A NOVEL APPROACH FOR THE THERMAL ANALYSIS OF AIR INSULATED SWITCHGEAR

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ABSTRACT

The international standard IEC 62271-200, stipulates a temperature rise type-test to be performed on switchgear cubicle. Given temperature limits are not to be exceeded. In order to reduce development test cycles, a calculation scheme based on the thermal net method (TNM) [1] is used. Due to certain limitations of the TNM, a combined CFD-TNM method is proposed. The flow field is calculated from CFD and fed into TNM. Knowing the approximated air velocities in- and outside of the switchgear, this information can be applied as parameters to the thermal elements in the TNM calculation. Thus will increase the accuracy of the results than what it would have been achieved with the use of just one simulation method.

INTRODUCTION

The TNM is an efficient calculation method for complex models [2]. It even is capable of solving the temperature rise in switchboards consisting of several switchgear panels, like those typically used for type-test. Requirements on computer hardware are low and calculation times are short. The consequent use of TNM throughout the design means a hierarchical and structural built up of a model library of single parts, three-phase devices, compartments and entire panels. Such an approach will also reduce the time requirements for preparing the final simulation models. Subsequent design modifications are fast and easy to implement, too.

Computational fluid dynamics (CFD) in principal offers a closed solution for fluid flow and the temperature rise. The CFD simulation can provide as much information as being provided by the initial 3D model, by the mesh resolution, by the turbulence models applied, and so on. Conjugate heat transfer is not an easy task in CFD, though. High mesh resolution and good mesh quality as well as a smooth mesh size variation are required to achieve a decent accuracy. Also numerical stability is not always achieved, especially for free convection problems.

Depending on the used hardware and numerical solver, a transient solution run will need lengthy calculation times. To achieve a solution within a reasonable time, usually models and meshes are simplified. This, however, limits the accuracy of the heat transfer calculated. Another draw-back of CFD is the requirement of an entirely new simulation in case of design changes like geometry modelling, meshing, solver set-up, simulation run, and post-processing. Thus, CFD only is not yet an efficient choice for the solution of the temperature rise problem of complete switchgear panels. For the description of physical phenomena CFD can provide needed supplemental information for more efficient methods, say the TNM. Here a combination of CFD and TNM methods is proposed. The flow field is calculated by a CFD simulation and velocities obtained are then being fed into a TNM model.

THERMAL NETWORK MODEL

For TNM the physical model is discretized into a circuit of thermal resistors and, if rise times are of interest, capacitors. Such a model can be solved with a circuit simulator like SPICE. The method utilizes the analogy between electric and thermal field problems [5, 6]. Accordingly, heat flow and temperature correspond to current flow and voltage potential, respectively.

The heat sources of a switchgear device are current carrying conductors, contacts, and connections due to their temperature dependent ohmic losses. The produced heat conducts along the current path and is then dissipated to the gas and to the enclosure by means of convection and radiation. From the enclosure the thermal flow is again done by convection and radiation to the ambient. For vented systems with openings, the major part of heat is directly transferred to the ambient by a convective heat transport of the fluid.

In TNM all heat transfer mechanisms are being represented by thermal resistors. Their thermal resistance is defined by the ratio of the temperature differences at the terminals and the power flow through the resistor.

$$R = \frac{\Delta T}{P_i}, \qquad (1)$$

Non-linear dependencies on temperature of power generation and heat transfer are implicitly included in the mathematical models of the circuit elements. By iteratively solving the thermal circuit the non-linearities are obeyed.

Contacts and connections are critical points along the current path. Temperature rise limits for movable contacts are lower than those for solid conductors and fixed bolted connections. These are also depending on surface plating of the connections. The limits are defined by the international standard IEC 62271-200 [4]. Since heat generated by the joint resistances can only spread via conduction, the joints form hot spots in the electric current path. These local gradients require a proper discretization of the conductor bar in order to resolve the temperature distribution. As a rule of thumb the size of discretization along the current path should be commensurate to the dimension of the conductor cross section.

Skin effect factor

Eddy current losses are very important issue in switchgear design. The tendency of alternating current to flow near the surface of the conductor causes a reduced effective cross sectional area for the current and therefore increases the effective resistance. The enhancement of power loss can be considered by a skin factor applied to the DC loss and must be considered when setting up a thermal network model. The TNM library readily provides fit functions for simple geometries of single line conductors [5]. The skin effect factor for double or triple rectangular bars can also be found in literature [5, 6]. Additionally, for a 3-phase-system the proximity effect has to be taken into account. The total induced eddy current losses can be calculated for any configuration by electromagnetic FEM simulation. An elevated temperature of the conductor should be considered, since this will reduce the skin depth. For a compact gas insulated three phase system, skin factors on the order of 1.5 can be found [1].

