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Thermal analysis of typical GIS compartment with Thermal Network Method using ATP-EMTP program

Abstract. *In electric power products development, thermal aspects are becoming very important because they guarantee the correct operation of product. The specified temperature limits cannot be exceeded. Thus, knowledge of temperature behavior is very important factor in order to predict reliability and performance in its working environment. In this paper some bases of Thermal Network Method (TNM) modeling in application to transient rating calculations of typical GIS compartment arrangements are presented. Thermal network composed of heat sources, thermal resistances and capacitances can be easily represented and calculated by means of ATP-EMTP programs (also OrCAD Capture environment).*

Streszczenie. *W dobie rozwoju produktów energii elektrycznej, aspekty cieplne stają się bardzo ważnym czynnikiem, ponieważ w celu zagwarantowania prawidłowego działania urządzeń i aparatów elektrycznych, temperatury nie powinny przekraczać wartości dopuszczalnych. Analiza warunków termicznych jest bardzo ważnym czynnikiem w celu przewidzenia skuteczności i niezawodności w danym środowisku pracy. W poniższym artykule zostały zaprezentowane podstawy modelowania z zastosowaniem metody sieci termicznych – metoda pozwala na wykonywanie obliczeń wartości znamionowych w typowych modułach stacji typu GIS. Sieć termiczna składa się ze źródła ciepła, rezystancji i pojemności termicznej oraz została zaprezentowana i zasymulowana w środowisku ATP-EMTP (a także w programie OrCAD Capture). (**Cieplna analiza typowego modułu stacji GIS metodą sieci cieplnych przy użyciu programu ATP–EMTP**)*

Keywords: Thermal Network Method, thermal parameters, GIS busduct, ATP-EMTP, modeling, simulation.
Słowa kluczowe: Metoda sieci cieplnych, parametry cieplne, szynoprzewód, stacja GIS, ATP-EMTP, modelowanie, symulacja.

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Introduction

Thermal analysis is a very important issue in electrical devices and apparatus design especially for high current ratings. According to the international IEC 62271-203 standard [2], a temperature rise type test has to be performed, in order to make sure that the allowed temperature limits are not exceeded. To optimize the number of needed design tests, it is important to predict the temperature rise with a simulation tool. Different approaches are available to thermal simulation, selection of which is always a matter of balance between the modeling complexity, accuracy, and computational cost [7-8]. Among them, the thermal network method (TNM) [3] has extremely low computational cost at decent accuracy. The basic idea of TNM is to describe a thermal problem by an equivalent circuit network and solve the network. If one uses the OrCAD software a thermal library is available (created and built at ABB [7-8]), that provides the needed circuit element symbols and the corresponding thermal models for, e.g., loss power, thermal conduction, convective heat transfer, radiation, and more. Alternative solution is to use the ATP-EMTP program to simulate the thermal behavior [5] by setting up an equivalent electrical circuit.

This paper addresses on thermal behavior of a typical ELK-3 GIS compartment using OrCAD Capture environment and ATP-EMTP program. Modeling and simulation results were built and compared. These analyses are a fundament for more advanced ATP-EMTP application in Thermal Network Modeling.

Thermal Network Method – general

Thermal Network Method (TNM) utilizes the analogy between electric and thermal field problems (Table 1), where heat flow and temperature correspond to current flow and voltage, respectively. Similar to the Ohms law for electric streaming fields, the following relation results between temperature difference $\Delta\Theta$, thermal resistance R and the transferred thermal output P is presented by formula (1)

Table 1. Thermal-electrical analogies [7]

Quantity	Electrical System	Thermal System
Potential	*U* [V]	*T* [K]
Flow	*I* [A]	*Q* [W]
Resistance	*R* [Ω]	*R* [K/W]
Conductance	1 / *R* [S]	*G* [W/K]
Capacitance	*C* [F]	*C* [J/K]
Ohm's Law	I = E / R	*Q*= T · G

$$\Delta\Theta = P \cdot R \tag{1}$$

where: voltage (U) and current (I) corresponds to temperature (Θ) and heat transfer rate (P), sources in thermal network mean power losses and are equivalent to current sources in electrical circuit [5], [9].

Thermal conduction, radiation and convection are represented by thermal resistors. There are four mechanisms of changing electric energy into heat:

- resistance of conductors,
- magnetic hysteresis of materials in magnetic field,
- eddy currents,
- selected phenomena in dielectric materials.

There are also three ways of heat transfer in electric devices:

- conduction,
- radiation,
- convection.

