DYNAMIC THERMAL SIMULATION OF GAS INSULATED SWITCHGEAR

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ABSTRACT

This paper presents experiences with the dynamic thermal network analysis in the design and development of MV GIS. A dynamic thermal network model was created for a four-panel GIS switchboard. The same switchboard was realized as physical test object for a temperature rise test. The simulation model was used to calculate the dynamic behaviour of the switchboard based on step functions. By variation of the steepness, the sensitivity of the dynamic model was proven. In addition a typical load curve of European urban networks was simulated. These simulation results are compared to the effective measurements. Taking a GIS, a simulation is done with deviations as low as 3 Kelvin.

INTRODUCTION

The utilization of the Thermal Network Method (TNM) [1] as presented in [2] has been given a major impact for the efficient development of MV GIS. Beside the speed-up of the development process and the reduction of expensive and time consuming temperature rise tests, new features were developed.

TNM emulates heat transfer processes analogously to an electrical network, where heat flow and temperature correspond to current flow and voltage, respectively. Thermal conduction, radiation and convection are represented by thermal resistors and capacitors, if time dependent effects are to be considered (Table 1, Fig. 1). Circuit simulation software packages like PSPICE can be used to build up and solve the network. A thermal library is available providing the needed circuit elements and the corresponding thermal models for, e.g., loss power, thermal conduction, convective heat transfer, radiation, and more.

Given the structural approach of the static calculation of complex GIS panels and complete switchboards, the dynamic behaviour of the equipment was moving into the focus of the further development of the TNM tool. Utilizing the proven and qualified static models of GIS panels, those models where extended by the thermal capacitances of the individual parts. This extension allows the time-dependent (dynamic) simulation of the temperature rise of a MV GIS panel, only depending on the electrical current and the surrounding temperature.

Table 1: Analogy between electrical and thermal properties

Thermal Property		Electrical Property	
Temperature Difference	ΔT	Potential Difference	ΔU
Heat Flow	P	Charge Flow / Current	I
Thermal Resistance	R_{th}	Electrical Resistance	R_{el}
Thermal Capacitance	C_{th}	Electrical Capacitance	C_{el}

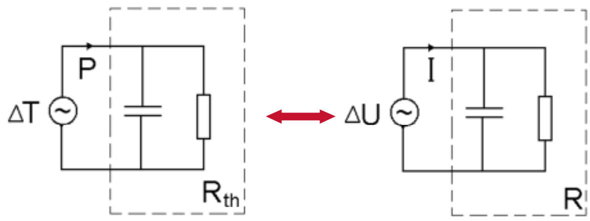

Fig. 1: Equivalence of thermal and electrical circuits

DYNAMIC THERMAL NETWORK METHOD

The heat sources of a switchgear device are the temperature dependent ohmic losses of current carrying conductors, contacts, and connections. Heat is conducted along the current path and dissipated to the gas and enclosure through convection and radiation. The heated enclosure is cooled down through convection and radiation to the ambient. Using TNM, the power loss of a conductor is calculated by its geometrical dimensions and material properties. Heat dissipations via radiation and convection are described by thermal resistances, which are calculated based on the surface areas, emissivity numbers and the installation conditions. An iterative solver is necessary due to the dependency of the conductor resistivity, and radiation coefficient on the temperature itself. Fig. 2 shows an example of a thermal network model for two pieces of conductors connected by a screw joint within a cubical, as a rudiment illustration of a switchgear model.

