

CFD Permits 30% Increase in Circuit Breaker Current Rating with No Increase in Cost or Size of the Device

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Introduction

The use of computational fluid dynamics (CFD) software allowed engineers at Eaton Corp. to increase the current rating of an existing medium-voltage vacuum circuit breaker by 30% without increasing its size or cost. Compared to prototype testing, the use of CFD to predict the thermal performance of the breaker allowed the evaluation of significantly more design alternatives. It also helped keep down the cost of the redesigned breaker by making it possible to compare the effectiveness of less-expensive stamped versus more-expensive machined heat sinks. The use of software specifically designed for thermal cooling applications eliminated the need to model complex breaker components such as heat sinks from scratch.

Eaton Corp. is a global manufacturer of highly engineered products which serve industrial, vehicle, construction, commercial, and aerospace markets. Headquartered in Cleveland, Ohio, the company has 54,000 employees and 155 manufacturing sites in 26 countries around the world. Eaton's extensive product line includes many types of circuit breakers, ranging in size from two inches wide to others that are six feet tall. One type, known as a vacuum circuit breaker, uses a vacuum interrupter (VI) to break or interrupt current in AC circuits within an evacuated envelope up to 38kV. VIs offer compact size, short stroke, high reliability, enclosed arc, and essentially maintenance-free operation. They are extensively

applied in medium-voltage circuit breakers or load break devices, contactors, motor starters, tap changers, distribution reclosers, metal-clad switchgear and other electrical distribution and protection equipment.

Recently, Eaton established a goal of increasing the current rating of the entire circuit-breaker product line by 10% to 30% without a corresponding increase in production costs. That means boosting capacity without increasing the size of the breakers, which is the normal method of increasing current without exceeding temperature-rise limits imposed by a series of industrial standards. The vacuum circuit-breaker mentioned above was a challenging redesign because the existing device operated with only a small margin below the temperature-rise limit. Since heat generation in conductors is proportional to the square of the electrical current, the target 30% increase in current rating would result in a 70% increase in power dissipation. To manage that within the existing frame size required a very different design.

The existing design was an assembly with three phases or sections, one for each of the three AC power connections. The VI consisted of a vacuum bottle containing stationary and movable contacts. The Line/Load end of the VI stems were connected to the Line and Load VI adapters, which in turn were bolted to the copper buses. Spring-loaded contact arms called Finger Clusters served as links between

the breaker conductors and the outside world. Copper extension bus bars, for both the Line and Load ends, were bolted on the finger clusters from the outside of the cabinet. Electrical cables were connected onto four-foot long buses. The major heat generation in the assembly took place inside the vacuum bottle at the contact spots.

This area accounted for 30% to 40% of the total heat generated. The finger clusters were a second heat-generation zone. Although one option in redesigning the breaker was to build and test prototypes, this costly and time-consuming method would have allowed engineers to investigate only a limited number of design options. Instead, engineers decided to evaluate design alternatives in software using CFD to solve the equations of heat transfer and fluid flow. CFD produces solutions for problems with complex geometries and boundary conditions. A CFD analysis provides fluid velocity, fluid temperature and fluid concentration values throughout the solution domain. The results of the analysis allow a designer or an engineer to optimize fluid flow patterns or temperature distributions by adjusting either the geometry of the system or the boundary conditions such as inlet velocity/temperature, wall heat flux, etc. CFD also can provide detailed parametric studies that can significantly reduce the amount of hardware experimentation necessary to develop a prototype and thus reduce design cycle times and costs.

The CFD software used was IcePak, from Fluent, Inc. of Lebanon, New Hampshire, a finite-element-based CFD program that uses FIDAP as its solver. Unlike general purpose CFD codes, IcePak was specifically designed for thermal analysis of electronic packaging applications. It differs from other CFD codes in its use of "objects" such as blocks, plates, vents, openings, fans, resistances, and sources. Objects, which are pre-defined 3D solid models, make it easier to generate system-level models. Users simply enter characteristics of a component such as thermal conductivity or specific heat, rather than

modeling it from scratch as with other CFD software. At Eaton, co-op students with no mechanical engineering training were able to generate thermal models using IcePak's objects.

IcePak's heat sink macro, which uses objects to model the complex geometry of heat sinks, was particularly helpful in this project. Heat sinks, with all their fins, are very difficult and time-consuming to model in software. With the heat sink module, however, a user constructs a heat sink from basic objects such as a Base Block, a Flow Source Block which defines fin orientation, and a Flow Resistance

Block. A Block is an IcePak term for 3D brick-like element whose properties can be defined by the user. The machined

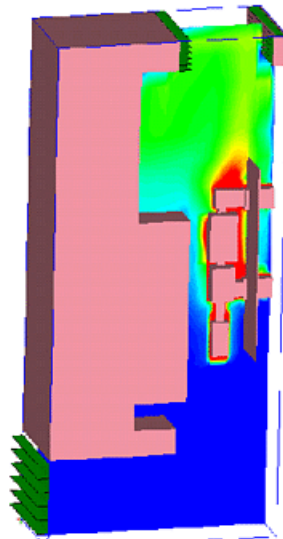


Figure 1. Temperature distribution with no heat sink attached to the upper vacuum interrupter adapter.

