# Modeling and Simulation of Generator Circuit Breaker Performance

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## Abstract

The authors describe a performance-evaluation tool for Generator Circuit Breakers (GCB) that assists in the process of selecting the right model and specifications from a number of customer requirements. The tool is based on a thermal-network library implemented in Modelica. A wrapper application based on Excel and .NET technology serves as user interface and driving application for the necessary simulations.

## 1 Introduction

Various methods are in use in order to map customer requirements to the performance of a selection of available products. Generator circuit breakers (GCB), i.e. circuit breakers installed between the generator and the step-up transformer, are available with rated power up 2000 MVA and must be able to switch short-circuit currents up to 200 kA.

The GCB types modeled here are 3-phase systems containing a circuit breaker and a disconnector (in series) in single phase enclosures (confer Fig. 1). Optionally the system can be equipped with auxiliary switches (earthing switches and switches to start up gas turbines), surge arrestors, voltage and current transformers (all integrated in the enclosure).

In order to find the proper current carrying capability of a specific type of GCB, particular conditions found at the customer's site have to be considered: ambient temperature, solar irradiation, temperatures of connecting parts, and special equipment (like e.g. current transformers) installed in the GCB are typical examples of such conditions. The maximum rated current of a GCB under certain operating conditions derives from the requirement that a certain limit for the temperature increase at the contacts should not be exceeded. For a GCB the maximum allowable temperature is $T_{max}$ = 105°C at silver-coated contacts and $T_{max}$ = 70°C at enclosure parts which could be touched by an operator [1]. This ensures a high degree of reliability and a long service life since a deterioration of the materials involved is thus excluded.

Often, detailed studies (i.e. CFD or thermo-electric PDE simulations) for mapping requirements are time-consuming and find their place rather in the product-development cycle than in the sales phase.

The presented tool supporting the sales process of GCBs had to be able to produce fast and reliable results, be simple to use by non-expert personnel and still keep the necessary modularity and maintainability in order to allow for systematic refinements of the underlying model. The tools and methods chosen were therefore a thermal-network model formulated in Modelica, wrapped in an Excel-based application.

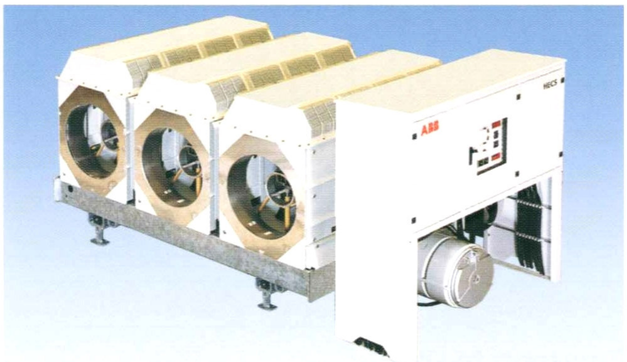

**Fig. 1: Generator Ciruit Breaker System**

## 2 Thermal-network library

A Modelica library of thermal-network elements with detailed implementations of various aspects of heat-transfer physics (conduction, radiation, forced and free convection at various pressures and for a number of materials) serves as reusable base of the model. A set of full models to be used for standard performance evaluations of a complete family of GCBs represent the available product range.

The library is fully self-contained. While its basic parts are modeled along the philosophy of the Heat Transfer Library shipped with Modelica 2.2, it adds a substantial number of standardized, reusable components modeling the heat transfer for objects of the size of some centimeters to meters.

### 2.1 Heat sources

Main heat sources in the GCB are "Ohmic" resistors, which transform a current flow (typically between 5 and 20 kA) into heat through Joule heating. First-order nonlinearity ($\alpha$) in temperature describes the dependence of the electrical resistance $R$ for the temperature-range of interest (from ambient to about 105°C) sufficiently well:

$$R = kR_0(1+\alpha(T-T_0))$$

The effective resistance of the current-carrying parts considers an effective increase through the (frequency-dependent) skin effect ($k$). For simple conductor geometries like rods or hollow cylinders $k$ can be determined analytically. For more complex geometries (like conductor parts with attached cooling fins or the rectangular enclosure of the individual GCB poles) $k$ was calculated with the help of FE models. For the GCB types modeled here typical values for $k$ are in the range of 1.1 to 1.3 for frequencies between50 and 60 Hz (the GCBs are used for 50 and 60 Hz).

Besides ohmic losses only constant heat sources are used in the model to take account of solar irradiation (in case of an outdoor installation of the GCB) as well as of losses of components like current transformers which are installed in the GCB.