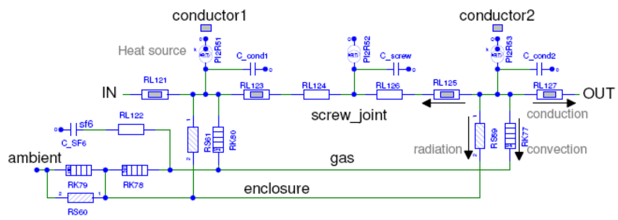

Fig. 2: Thermal network model for two connected conductors inside an enclosure with thermal capacitances

Contacts and connections are critical points for a temperature rise test. On the one hand, the temperature limit is lower for the contacts than that for the conductors. On the other hand, heat generated by the contact resistances could only be dissipated through conduction. This makes the contacts hot spots in the electric current path. Having a good estimation for the contact resistance at these spots is very important for a successful simulation. This requires a proper discretization of the conductor in order to resolve the temperature distribution. Normally the granularity should be

commensurate to the dimension of the cross section.
For all parts of the networks linked to thermal conduction, a thermal capacitance has to be introduced.

$$C = \frac{\Delta Q}{\Delta \vartheta} \quad (1)$$

The specific capacitance is mass-dependent:

$$c = m\frac{\Delta Q}{\Delta \vartheta} \quad (2)$$

Between isochoric ($\Delta V=0$) and isobaric ($\Delta p=0$) changes, the following relation is valid:

$$C_p - C_V = \vartheta \cdot V \frac{\alpha^2}{\kappa_\vartheta} \quad (3)$$

whereas α as the thermal expansion coefficient is defined:

$$\alpha = \frac{1}{V}\left(\frac{\partial V}{\partial \vartheta}\right)_p \quad (4)$$

and κ_T describes the isothermal compression:

$$\kappa_\vartheta = -\frac{1}{V}\left(\frac{\partial V}{\partial p}\right)_\vartheta \quad (5)$$

For ideal gases the correlation is described with:

$$C_p = C_V + N\kappa_B = C_V + nR \quad (6)$$

with κ_B as Boltzmann constant and R as the universal gas constant.
The specific thermal capacitance can be determined with a calorimeter or with a DSC (differential scanning calorimeter). For the measured temperature range, the material will not run through a phase change. Using DSC, the measurement should be done in comparison with sapphire. To increase accuracy the DSC oven should be cooled down to a steady state by a liquid cooling system and afterwards the sample should be heated with a low rate against the cooler.

DYNAMIC GIS MODEL

Fig. 3: Side view of a GIS type GHA Double Busbar

The dynamic TNM was applied to a GIS of type GHA (Fig. 3). The physical structure was translated into a hierarchical approach, reusing components and compartment structures for complete switchboards. The used hierarchical approach is defined in Fig. 4 - practical showcases are described in [2]. The switchgear will be discretized into its major compartments: busbar, circuit breaker (CB), cable compartment. Each compartment again will be broken down into it parts, whereas one-phase parts and 3-phase parts can be used. The description of the individual part will be done with the elements of the TNM-software, describing the physical properties and the geometrical dimensions of the individual part. Complex questions like the thermal flow of gases will be solved with CFD. Validated CFD-models will be than used for a parameter study to generate a new element for the TNM.

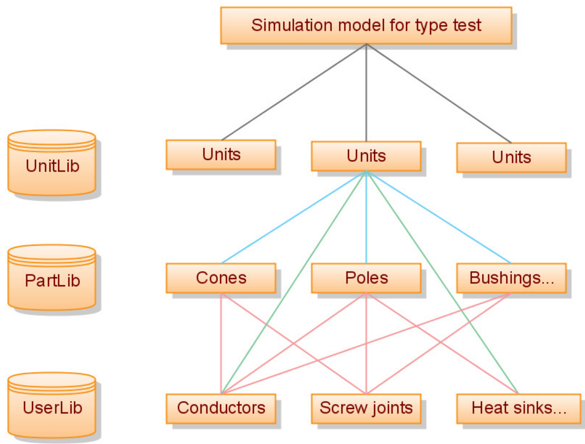

Fig. 4: Structural approach of on hierarchical TNM

VALIDATION OF THE DYNAMIC MODEL

To validate the model, switchgear of 4 panels was built up. This switchgear combined an incomer and 3 feeders. A group of high current transformers were connected in such a way, that the feeder to be investigated and the busbar were always on 100% of their rated load current. The injection of the current was realized via the incomers and the other feeders. This setup was guaranteeing that also neighbouring feeder panels where always charged with a load current.
The validation of the model was done twofold: a Load-Step-Test and a Switch-on/off-Sequence.