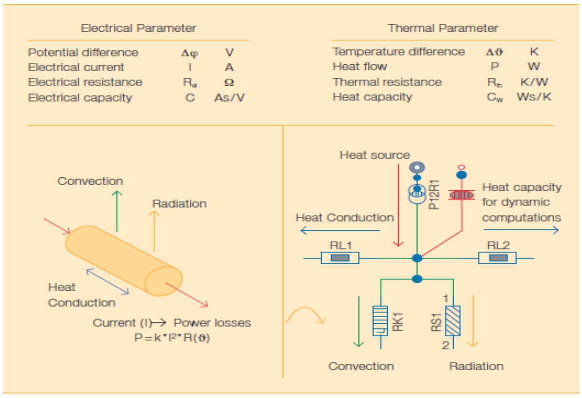

Fig.1. Thermal Network Method (TNM) – analogy between electrical and thermal problem [4]

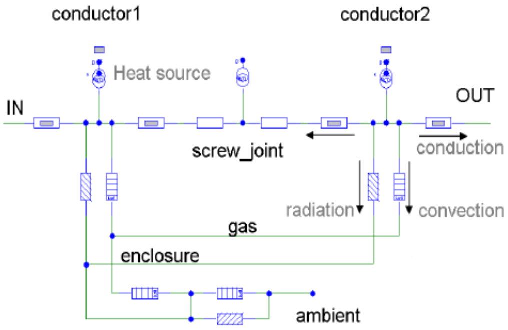

Fig.2. Typical diagram of Thermal Network Model in OrCAD program for two connected conductors inside an enclosure [3]

It is commonly known that differential equations for heat transfer are similar to equations, which describe electric current flow. This fact enables simplification of thermal simulations by using thermal network method. Main aspect of this method is replacement of real geometrical elements and thermal phenomena by electrical elements such as resistors, current sources and capacitances.

The network model for a thermal problem could be created and solved using a circuit simulator. The full set of thermal – electrical systems' analogies is presented in Fig. 1 [4]. 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, the convective heat transfer coefficient and radiation coefficient on the temperature. 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 [3].

GIS busduct – model for analysis

The purpose of this section is to establish the dimensions and technical parameters of GIS busduct elements and coating material that will be used for calculation of thermal behavior of a typical ELK-3 GIS compartment.

The object of these analyses is typical ELK-3 GIS busduct. The simplified GIS busduct for analysis is shown in Fig. 3.

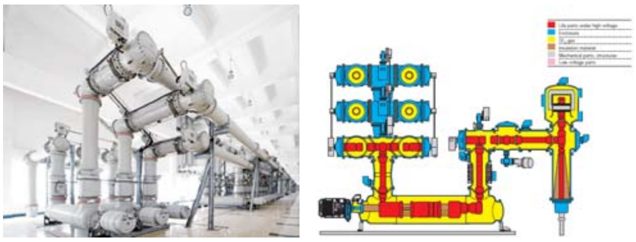

Fig.4. Typical compartment of GIS ELK-3 [6]

Nominal parameters of the GIS ELK-3 for which the solution is intended are indicated. Typical GIS busduct dimensions for analysis (in Fig. 3):

- conductor length (full), 2570 mm;
- conductor diameter (outer), 160 mm;
- conductor diameter (inner), 150 mm;

Main physical properties for simulation

- Aluminum alloy (Al), not painted,
- Thermal conductivity (Al) – 220 W/(m·K);
- Electrical resistivity (Al) – 2,63 x 10e-8 Ω;

Boundary conditions using to simulation

- rated current: 6300 A;
- frequency: 50 Hz;
- SF$_6$ absolute pressure: 5 bar (SF$_6$ pressure influence on the thermal convection capacity);
- surrounding air pressure: 1,013 bar;
- ambient temperature: 25°C.

Thermal analyses description and simulation results

First step in tool building was to prepare thermal library (OrCAD Capture), which allows constructing electric diagrams and solving them with PSpice solver. After solving, all potentials represent temperatures and current values represent heat fluxes.

In the following an example of TNM simulation for GIS compartment is presented. The purpose of this analysis was to estimate the temperature rise for a different ratings current of single GIS busbar. TNM method of simplified GIS conductor model was built using OrCAD Capture program (solved by PSpice solver) and ATP-EMTP (by ATPDraw/ MODELS). Modeling and calculations were made for approaches:

(1) GIS busduct without enclosure – surrounding air pressure (model 1, according to Fig. 3);
(2) GIS busduct with enclosure – SF$_6$ pressure inside (model 2, according to Fig. 3).

