

## AUTOMATIC GENERATION OF A THERMAL NETWORK MODEL FOR A MV GIS

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### ABSTRACT

The thermal network method (TNM) is widely used for temperature rise computations due to its short computation time. This paper describes a method for automatically generating a thermal network (TN) for a circuit breaker compartment of a medium voltage gas insulated switchgear (MV GIS). The convective and conduction heat transfer are calculated with numerical methods. The resulting TN is intended to mimic complex 3d-models and is verified with a finite element (FE) model and the computational fluid dynamics (CFD) results.

### INTRODUCTION

A method to compute the temperature rise is required during the development of switchgear in order to reduce the number of design tests and to fulfill the demands of IEC 62271. The method has to be sufficiently accurate and to be applicable with limited user effort. It should enable the user to calculate the temperature rise for different cases within short computation time. In MV GIS using SF<sub>6</sub> the temperature rise considerably depends on the convective heat transfer. The resulting heat transfer coefficients (HTC) significantly depend on the flow characteristics of the device. Thermal modeling hence requires knowledge of those coefficients from either experiments or flow computations. As experiments require prototypes and, therefore, slow down the design process, flow computations using computational fluid dynamics (CFD) are to be preferred. Due to the relatively high computation time of CFD models it is impossible to perform many computations of varying cases. Hence, the heat transfer results have to be converted into a less time consuming modeling approach to perform parameter studies. The TNM is suitable as it allows calculations within seconds [1,2] and the TN can be generated automatically by a method presented in this work, which considerably reduces the user effort and faults.

### COMPUTATION

The circuit breaker compartment in a MV GIS (see Figure 1) is considered for automatic generation of a TN. It consists of several individual parts like conductors, bushings, insulators and circuit breakers for each of the three phases and the capsule. The modelling of that configuration in a TN involves significant effort, so the automatic model generation (AMG) is beneficial. The resulting TN can be combined with other ones to form a complete MV GIS. The flow in the given compartment can be computed with a model consisting of five million

elements. Hence, a workstation computer suffices.

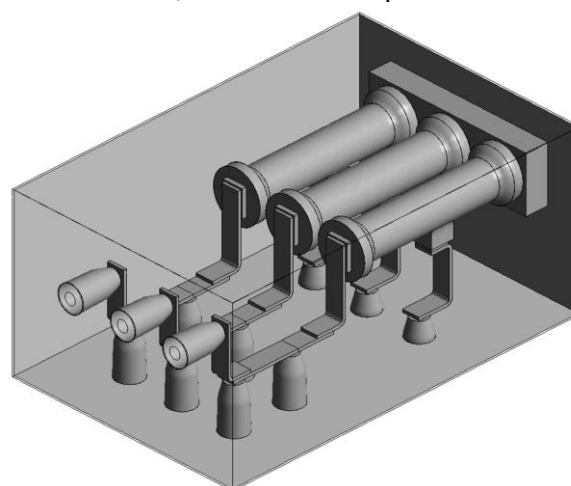


Figure 1: Circuit breaker compartment of MV GIS

The computation of the flow and of an exemplary temperature distribution is performed using a CFD model. The results provide a basis for parameterizing the TN (see Figure 2).

