core tie-plates and the core itself, it is important that the temperatures of these components are verified for all service conditions. If not, gassing could be produced if the temperatures are too high. In fact, it is worth considering that Nomex or fiberglass be used for all insulation in contact with the core instead of pressboard.

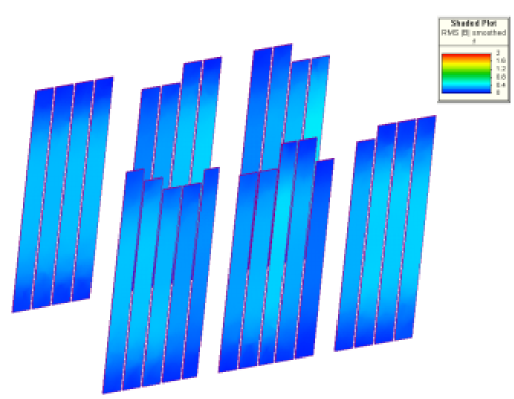

Figure 7: Flux density distribution on tank shunts

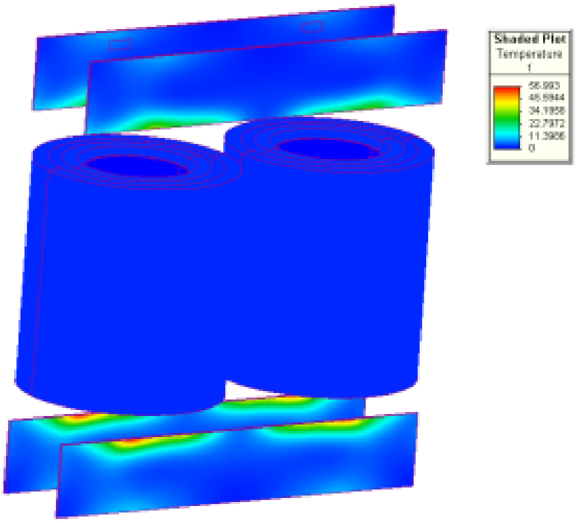

Figure 8: Core Clamp temperature rise distributuion over the oil in the tank

Lead exit temperatures

Transformer design should also consider the temperature of the lead exits during normal and any overload service conditions. Due to dielectric reasons the thickness of insulation on the exit is more than that on the winding. This should always be checked, and if needed, the winding cable split to reduce the temperature. Nomex insulation should be considered as this has higher temperature characteristics than thermally upgraded insulation.

It is also important to note that the only way of measuring the temperature at the lead exit is by the use of fiber optics. The rating of the transformer should not be dictated by the exits and excessive heat could also lead to gassing when in service.

Dielectrics and transient studies

One of the biggest challenges for manufacturers when designing high-voltage large power transformers is transportation. Just because a unit was cleared to a particular site before does not mean that it will in the future (even for a duplicate design). Bridges may be downgraded, for example, rendering them unable to support the same weight. There is always the option of going by ship, but this can be very expensive. Also, as utilities manage their assets and minimize spares it becomes increasingly likely that a given unit will be moved during its lifespan. Accordingly, the design should account for this eventuality by minimizing overall dimensions, weight and footprint.

If internal clearances need to be reduced to create a smaller transportation profile, 2D finite element analysis can be used to evaluate dielectric stresses and verify they are within acceptable limits. However, when considering extra high voltage (EHV) transformers, it is more prudent to perform a 3D analysis, as this provides greater accuracy than 2D. Figure 9 below gives an example of one such study.

Conclusion

The adoption of 3D modeling techniques allows transformer manufacturers to anticipate, identify and address a range of issues in the design phase that otherwise could precipitate serious problems once the unit enters service. This is especially true in cases of high currents, loading levels, overvoltages and dielectric stresses. Manufacturers who take advantage of 3D modeling are thus able to offer a host of benefits and best practices to the utility that purchases the equipment:

- Reduction of hot spots and improved hot spot control to increase the transformer life expectancy
- Increase of safety margins to guarantee transformer performance even in cases of overloading conditions
- Reduced footprint and transportation profile
- Use of high temperature materials like Nomex
- Use of fiber optics at lead exits and clamping structures

While currently the state of the art, it seems likely given these advantages that 3D modeling will soon be widely adopted as an industry standard in transformer design practice.

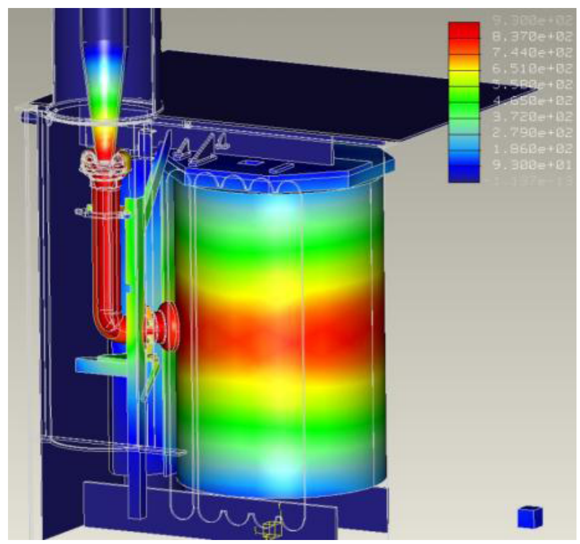

Figure 9: 3D model of dielectric stress analysis

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