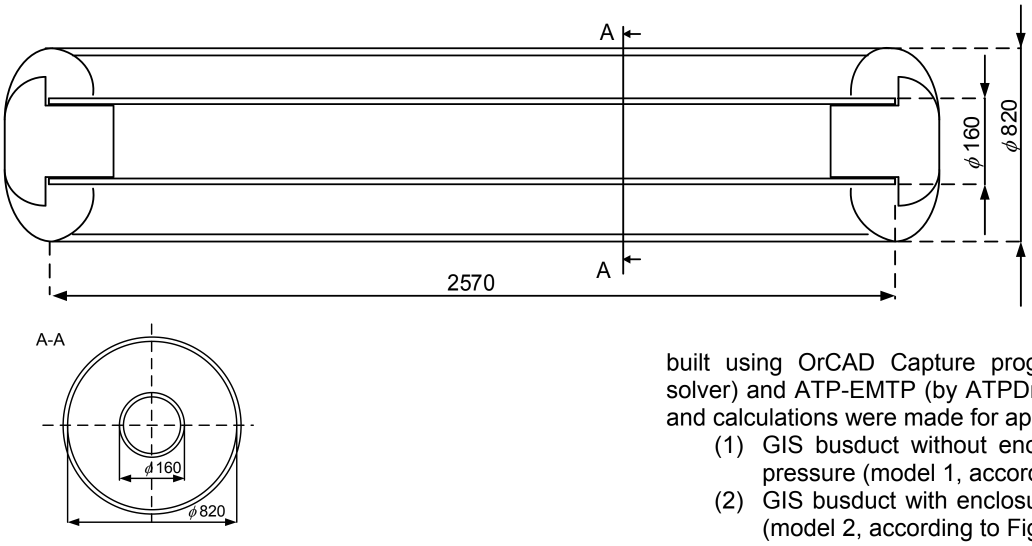

Fig.3. Typical dimension of GIS ELK-3 type compartment

Studies were carried out for typical GIS compartment with aluminum conductor/pipe, enclosure, surrounding air environment and pressured SF_6 gas.

Based on EEUG Technical Paper [5] thermal network components (thermal resistance, heat source, thermal capacitance) in MODELS were created and built in ATP-EMTP program. MODELS were created following typical procedure in ATP-EMTP environment [1]. The voltages taken from the circuit are used to determine a non-linear resistance R. In this equivalent mode the voltages represents temperatures of different components. Thermal capacitances of inner pipe, SF_6 gas and GIS enclosure (196,8 J/K, 325 J/K and 935 J/K, respectively) are taken into account. This kind of MODELS usage together with type91 $R(t)$ [5] will be widely applied in dynamic TNM modeling.

The OrCAD capture and ATP-EMTP simulation results for steady state final temperature were compared in Table 2. Drawings and diagrams are presented in Figures 5÷9.

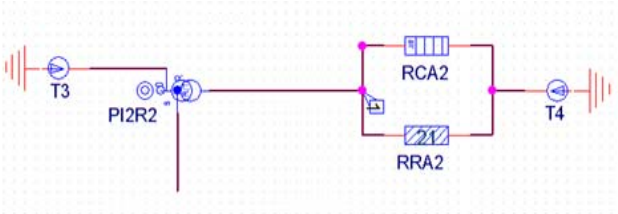

Fig.5. Thermal network diagram for model (1) – OrCAD program

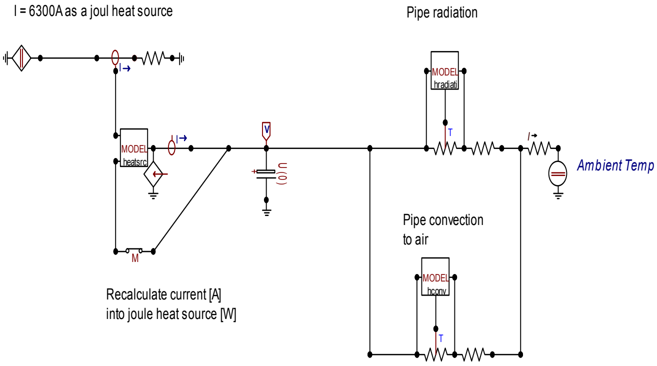

Fig.6. Thermal network diagram for model (1) – ATP-EMTP program (corresponding to Fig. 5)

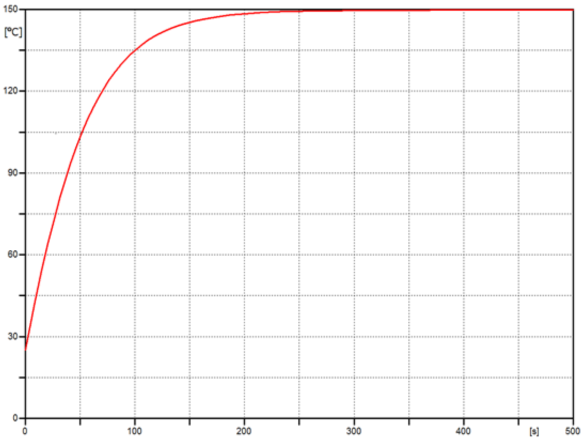

Fig.7. ATP-EMTP simulation dynamic result for conductor in air (without enclosure element)