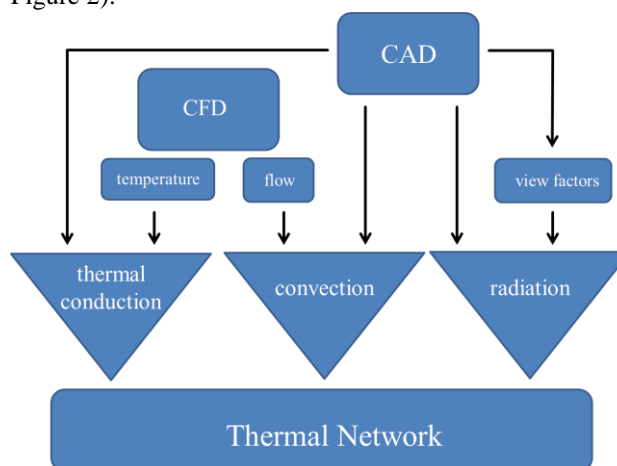


Figure 2: Scheme of AMG

### CFD computation

The convective heat transfer coefficient  $\alpha_{conv}$  is a function of gas density, surface and gas temperature. Since the exact temperature distribution will only be calculated with the TN, a sufficiently general equation for the HTC is required. With similarity functions it is expressed as Nusselt number  $Nu$ , which is a function of the Rayleigh number  $Ra$  [3]:

$$\alpha_{conv} = \lambda(\vartheta) \cdot Nu(Ra) / l_w = \lambda(\vartheta) \cdot c_1 \cdot Ra(\vartheta, p)^n / l_w. \quad (1)$$

The Rayleigh number for a given geometry is a function of

the gas density and its temperature:

$$Ra(\varrho, p) = l_w^3 \cdot \Delta T \cdot \rho^2(\varrho, p) \cdot \beta(\varrho) \cdot g / (\lambda(\varrho) \cdot \eta(\varrho)). \quad (2)$$

$l_w$  is the characteristic length and equal to the buoyancy height of the geometry:

$$l_w = \max(z) - \min(z), \quad (3)$$

with  $z$  being the coordinate direction of the gravity  $g$ . The impact of the geometry on the HTC is expressed with the parameters  $c_1$  and  $n_1$ . These parameters are valid for a wide range of temperatures and gas densities. They are required to model the convective heat transfer in a power device and result from the flow computation.

The exact geometry of the circuit breaker compartment cannot be modelled in CFD, because the multitude of small shape features like round busbar edges or the exact shape of the circuit breaker interfere with an efficient grid generation. A low quality grid or a high number of volume elements would be the consequence which may lead to slow convergence and impairs the computation results. An exaggerated element number will make the calculation too time consuming and memory intensive. Therefore, the best accuracy is achieved with a sound compromise in geometry complexity.

The fluid domain consists of sulfur hexafluoride ( $SF_6$ ) with a filling pressure of 1.2 bar. It is modeled as an ideal gas, so the variation of density with temperature is accounted for. The difference between the used ideal gas law on the one hand and the van der Waals equation [4] on the other is for  $SF_6$  at the given pressure and temperatures sufficiently small and can be neglected. The gas properties, namely its specific heat capacity at constant pressure  $c_p$ , its thermal conductivity  $\lambda$  and its dynamic viscosity  $\eta$  are modeled temperature-dependently [5]. The turbulence of the flow is modeled with the shear stress transport turbulence model [6]. The temperature rise of the conductors is caused by injected heat that mimics the ohmic losses.

### Derivation of TN

During the AMG a TN is created that computes similar temperature rise as the CFD model does in a fractional amount of time. It is based on the geometry and on the results of the CFD computation. The AMG hardly requires user effort if it is implemented into a software tool. The output of the software tool could be a netlist [7] that can be loaded in e. g. a PSPICE solver to compute the resulting temperature rise. In order to set up the TN, its structure and the parameters to describe its elements have to be derived. The structure has to cope with heat conduction, convection and radiation. The model consists of a multitude of nodes. Each node has a temperature and connections to other nodes via conduction, convection or radiation.

### Conduction

To mimic the heat conduction, the connections between the nodes and the respective value of heat conductance have to

be determined. Each surface of the geometry model is represented by one node. Two nodes are connected, if their respective surfaces are touching. This can be checked with the bounding box algorithm. If the bounding boxes of two surfaces touch, then the surfaces may touch as well (see Figure 3).