Convective heat transfer

In TNM the convective heat transfer coefficient α is being calculated by the Nusselt number approximation, according to the theory of similarity

$$\alpha = \frac{Nu \cdot \lambda}{l_c}, \tag{2}$$

where l_c is a characteristic length, and λ is the thermal conductivity of the fluid. For forced convection, the Nusselt number is defined as a function of Reynolds number,

$$Re = \frac{v \cdot l_c}{\kappa}, \tag{3}$$

and the Rayleigh number Ra, as

$$Nu = c_2 \cdot \sqrt{Re^2 + (c_3 \cdot Ra^{n_3})^2}^{\,n_2}, \tag{4}$$

where v is the fluid velocity and κ is the kinematic viscosity. The second term under the root on the right hand side of (4) takes the contribution of natural convection into account. The constants c_i and n_i depend on geometry and were determined by experiment. Tabular values for these constants can be found for example in [5, 6].

The TNM works well for a closed volume system where flow velocities are low and do change little throughout the domain. Then, the convective heat transfer coefficient becomes a function of the Rayleigh number only. Most of the air insulated switchgear are using vented systems with or without forced cooling. There velocities are often large enough to require a calculation of the heat film coefficient as a function of velocity according to (4). Additionally, local velocities vary strongly with the location which influences the heat transfer at the different conductor surfaces significantly. The TNM itself lacks off a self-consistent solution for the flow field, which has to be considered in calculating the temperature rise.
However, this can be supplied to by computational fluid dynamics (CFD).

CFD

The basic equations describing fluid dynamics are the conservation laws of mass, momentum, and energy. In CFD the solution of these equations are obtained numerically using finite volume method [3]. The conservation principle of mass, momentum and energy are applied to the control volumes. The whole fluid/solid domain is discretized by many control volumes. Solving the conservation equations yields to the flow field and temperature distribution in the domains.

Mass conservation equation:

The mass conservation or continuity equation is based on the fact that the rate of change of mass inside the fluid element is equal to the net rate of the mass flow into or out of the fluid element across its surfaces.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \cdot \vec{v}) = 0 \tag{5}$$

In equation (5) ρ is the fluid density and v is the velocity vector.

Momentum conservation equation:

Newton's second law states that the rate of change of momentum is equal to the sum of the forces on the fluid. These forces are in general surface forces and body forces. While the surface forces like pressure and viscous forces are normally considered as separate terms in the momentum equation, body forces like gravity and centrifugal forces are in general included in the source term. With this convention, the three-dimensional momentum conservation equation reads

$$\frac{\partial(\rho \cdot \vec{v})}{\partial t} + (\rho \cdot \vec{v} \cdot \nabla)\vec{v} = -\nabla p + \nabla \cdot (\eta \cdot \nabla \vec{v}) + S_{Mx} \tag{6}$$

where η is the dynamic fluid viscosity, p the pressure and S is the source term of force.

Energy conservation equation:

The first law of thermodynamics states that the rate of change of energy of a fluid element is equal to the rate of heat supply plus the rate of work done on the element mainly by surface forces. The energy equation expressed in terms of total specific enthalpy

$$\frac{\partial(\rho \cdot h_0)}{\partial t} + \nabla(\rho \cdot h_0 \cdot \vec{v}) = \nabla(\lambda \cdot \nabla T) + \frac{\partial p}{\partial t} + \nabla((\tau_{ij}) \cdot \vec{v}) \tag{7}$$

where h_0 is the specific enthalpy, λ is the heat conduction coefficient, T is the temperature, and τ_{ij} is the viscous stress tensor. Equations (5), (6), and (7) form a closed loop solved by the finite volume method.

COMBINING CFD AND TNM

The combined CFD and TNM method was applied in the development of a 5000 A air insulated switchgear as part of the PIX AIS family. The plot for the new 5000 A unit was based on an existing panel designed for a rated current of 3150 A at natural cooling.