### 2.2 Heat transfer

Heat flow by conduction is implemented for a variety of shapes and geometries. Mostly, flat geometries and surfaces are modeled; size and thickness of the parts determine their total heat-conduction properties. In the simplest case of a plate or rod (thickness $d$, cross section $A$ and thermal conductivity $\lambda$) the effective thermal resistance is then given by:

$$R_{cond} = \frac{d}{\lambda A}$$

Radiation resistances model radiation-based heat transport between two plates of unequal size and unequal emissivity (gray-factor). The effective radiation resistance can be parameterized as

$$R_{rad} = \frac{1}{\alpha_r A_1} \text{ with}$$

$$\alpha_r = \varepsilon_{12} C_S \frac{T_2^4 - T_1^4}{T_2 - T_1}$$

$C_S$ is the Stefan-Boltzmann constant. For $A_1 < A_2$ $\varepsilon_{12}$ is given by the emissivities and areas of the plates by:

$$\varepsilon_{12} = \left(\frac{1}{\varepsilon_1} + \frac{A_1}{A_2}\left(\frac{1}{\varepsilon_2} - 1\right)\right)^{-1}$$

Convection is implemented for air, insulating gases, and again a number of shapes and flow patterns according to effective models of fluid dynamics. The convection elements cover free and forced convection, and they require typically only experimentally available or tabulated values for parameters such as, kinematic viscosity or heat conduction $\lambda$ (all as functions of temperature and pressure).

The effective resistance for free convection is modeled as:

$$R_{conv} = \frac{1}{\alpha_c A_c} \text{ with}$$

$$\alpha_c = \frac{\lambda}{l_w} c_1 (Gr\,\mathrm{Pr})^{n_1}$$

The geometry of the flow pattern is taken into account by effective length-scales ($l_W$) of the element-shapes. Basically, the same formula holds also for the case of forced convection: Besides an appropriate choice of the parameters $c_1$ and $n_1$ the product of Grashof and Prandl numbers in the above formula has to be replaced by the Reynolds number. The model parameters $c_1$ and $n_1$ were taken from literature with the exception of special configurations like tilted heat fin arrangements. For such configurations $c_1$ and $n_1$ have been determined experimentally.

The library is programmed in a hierarchical way and consists of several levels of partial classes in order to allow for a consistent treatment of phenomenological constants and systematic extension and specialization. All elements extend base classes with icons and descriptive text.

## 3 Full Models

In the stationary state the highest temperatures in a GCB are reached at the center phase of the 3-phase system since for this phase heat transfer from the enclosure via radiation is impeded by the two neighboring phases. The side walls of the center phase are facing walls with almost identical temperature (from the two outer phases) and radiation heat transfer is negligible for these parts. Thus it is sufficient to model the center phase alone, taking into account appropriate boundary conditions for the enclosure.

The model of the full circuit breaker (central phase) is composed of two to three levels of sub-elements. The variability between the individual types within the family of GCBs has been implemented fully on a parameter level. This leads to the clear advantage of keeping the topology of the full model unchanged while allowing simulations for the whole product range by simply changing some input parameters at simulation time.

Basically, all model classes extend a (unevaluated) parameter-class. Those parameters that differ from model to model are stored in arrays, selecting the model index leads to a full propagation of all parameters to the individual sub-models. As the wrapper application will only set parameters and initial values via the dsin.txt file governing each simulation, parameters must all be evaluated at run-time only.

The topology of the thermal network representing the GCB is based on earlier work and new experience. It has been unified and newly arranged making use of the practice of avoiding redundancy and inconsistency through a systematic identification of similarities and structural components. Still, a physical picture of the GCB was kept in order to make the model not too abstract and in consequence too hard to maintain.

As an example Fig. 2 shows the breaking chamber of a GCB. It consists of two metallic castings (including the connection zones to neighboring system components) the insulator (white) and the contact system (invisible underneath the insulator). Each component (castings, insulator, and contact zone) is modeled as sub-element of the breaking chamber in which GCB-type specific features like the cooling fins are controlled by parameters.

The main structure of sub-elements on the lowest hierarchy level of the model is shown in Fig. 3 representing a section of the main conductor. The structure contains a heat source (P_TR) which obtains the current flowing in the conductor via the electrical pins p and n, thermal conduction resistances whose "outer" heat ports are connected on the next hierarchy level to the neighboring sections, a convection (Rconv), and a radiation resistance (Rrad). The latter elements transfer heat to the air surrounding the section and to the enclosure, respectively (via the corresponding heat ports of the sub-element).