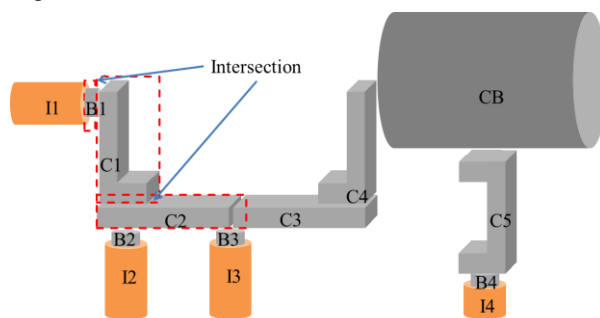


Figure 3: functional principle of bounding box approach for single phase of circuit breaker compartment

The result is an adjacency matrix, which indicates the connections between the nodes. The actual adjacency matrix and the one found with the bounding box approach are compared for a single phase (see Figure 4).

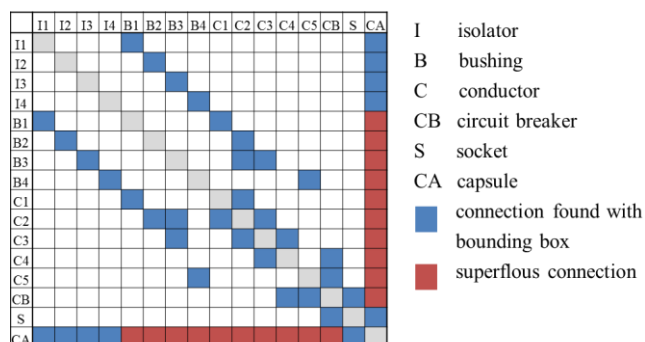


Figure 4: Comparison of adjacency matrices of single phase and found by bounding box approach

The results of the bounding box algorithm are ambiguous, as e. g. the bounding box of a conductor and of the capsule do generally touch, even though there is no direct heat conduction between them. Hence, further criteria are necessary. They are gained from general rules. For instance, there is generally no connection between a conductor and a capsule element, which allows to identify and to suspend superfluous connections from the adjacency matrix.

A model consisting of  $n$  nodes may have the maximum of

$$v_{\max} = n \cdot (n - 1) / 2 \quad (4)$$

heat conducting connections between the nodes. For most cases, the actual number of heat conducting connections  $v$  is considerably smaller than  $v_{\max}$ , so  $v \ll v_{\max}$ . For the given circuit breaker compartment with  $n = 51$  nodes, there are  $v = 81$  connections in all three phases but  $v_{\max} = 1275$  are possible according to equation (4). In order to parameterize the 81 heat conduction elements in the three-phase adjacency matrix, at least 81 equations are necessary. The

system of equations

$$\underline{P}_{th} = \underline{G}_{th} \cdot \underline{\Theta}, \tag{5}$$

which describes the heat conduction with the heat flux vector  $\underline{P}_{th} \in \mathbb{R}^{n \times 1}$ , the thermal conductance matrix  $\underline{G}_{th} \in \mathbb{R}^{n \times n}$  and the temperature rise vector  $\underline{\Theta} \in \mathbb{R}^{n \times 1}$  consists of  $n = 51$  equations. Additional  $\nu = 81$  equations are derived from guessed values for the heat conductance along each connection. The guessed values are based on the geometry and the thermal conductivity  $\lambda$ :

$$G_{th,i,j} = \lambda_{i,j} \cdot A_{i,j} / l_{i,j}. \tag{6}$$

The distance  $l_{i,j}$  between the nodes that represent the surfaces is guessed using the mean coordinates of the surfaces. The cross section  $A_{i,j}$  is guessed from the volume  $V_{i,j}$  and the distance  $l_{i,j}$ :

$$A_{i,j} = V_{i,j} / l_{i,j}. \tag{7}$$

The guessed thermal conductance values (see Figure 5) are close to reality if a sufficient number of nodes are used to represent the geometry.

