Power Play

Multiphysics-based simulation reduces transformer size, cost and noise.

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In the power transformer industry, design engineers face the challenge of developing complex next-generation power transformers within demanding time frames. Some of the intricacies cannot be addressed using customary empirical-based standards or even traditional thinking. Pennsylvania Transformer Technology Inc. (PTTI) has developed a new multiphysics-based simulation-driven design methodology that reaches across physics, across engineering disciplines, and across departments to optimize transformer design. Multiphysics-based simulation-driven development using software from ANSYS enables PTTI engineers to efficiently evaluate many alternatives within multiple domains, conduct what-if studies, predict transformer behavior in real-life operating scenarios, and optimize final designs. Simulating systems allows engineers to optimize the design of cores, windings, tanks and other components to reduce size and cost while ensuring that the unit meets all design requirements, including the ability to withstand surges and short circuits while avoiding excessive temperatures and reducing noise.

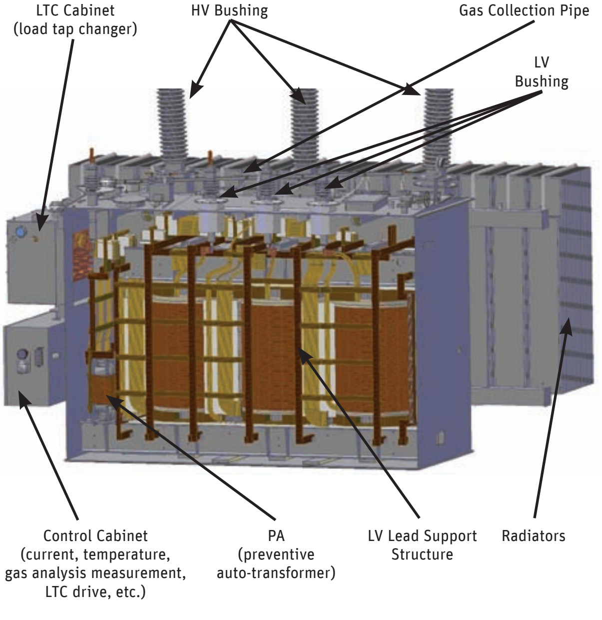

Diagram of a low-voltage power transformer

Transformer from Pennsylvania Transformer Technology

PTTI produces a wide range of sizes and types of single- and three-phase power transformers and voltage regulators for investor-owned electrical utility, public power, municipal power and industrial markets. PTTI looks at transformers as electromagnetic-centric multiphysics devices in which the electromagnetic field distribution simulation is of primary importance. Second-order consequences of electromagnetic fields such as force density distribution and power loss density distribution are also important. These produce effects that define many of the main manufacturer-guaranteed characteristics, such as behavior during a short circuit, behavior during exposure to geomagnetically induced currents (GICs) due to solar flares, seismic behavior, acoustic behavior, and thermal response to normal loads and overloads. These characteristics have a major effect on the lifetime of the transformer, which is often an investment worth a few million dollars.

Electromagnetic Field Simulation

The first step in simulation is to bring the geometry from AutoCAD® Inventor® into the ANSYS Workbench environment for pre-processing. PTTI engineers finalize the setup to accurately reflect the customer's acceptance testing and applicable IEEE® standards. PTTI has found ANSYS software to be the only toolset with the breadth to accurately simulate most aspects of transformer design prior to the manufacturing stage. The engineer enters material properties for key transformer components, such as the

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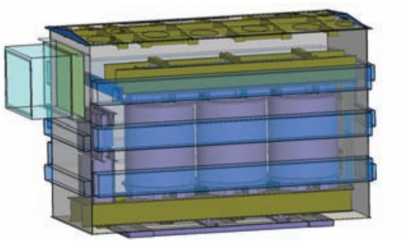
winding material, cellulose-based insulation components and mineral oil, using ANSYS Maxwell low-frequency electromagnetic field simulation software. Excitations and boundary conditions are specified based on a predetermined voltage distribution designed to stress the insulation barriers. Design variables are often parameterized to enable the software to generate optimized values. The solution process is automatic and includes adaptive mesh refinement to the specified level of accuracy.

Engineers visualize the electromagnetic field distributions generated by the most stressful combination of input conditions. Based on the field lines spectrum, the team evaluates the strength of the oil gaps portion of the insulation system, calculates safety factors and compares them with design guidelines. Long before the physical windings are built and placed on the legs of the magnetic core, engineers virtually test the most demanding combinations of excitations. This occurs while minimizing the usage of cellulose-based insulating material as well as the clearances between windings and, at the same time, maintaining the insulation system's required safety factor. The components comprise relatively expensive materials, so PTTI can achieve substantial cost savings in most cases.