Load-Step-Test

The load current was increased in discrete steps until the maximum load current was reached. The time between the steps was defined by the dynamic response of the test object. Reaching a steady state for the temperature was the pre-requisite to increase the load current. Fig. 5 shows the results of this test. For reasons of comparison the load current was related to the maximum load current. The temperatures were measured with 134 thermocouples. Here the temperature difference ($\Delta\vartheta$) between the ambient and the middle phase of the CB and the centre of the rear wall of the CB-tank were taken as a reference. These measured $\Delta\vartheta$ were related to the maximum allowed over-temperature.

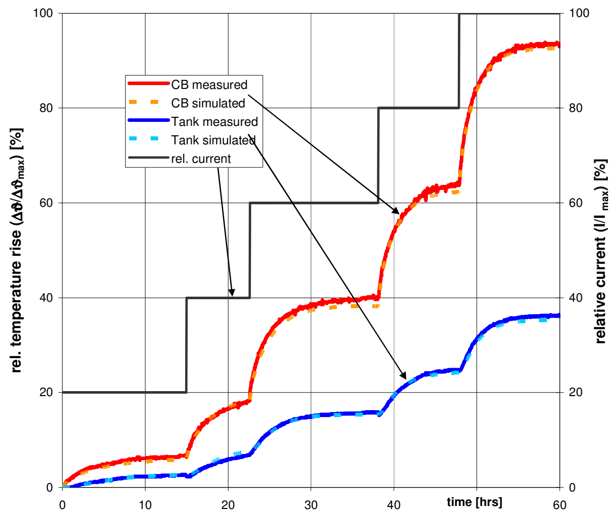

Fig. 5: Temperature values of measurements and dynamic TNM simulation for stepwise increased load current

To evaluate the accuracy of the model, the absolute deviation between measured and simulated results were derived and shown in Fig. 6. The visual good conformity of simulation and measurement could be approved; the deviation is always less than 2 K.

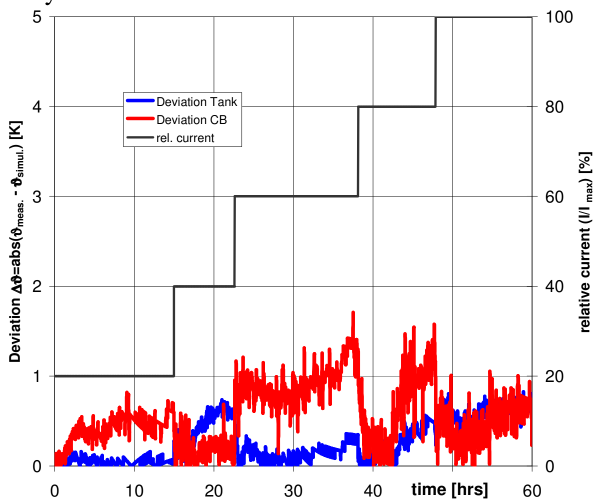

Fig. 6: Temperature deviation between measurement and simulation for stepwise increased load current

Switch-On/Off-Sequence

To evaluate the dynamic behaviour before reaching the steady state, and to see the reaction towards an overload current, a Switch-On/Off-Sequence was done. The current applied during the ON-cycle was at 110% of the maximum load current during 3,3 hours. During this time 90% of the maximum allowed over-temperature was reached. This result gives a clear input about the overload capability of this specific GIS. Also here the obvious good agreement between measurement and simulation was proven with absolute deviation (Fig. 8). The maximum deviation was 3,3 K for a singular event, the average deviation is around 1 K.