The total power loss is proportional to the square of current, that is

$$P_{el} = k_{ac} \cdot R_{el} \cdot I^2 , \qquad (5)$$

Here, k_{ac} is the effective eddy current increase of losses at AC current and R_{el} be the total resistance in the current path. Thus, the power loss on the same unit at 5000 A would be more than 250% of the power loss at 3150 A. To keep the temperature rise at the same level, this loss increase must be balanced by use of substantially more material to reduce losses and by provision of substantially more cooling surfaces, which again means more material. Considering the main dimensions and targeting a reasonable cost limit, this cannot be achieved by simple up-scaling of the parts. The design for the new rating was therefore mainly addressed by application of forced convection and optimization of the airflow.

For reasons of comparison a CFD heat transfer simulation on a simplified model was performed. The simplification was such, that the calculation could be performed on a standard simulation workstation in a reasonable time. Based on prior simple sub-models, the mesh refinement needed near the heat transferring surfaces was determined according to the standard k-ε model for turbulent flow. Some crucial details, like the inlet and outlet flow resistances were separately analyzed on sub-models in detail. The findings were then been incorporated into the low resolution full panel model. Fig. 1 shows the temperature profile obtained by the simplified model.

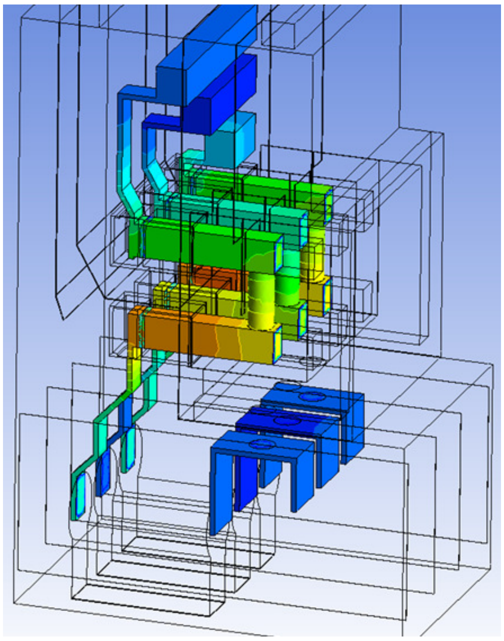

Figure 1: Temperature distribution obtained by the CFD conjugate heat transfer model, represented by coloured contours

Comparing the temperatures calculated at selected measurement points with a physical measurement, the calculation yielded a rough approximation to the temperature distribution. (Fig. 2).

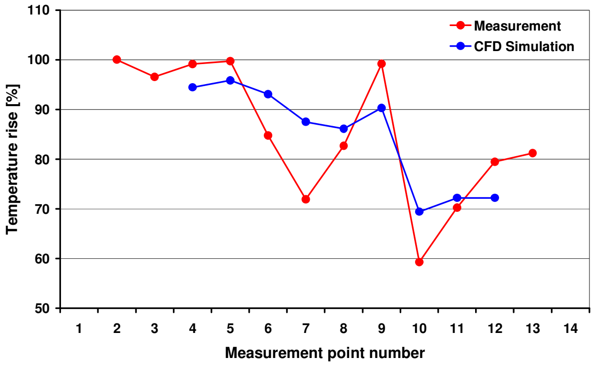

Figure 2: Comparison of temperature rise obtained by CFD simulation and by physical test

Similarly using TNM alone yielded some deviation from measurement as shown in Fig. 3.

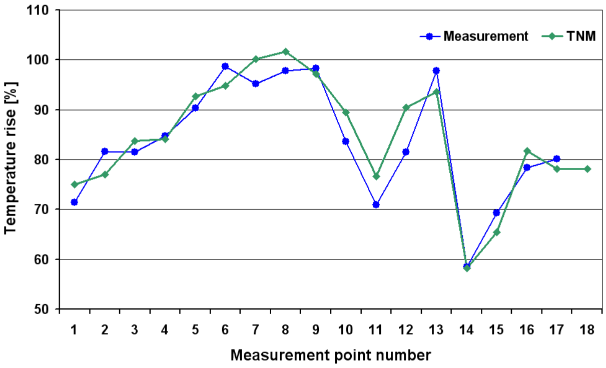

Figure 3: Comparison of temperature rise obtained by TNM simulation and by physical test.