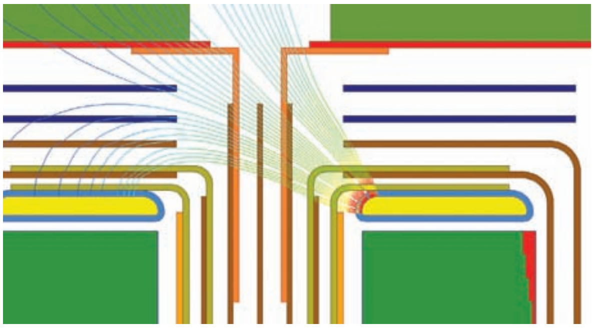


230 KV transformer CAD model

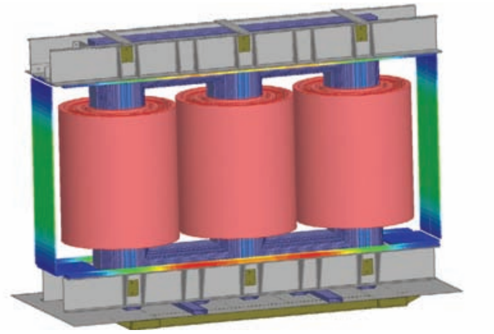
For example, during a recent design review, PTTI presented a 500 KV design to a prospective customer. Simulation analysis provided insight into how to expand existing design limitations and to optimize the configuration of the insulation system while reducing overall size by 2 feet in length and 1.5 feet in both height and width. The resulting design uses less steel and oil and, thus, is less expensive to build and operate — yet it offers equal performance to competitors' products.

Reducing internal clearances typically brings windings and associated magnetic fields closer to steel parts, which can lead to additional eddy current power losses. One way to control the power loss at relatively low levels is to protect exposed metallic parts from the effects of stray fields using magnetic shunts. The shunts are made of bundles of silicon steel laminations that shield the mild (carbon) steel in tank walls and core frames from magnetic fields. This controls and minimizes the overall power loss in mild steel components, since the specific loss of silicon steel laminations is relatively low.

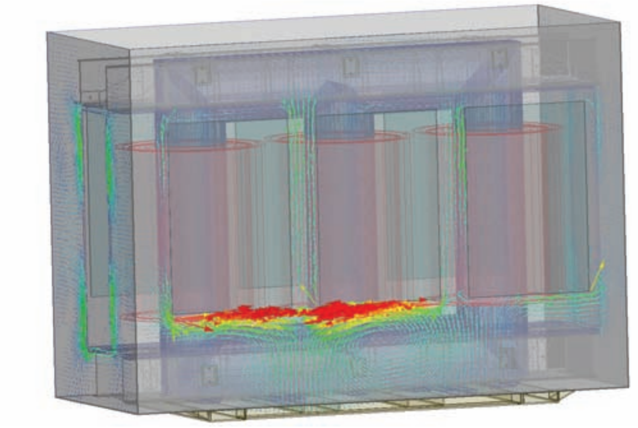
Calculating the power loss density distribution in mild steel components is challenging because at 60 Hz the magnetic field is mostly distributed on the surface instead



Electric field distribution between two adjacent high-voltage windings



Magnetic flux density distribution in magnetic shunts



Eddy currents induced by stray fields in tank walls

of fully penetrating the steel. When combined with the irregular shapes of many mild steel components and significant power loss inside the transformer, this creates modeling difficulties. PTTI uses a proprietary approach to create and solve the Maxwell model. The finite element model's overall size can reach 5 million nodes for average-size power transformers and even more for very large units.

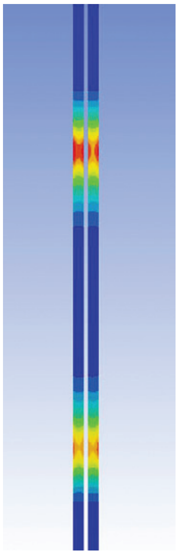
Frames made of less-expensive mild steel can overheat when exposed to excessive stray flux. It is customary to protect them with shunt bundles made of silicon steel laminations similar to those used to protect tank walls. Design engineers use simulation to optimize the lamination bundle thicknesses so they do not saturate at peak load.