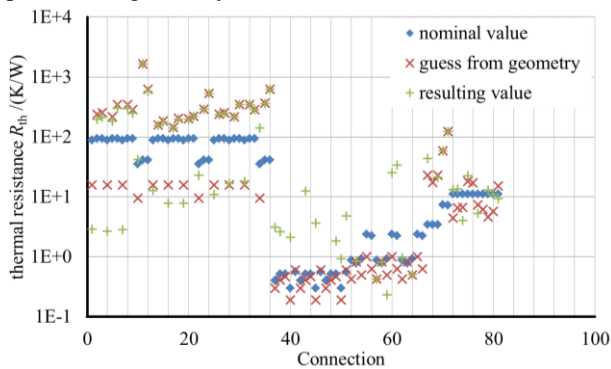


Figure 5: comparison of thermal resistances of conduction (nominal values, guessed value based on geometry and resulting values)

The deviance between the guessed and therefore also the resulting thermal resistances if compared to the nominal values exceeds one order of magnitude in several cases. Even though, the resulting temperature distribution is the only significant measure for accuracy, it can be assumed that the number of  $n = 51$  nodes is not enough to entirely represent the heat conduction for the given geometry.

### Convection

The convective heat transfer is described with equation (1). For the convection heat transfer element the surface area  $A$ , the characteristic length  $l_w$  and the parameters  $c_1$  and  $n_1$  have to be specified.  $A$  and  $l_w$  can be determined from the geometry automatically. The parameter  $n_1$  depends on the flow regime. Laminar flow is described with

$$n_{1,lam} = 1/4 \tag{8}$$

and turbulent flow with

$$n_{1,tur} = 1/3 [3]. \tag{9}$$

The turbulence of the flow increases with  $Ra$ . From the

critical Rayleigh number

$$Ra_{crit} = 10^9 \tag{10}$$

the flow is considered to be turbulent. The remaining parameter  $c_1$  is determined from the results of the flow computation:

$$c_1 = Nu_{comp} \cdot Ra_{comp}^{-n_1}. \tag{11}$$

The parameters and the geometry data specify the convection elements for the TN. In order to place the elements, the surfaces have to be distinguished into the ones that transport heat to or from the encapsulated gas and the ones that transfer heat to the environment. The latter are connected to the node that represents the environment temperature while the former are connected to the node that represents the mean insulating gas temperature.

### Radiation

The radiation heat transfer among the surfaces and to the environment is described with the Stefan-Boltzmann law and the view factors [8]. View factors are specified for each connection between the surfaces. The total number of connections between  $n$  surfaces is computed with equation (4). For each connection an element has to be placed. It is parameterized with its respective view factor, its surface area and its surface emissivity. The determination of the view factors is not addressed here.

### VERIFICATION

The generated TN is verified in two steps, in order to test the transformation to the heat conduction network and flow-describing convection network separately. An additional temperature computation using a finite element (FE) model is performed for this purpose. The FE model is based on exactly the same geometry as the CFD model. In contrast, the gas temperature is assumed to be uniform, which is equivalent to the generated TN. Radiation is integrated into the FE model and the TN (see Figure 6). The power losses in the conductors, the bushings, the circuit breakers and the capsule due to eddy currents are the same in the FE model and in the TN. The comparison of the resulting temperature distributions computed with each model indicates the accuracy of the heat conduction network (see Figure 7).