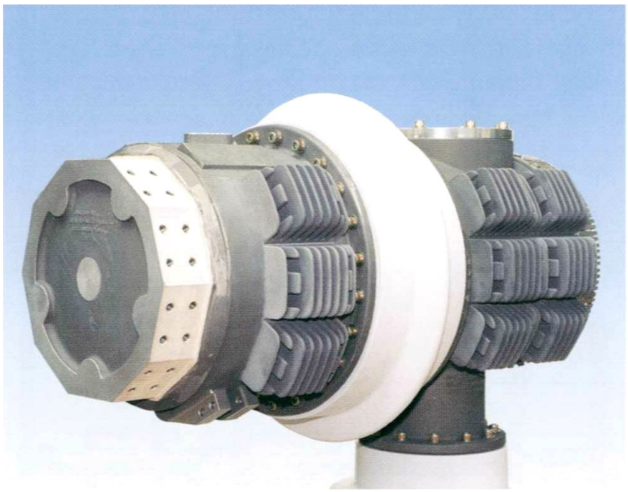

**Fig. 2: Breaking chamber of a GCB. The type shown is equipped with cooling fins to enhance the heat transfer to the ambient air.**

A straight forward and simple extension of the model would be to add a heat capacity element to the central node in Fig. 3. This would allow to perform dynamic simulations, e.g. to evaluate the influence of temporary overloads (changing load currents). However, at the present state the model is intended to determine the stationary state only.

The final models consist to a high degree of nonlinear systems of equations. They are almost exclusively algebraic in nature, as the steady-state solution of a model is of main interest.

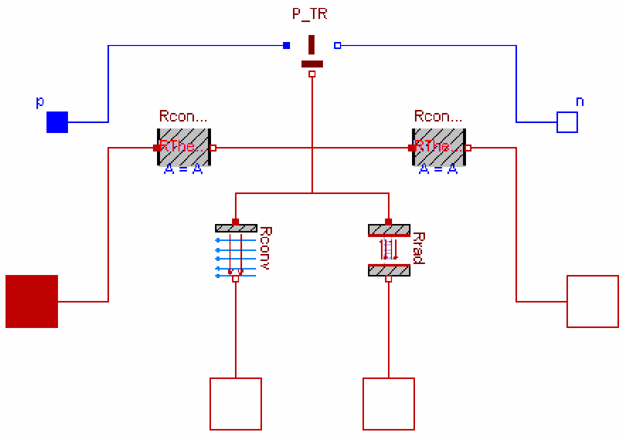


**Fig. 3: Thermal network for a section of the conductor path of a GCB.**

## 4 Wrapper application

Interface libraries developed in MS.NET and VBA form the components of an Excel-based application with a simple top-level user interface. A form for input and triggering simulations is presented to the user (Fig. 4). A number of additional tables and charts are used for presenting the results.

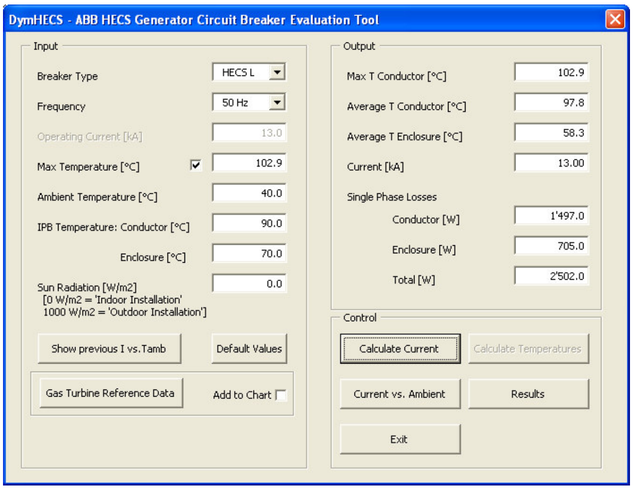


**Fig. 4: Front end of the user-interface. A limited number of parameters and simulation options are presented to the user.**

Fig. 5 shows a component view of the full application and its main task flow. As a result of the modeling, a simulation server (dymosim.exe) is produced and packaged with the application. An interface library (dsacces.dll), implemented in C, serves as proxy between Excel and the simulation server.

While the user defines parameters and nature of a desired evaluation fully in Excel, the definition file (dsin.txt) as well as the results of the simulation run (dsout.txt) are written and read with the use of routines contained in the proxy library. This task flow is completely transparent to the user; the user does not have to interfere with the actual formats and types of input and output of the simulation at all.