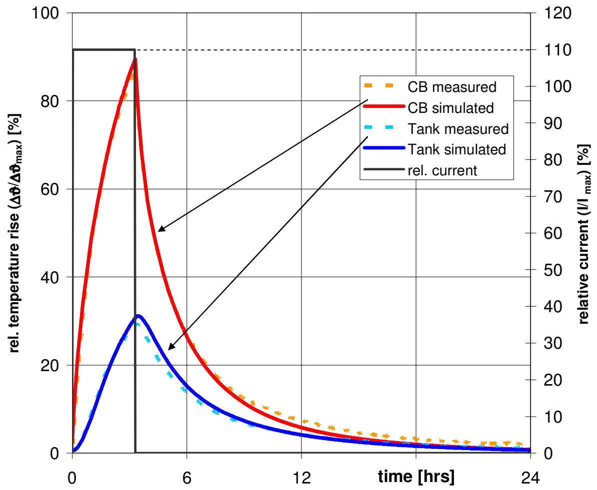

Fig. 7: Dynamic thermal behaviour for Temperature deviation between measurement and simulation for On/Off sequence

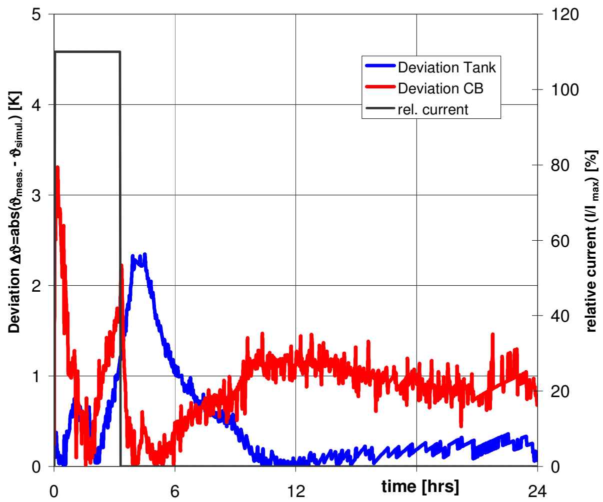

Fig. 8: Temperature deviation between measurement and simulation for switch on/off sequence

Statistical Analysis

Based on the known behaviour of network solver used for the dynamic TNM like PSPICE, it was assumed that simulation errors in the time domain are following a statistical normal distribution. The reference parameters like minimum maximum and mean value, as well as the standard deviation where calculated (Table 2) for the following populations: Step Function (n=1801) and On/Off-Sequence (n=720).
Taking in consideration that the used thermocouples have an intrinsic uncertainty of measurement of 0.5 K, the maximum deviation for a single value is calculated to 3.3 K. This is an outstanding result for the dynamic mode. The mean value is below 1 K for all four measurements.

Nevertheless it has to be stated that the transient behaviour of the simulation model is sensitive to the rise time of the current. Very steep changes will induce a higher deviation of the simulation from the measurement. As the time step for the measurement is chosen in such a way that a dynamic effect to the measurement is excluded, the deviation will come from the simulation. A potential reason for this sensitivity it can be presumed, that the temperature dependent similarity functions used in the TNM will cause the additional dynamic of the simulation result in the time domain. Comparing the results of Tank and CB, the functions for convection and radiation seems to be more insensitive than thermal sources and thermal conduction.