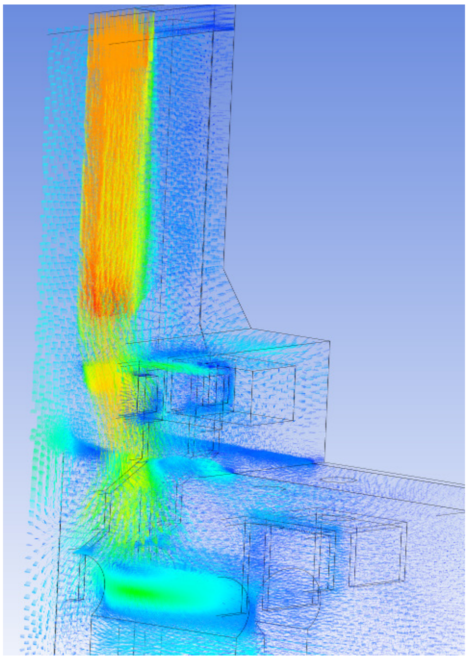

Figure 4: Flow velocities in the cable compartment. Velocity of air flow shown as coloured vectors.

The velocity field is provided by the CFD solution. Fig. 4 show simulation results for the cable compartment. Shown are the velocity vectors of air coloured by magnitude.

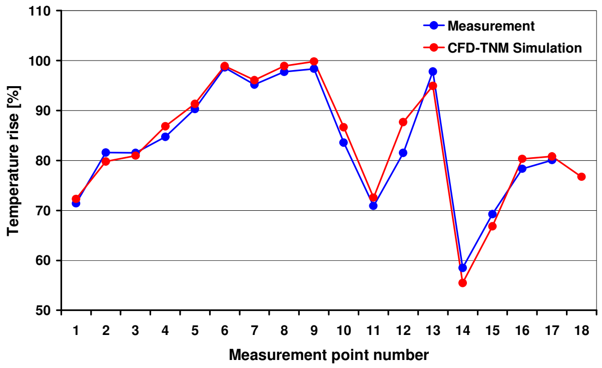

Figure 5: Normalized CFD-TNM temperature comparison with measurement

Such simulations were performed on all compartments of the switchgear. Even a rather coarse mesh in CFD, which will not fully resolve the surface gradient layers, will give a sufficiently approximated velocity. The velocities obtained were then used as input parameters for the convective heat transfer elements in the thermal network. Still, to get a satisfactory validation of the model with a subsequent measurement, lab tests are needed to get hands on the resistances of joints and connections. With these additional information supplied, the temperature rise solution from TNM comes significantly closer to measurement values, as shown in Fig. 5. The resulting temperature rise is much more accurate than what would have been achieved by use of just one method, at still acceptable processing time. For subsequent design changes, in which the flow pattern was not expected to change considerable, modifications could be done in thermal network model only and the results were obtained very fast.

Procedure

Combining CFD and TNM offers the opportunity to enter a strategic approach for the development of a new switchgear or device. TNM offers a quick and reliable tool for identifying the problematic parts and for predicting the effect of modifications. CFD on the other hand, in spite of being by nature computational expensive, supplies information on the flow field, which is hard to get from testing. Speeding up CFD by reducing the numerical problem to a simple flow field analysis is possible, when dealing with the energy balance in a different tool like TNM. Combining the two tools together with measurement delivers a solid base for a straightforward development. Fig. 6 illustrates the steps of the development loop. Loops cannot be omitted in development. Scientific calculation can greatly reduce the number of tests needed. Within the testing loop, however, latency due to analysis and redesign needs to be kept short. For thermal management the proposed combination of tools seems to be advantageous. Archiving a proper validated TNM model adds the benefit of being able to calculate the performance for changed boundary conditions, for example due to the setup condition in a switchboard, or for modified parts very quickly.

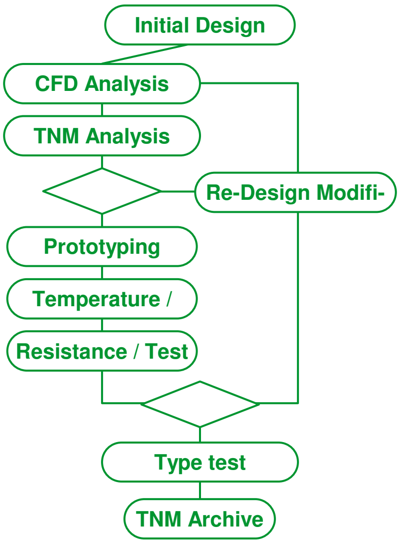

Figure 6: Procedure employing CFD-TNM in the development process of electric device

CONCLUSIONS

The benefits of TNM and of CFD for thermal management of medium voltage switchgear device were discussed. As demonstrated by a recent application, it was concluded, that the combination of the two different numerical calculation methods provides a most efficient analysis scheme for static temperature rise in AIS.

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