For units that are to be installed in geographical areas susceptible to GICs, simulation helps to determine the distribution and magnitude of eddy currents induced in tank walls and other massive pieces of steel inside the tank. GICs are caused by space weather events that induce changes in the earth's magnetic field and, in turn, generate low-frequency currents in transformer windings. Simulation ensures that steel parts do not experience excessive heating and that combustible gases are not produced inside the unit. PTTI engineers use analysis to study local effects, such as hot-spot temperatures on core frames, end guides, magnetic shunts or lock strips. The design team applies an ANSYS software feature that automatically maps the power loss density distribution from Maxwell to the ANSYS Mechanical thermal mesh for use as the thermal boundary condition. The thermal solution determines the temperatures at every point in the solution domain.

PTTI has validated its simulation results with physical measurements. The power loss in eddy current simulations compares within 5 percent to 8 percent with stray loss power in models with millions of finite elements. Calculated temperatures for end guides, lock strips and transformer frames is normally within 4 percent of measured data from fiber-optic probes.

Structural Simulation

ANSYS Mechanical structural simulations range from stresses caused by "pull vacuum" test on the whole unit to short-circuit forces, vibration modes of core and tank with implication on the noise generation, to complex seismic analysis of power transformers and circuit breakers.

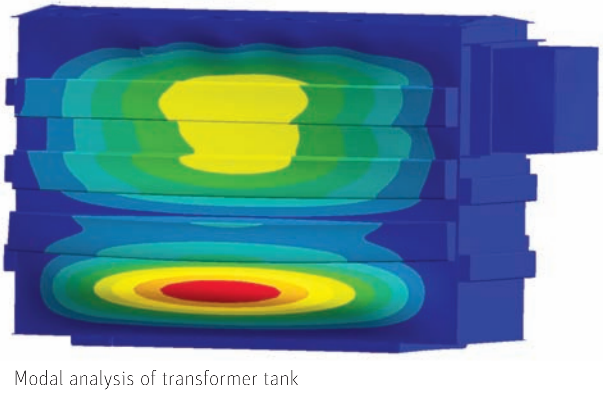


Temperature distribution in coupled ANSYS Mechanical model

For example, customers sometimes require low-noise units for residential areas. The main noise sources are magnetostrictive vibrations of core laminations and movements of coils and other structures due to Lorentz forces. These vibrations propagate through the oil inside the tank and represent the main audible noise cause. Thus, it is important to study the vibration modes of the core, tank and other subassemblies while designing such special units.

The vibration from the core due to magnetostriction contains a 120 Hz component and harmonics, while the vibration from the windings has mainly a pure 120 Hz tone if currents in the windings themselves are free of harmonics. Since the goal is to avoid vibrations from the core, windings, and other parts that excite the structure's natural vibration modes, measures can be taken to reduce the harming effects of resonances, such as moving or strengthening the tank braces or adding new braces.

A number of customers require seismic analysis of power transformers and circuit breakers in accord with IEEE standards. PTTI engineers perform modal analysis followed



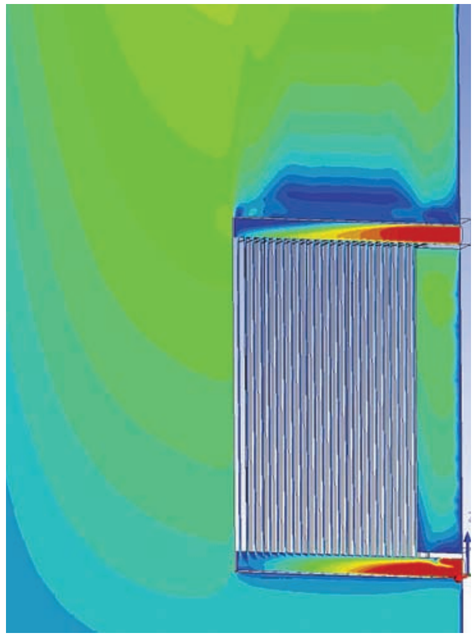
Modal analysis of transformer tank

by a response spectrum simulation in which the acceleration versus frequency spectrum is applied on the x, y and z axes concurrently, with the results of this dynamic analysis then combined according to an SRSS algorithm.

Fluid Flow Simulation

Recently, PTTI acquired the ANSYS Fluent computational fluid dynamics (CFD) package that allows use of eight parallel processors in solving large models. The team is using the software to better understand oil flow patterns inside transformers and radiators with expectations of improving cooling system performance and reducing the cost of heat exchange system components.

Management and design engineers apply their simulation toolset to meet the many challenges of transformer development. PTTI's new methodology integrates the traditional workflow of electromechanical design with a state-of-the-art simulation environment based on ANSYS software. The use of multiphysics numerical modeling wherever possible greatly enhances calculation accuracy. The result is that PTTI can evaluate many alternatives that provide substantial performance improvements prior to manufacturing. ■



ANSYS Fluent simulation shows velocity contours of oil in radiator fins and air flow around radiator.