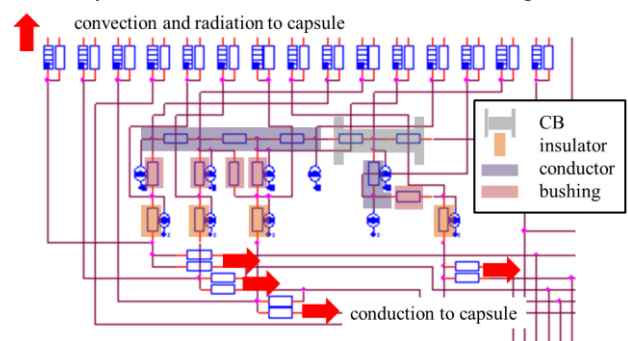


Figure 6: TN of circuit breaker compartment (single phase)

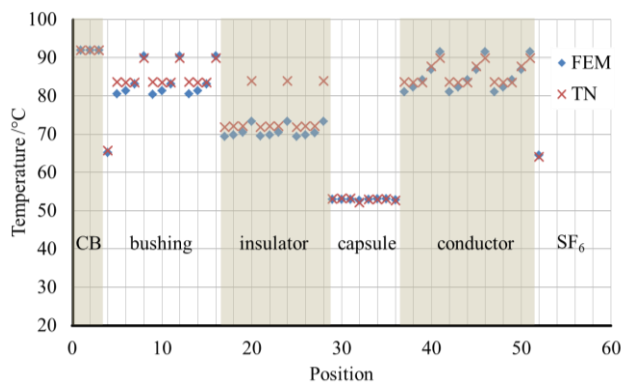


Figure 7: Comparison of temperature computed with FE-model and with TN

The difference between the computed temperatures of the FE-model and the TN only exceeds 2 K for one insulator of each phase. This performance can be still improved by increasing the number of nodes in the TN. To verify the convection network that only considers a mean gas temperature, another generated TN is compared to the CFD model, which actually considers the flow and the temperature distribution within the gas (see Figure 8). The same heat conduction elements as in the first TN are applied, but radiation is neglected in both, the CFD model and the TN, in order to verify only the convection heat transfer. The parameters  $c_1$  and  $n_1$  are adjusted according to the computations with the CFD model.

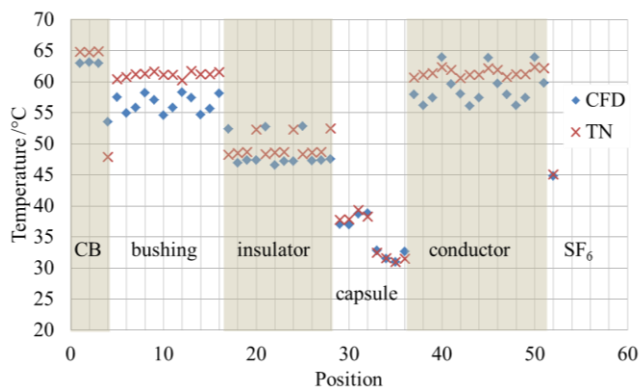


Figure 8: Comparison of temperature computed with CFD-model and with TN

The temperatures of the insulators computed with the TN deviate from the CFD model. The insulators have a low thermal conductance and therefore, their temperature is only slightly coupled to the conductors or the capsule. Hence, they tend to adopt the local gas temperature, which is different from the mean gas temperature in the vicinity of some insulators. The mean conductor temperatures are reproduced by the TN, but the temperature distribution is not resolved. An increased number of nodes does improve this performance.

## CONCLUSIONS

A method for deriving thermal networks of gas insulated switchgear from CFD simulation data and CAD geometry data is presented for the example of a circuit breaker compartment of a MV GIS. The method can be automated and hence allows straight forward thermal computations with significantly reduced user effort and minimal user faults. The heat conduction network is determined from the geometry data and the computed temperature distribution. The intensity of the convective heat transfer is computed with a single CFD simulation. The similarity functions are necessary to use the convection results for arbitrary temperature distributions and variant filling pressures. The resulting TN has been evaluated for heat conduction and convection separately. The computation of the temperature rise of a real component nevertheless requires the view factors and exact modelling of power losses, which are not the scope of the given work. The performance of the AMG is promising, but it needs to be improved further in order to describe the thermal behaviour of arbitrary switchgear components properly. An increased number of nodes can improve the accuracy of the determined heat conductance elements and of the computed temperature distribution.

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