Table 2: Statistical analysis of the deviation of measured and simulated results

Statistical Values	Step Function		On / Off	
	Tank	CB	Tank	CB
Minimum Value $\Delta\vartheta_{min}$ [K]	$6{\cdot}10^{-5}$	$2{\cdot}10^{-4}$	$3{\cdot}10^{-3}$	$2{\cdot}10^{-3}$
Maximum Value $\Delta\vartheta_{max}$ [K]	0,8	1,7	2,3	3,3
Mean Value $\overline{\Delta\vartheta}$[K]	0,27	0,57	0,45	0,9
Standard Deviation $\sigma_{\overline{\Delta\vartheta}}$	0,23	0,34	0,54	0,43

For thermal losses of conductors it can be stated [3]:

$$P_{loss}(t) = k \cdot \frac{dI^2}{dt} R(\vartheta) \qquad (7)$$

With k as current displacement factor and

$$R(\vartheta) = \frac{\theta_{20} \cdot \ell}{A}\left[1 + \alpha_T R(\vartheta - 20°C)\right] \; ; \; \alpha_T = f(\vartheta) \qquad (8)$$

The thermal conduction is described by [3]:

$$P_{cond} = -\lambda A \, grad\vartheta \qquad (9)$$

In case of a transient heat density

$$q = \frac{dP_{cond}}{dA} \qquad (9)$$

the heat quantity will change per volume unit:

$$Q(t, V) = c\rho \frac{d\vartheta}{dt} \qquad (10)$$

with c as the specific capacitance and the density ρ.

SIMULATION OF A TYPICAL LOAD CURVE FOR AN URBAN ENVIRONMENT

Utilizing the same test object as for the validation process described above, a typical load curve for a European urban environment was tested and simulated (Fig. 9). During a 12-hours period a base load for a steady state temperature was applied, followed by the dynamic test current. During the demand peak hours an overload of 110% of the rated load current was used. Also here a very good correlation between measurement and simulation was achieved. These results show that the applied model can be utilized not only for the design of GIS, and also for the prediction of the overload capability of the switchgear. The specific GIS have also shown a significant overload capability, as a 110% overload led to 85% coverage of the maximum allowed temperature rise.

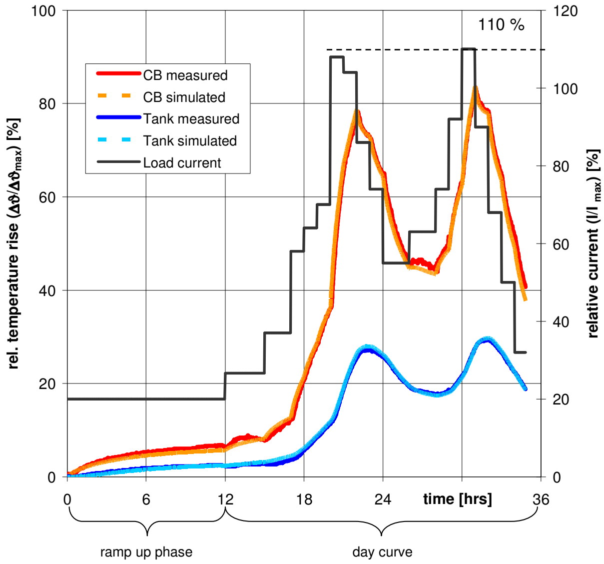

Fig. 9: Comparison of measurement and dynamic TNM simulation for a typical load curve (urban environment)

CONCLUSION

The approach of the Thermal Network Method was extended from the thermal steady state situation of complex structures to the transient thermal simulation. Also here a structural approach for the architecture of the thermal network was used. To implement the time dependency, thermal capacitances have been implemented into the model.

The model was validated with measurements on a typical switchboard with incomer and feeders. In a first reference trial the rated load current was applied stepwise. In a second trial, a higher dynamic of the transient behaviour was achieved with an On/Off-sequence and a 110% overload. Both tests showed an encouraging good correlation between measurement and simulation. Based on a statistical evaluation a dependency of the simulation error on the dynamic was found. This dynamic is mainly focussing on heat sources and thermal conductance, as here the time and temperature dependencies play a major role. Convection and radiation for the interesting temperature range are fairly good described with the uses similarity function.

The dynamic model was demonstrated with a typical urban load curve. Also here a good agreement between measurement and simulation was found. The model was also proven for the prediction of the overload capability of GIS.

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