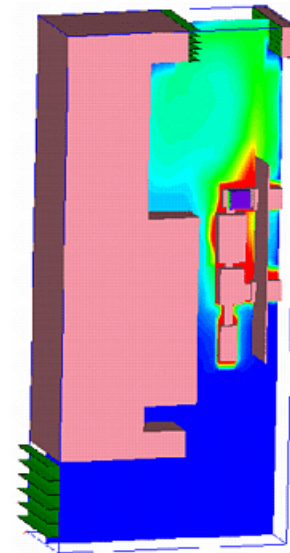


Figure 2. Temperature distribution with heat sinks attached to the upper vacuum interrupter adapter.

copper heat sink evaluated by Eaton engineers was created by combining five such blocks. The stamped and laminated heat sink was the combination of four heat sink blocks. The heat transfer parameters required by IcePak obtained separately for each module.

Evaluating different heat sink configurations was the first step in the breaker redesign. Engineers opted to analyze heat sinks separately from the rest of the breaker because the complexity of heat sinks resulted in a long solution time. Two heat sink configurations were analyzed under a number of flow conditions. The results, which were in terms of effective thermal conductivity and flow resistance to obstruction of air flow by the fins, were then used as inputs to the

system-level model.

This model incorporated several simplifications and approximations to the individual components to make system-level analysis feasible in terms of computational cost. For example, air flow was modeled only inside the cabinet. Convection and radiation effects on the bus extensions were modeled by applying respective heat transfer coefficients as boundary conditions on the surfaces while conduction was modeled using the IcePak solver. It was also assumed that there was little temperature drop from the breaker end of the four-foot long copper busbars to the cable end. The enclosure containing the breaker mechanism was considered to have insulated walls since it was separated from the VI compartment by a plastic divider. The vents on the cabinet were modeled in IcePak using a loss coefficient and the measured free-area ratio as inputs.

Most of the system-level simulations involved laminar flow for which standard coupled, non-linear, second-order partial differential equations for the continuity, momentum, and energy formed the basis for the CFD simulation. They were run on a Silicon Graphics PowerChallenge compute server and took less than eight hours to reach a converged solution.

The system-level model allowed engineers to use IcePak results to guide the redesign. One design change they evaluated was a reduction in contact resistance in the VI. They designed a new actuator that delivered higher contact pressure between the movable and stationary VI contacts, and modified existing contacts and contact surfaces to ensure better contact at the interfaces. These changes reduced contact resistance 30% compared to the existing design and reduced the maximum temperature rise by about 16 degrees C according to IcePak results.

Engineers also evaluated the effect of an increase in conductor size. Since the VI systems are the primary path for heat removal in a vacuum circuit-breaker, increasing their diameter was an obvious means of improving thermal performance. Engineers made them twice the size of those in the original device. This led to a drop of 6.5 degrees C in maximum temperature rise.

Another design change they investigated involved

phase-to-phase spacing. When AC current flows through the three phases of the breaker, eddy currents are induced, leading to a maldistribution of current density in the conductors which in turn results in large electrical resistance and heat dissipation. Engineers investigated increasing phase-to-phase spacing by 40% to alleviate this problem using IcePak's graphical depiction of flow and thermal distribution within the model. This size increase, which was all that was possible given frame size constraint, had no significant effect on the overall temperature rise.

Similarly, IcePak results were used to find ways to improve the venting configuration of the breaker to maximize air flow. Vents were added to the cabinet directly above and below the vacuum interrupt compartment. Adding vents to the model was done using the software's CAD-like modeling tools, which permitted easy sizing and interactive placement of the vents. However, additional vents did not seem to have a pronounced effect on internal temperature rise of the breaker.

To validate the computational model, Eaton engineers tested a modified breaker configuration under steady state conditions at the 30% higher current level. Sixty-six J-type thermocouples were attached at various locations along the entire current path to measure the temperature rise of the breaker every 15 minutes. Electrical resistance was measured using the DC millivolt drop technique across different sections of the current path, before and after the experiments. The measured temperature rise demonstrated good agreement with the predictions made by IcePak. The maximum temperature difference between the experiment and IcePak results was less than six degrees in the vicinity of the VI.

Engineers concluded from these results that the computational model reflected reality well, and that the judicious use of thermal modeling in software such as IcePak could be useful in the design of electrical devices. They feel this is particularly true of parametric studies where only small changes are made from simulation to simulation. In the redesign of the vacuum breaker, the use of CFD allowed Eaton to improve the performance of a device without increasing production costs.