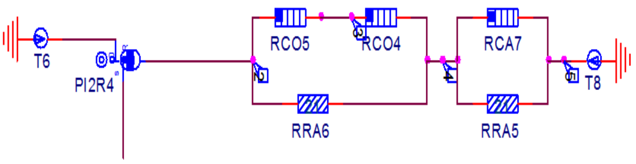

Fig.8. Thermal network diagram for model (2) – OrCAD program

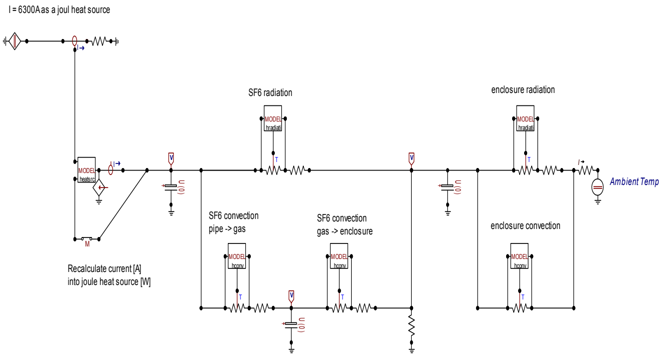

Fig.9. Thermal network diagram for model (2) – ATP-EMTP program (corresponding to Fig. 8)

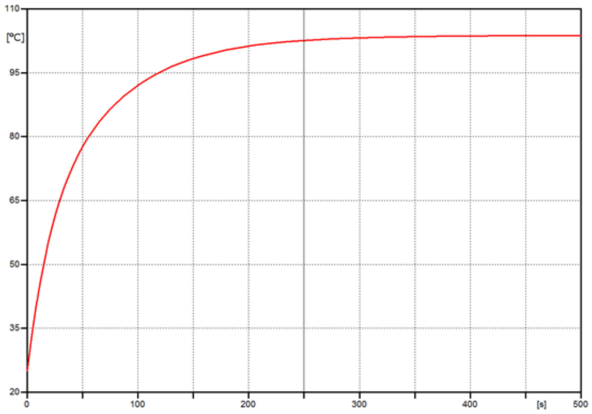

Fig.10. ATP-EMTP simulation result for conductor, SF_6 pressured gas and enclosure element

Table 2. Simulation results – temperatures on conductor comparison

Current [A]	Setup	OrCAD Capture [°C]	ATP-EMTP [°C]
1250	Model (1)	29,5	31,4
	Model (2)	27,0	29,0
2500	Model (1)	45,1	46,8
	Model (2)	37,3	39,1
4000	Model (1)	75,0	76,5
	Model (2)	56,7	58,7
6300	Model (1)	149,5	149,8
	Model (2)	101,8	103,7

To validate the ATP-EMTP model several currents (untypical) levels were used as a heat source. Results presented in Table 2 indicate the ATP-EMTP models correctly estimate the final temperature of the whole compartment. OrCAD software is a program dedicated to the electrical calculation – using thermal library (created and built at ABB [7-8]) can be dedicated to the thermal network calculations. ATP-EMTP program has allowed us to achieve the approximate value based on the initial assumptions.

The difference between OrCAD and ATP-EMTP comes from the fact that the OrCAD utilizes more sophisticated thermal model to calculate the temperature.

Conclusions

Heat phenomena in working electrical apparatuses are the condition which defines their current limits. Therefore using the computational techniques allows engineers to analyze thermal aspect of systems in the early design stage and is a must for modern designers. Such analysis helps in the estimation of the required cooling or alternation of the construction to meet thermal requirements. Therefore the thermal network concept offers approach which is simple and intuitive, especially for electric engineers. And with high speed of computations and good precision it is worth to be considered.

The thermal networks of two models of ELK-3 GIS busduct have been built. Calculations were made for two approaches: GIS busduct without enclosure – surrounding air pressure (model 1) and GIS busduct with enclosure – SF_6 pressure inside (model 2). All calculations were made for simplified GIS busduct design and were simulated for operating currents: 1250, 2500, 4000 and 6300 A.

Both models returns relatively close solutions for the compartment temperature. Additionally if one utilizes the ATP-EMTP software time constants for temperature increases can be read. ATP-EMTP model overestimate the thermal value by the several Celsius degrees. This is due to fact that ATP-EMTP utilizes only fundamental thermal dependencies. Further expansion is possible. Important fact is that ATP-EMTP allows for fast and easy assessment if the thermal conditions are meet or are close to their limits.

Following conclusions can be listed, based on simulation results:

- For typical atmospheric pressure without enclosure temperature on conductor was equal approx. 150°C (not applicable according to IEC 62271-203 [2]);
- If GIS busduct with enclosure and SF_6 gas pressure inside – temperatures are below limit 105°C [2].

Generally, ATP-EMTP program with created and validated MODELS can be utilized as tool to thermal behavior modeling and dynamic heat rise simulations during electrical devices and apparatus design process.

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