A typical evaluation is done within a few seconds. The Excel application is implemented as a template, such that results and used cases can be saved and restored in a natural way.

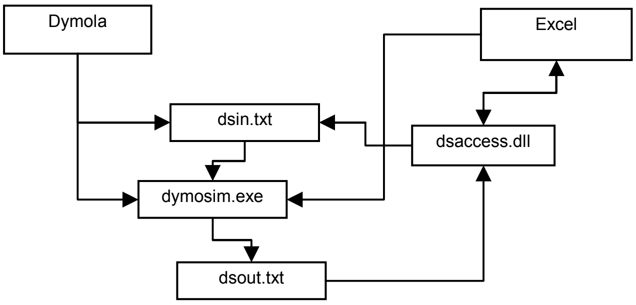


**Fig. 5: Component view of the full application.**

## 5 Results and Conclusions

Fig. 6 shows the cross section of a GCB that was used in a thermal type test at the ABB high current test laboratory. The enclosure of the circuit breaker pole (surrounding rectangular box) is only indicated.

The resulting temperature profile along the axis of the circuit breaker (inner conductor) of the thermal type tests are shown in Fig. 7 as well as the simulation result.

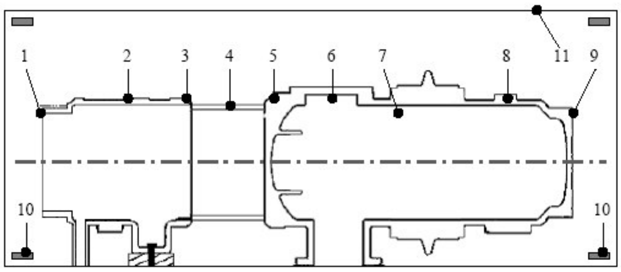


**Fig. 6: Schematic cross section of a GCB. The numbered dots indicate positions of temperature sensors in temperature rise tests.**

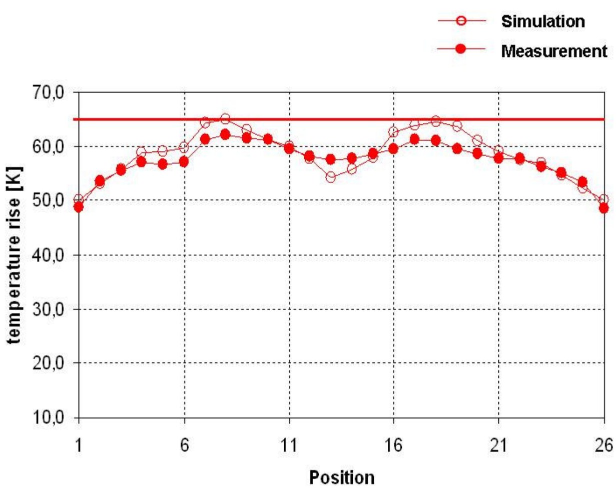


**Fig. 7: Temperature rise above ambient temperature vs. position along the conductor of a GCB. The red line indicates the maximum permissible temperature rise.**

Fig. 7 shows that the calculated temperature distribution agrees very well with the measured temperatures. The maximum deviation is approximately 4 K at a temperature rise of >60 K (7%) at the contact zones. The reason that the model yields conservative results is mainly due to slightly pessimistic values used in the model for the material parameters and the contact resistances. The agreement between measurement and simulation obtained for all other GCB types covered by the thermal network model was also better than 10%.

For benchmarking the results of the simulations to previously used methods, a great number of standard experiments were defined and extensively tested. In particular, the identification of the temperature of hot spots in the GCB under a given current load and the inverse problem, i.e., the identification of a maximum load current while staying below a given acceptable operating temperature were performed. Finally, the whole application (without the modeling environment) was packaged and rolled out, the productive phase started roughly half a year after the project definition.

While the implementation of the necessary proxy library and VBA code presented no major challenges, a particular difficulty of the model refinement was the choice of stable guess-values for the substantial amount non-linear equations. Through a restriction of the empirical parts of certain model classes to physically meaningful value ranges, a sufficient reliability of the initial-value calculation could be achieved.

The authors conclude that a thermal-network based application is an industrially productive solution for a performance-evaluation tool with an underlying model of high complexity and accuracy. The case for such a tool is underpinned by substantial savings on license costs, the use of standard tools requiring no training, and the competitive advantage of a substantially reduced time to offer.

## References

[1] IEEE C37.013-1997: IEEE Standard for AC High-Voltage Generator Circuit Breakers Rated on a Symmetrical Current Basis