

A Statistical Analysis of the Thermal Behavior of Electrical Distribution Systems

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ABSTRACT

For the prevention of technical risks and the optimum design of an electrical distribution system, considerable efforts have been made to implement thermal models of wires, bundles, and electromechanical components in order to improve thermal analysis. Unfortunately, in most cases, important input parameters such as the position of a wire within a bundle or the profiles of the currents are unknown. This leads to the use of worst-case scenarios, frequently providing unrealistic results and uneconomic over-dimensioning.

The proposed approach is based on the thermal simulation of a large number of randomly-generated bundle configurations for given profiles of currents. Thus one gets a temperature distribution, allowing a much more precise analysis compared to a simple worst-case calculation. By applying the same method to various current profiles, one gets temperature distributions for each wire as a function of a normalized total bundle current. The finding is that statistics allow a very good thermal assessment despite unknown bundle configurations and current profiles. The paper presents initial experimental data and simulation results followed by a discussion of future possibilities.

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INTRODUCTION

Both the prevention of technical risks and the optimum design of an electrical distribution system are based on a profound understanding of thermal behavior. For this reason, considerable efforts have been made to implement thermal models of wires, bundles, and electromechanical components in order to improve thermal analysis through simulation. Unfortunately, in most cases, important input parameters are unknown: The position of a wire within a bundle is not defined due to the partly manual production process (Fig. 1), and the profiles of the currents are not determined. To overcome this deficiency, worst-case scenarios are often assumed, which, however, frequently lead to unrealistic results. Thus, the question is whether, despite the stochastic character of wire bundles, it is possible to build a model that provides reliable results.

The proposed approach is based on an existing thermal model for wire bundles validated by using a specific measurement method and which has been previously presented [2]. However, because the positions of the wires are unknown, a statistically-significant number of bundle configurations are generated randomly and a thermal simulation is done in each case for given profiles of currents. Thus, instead of a single

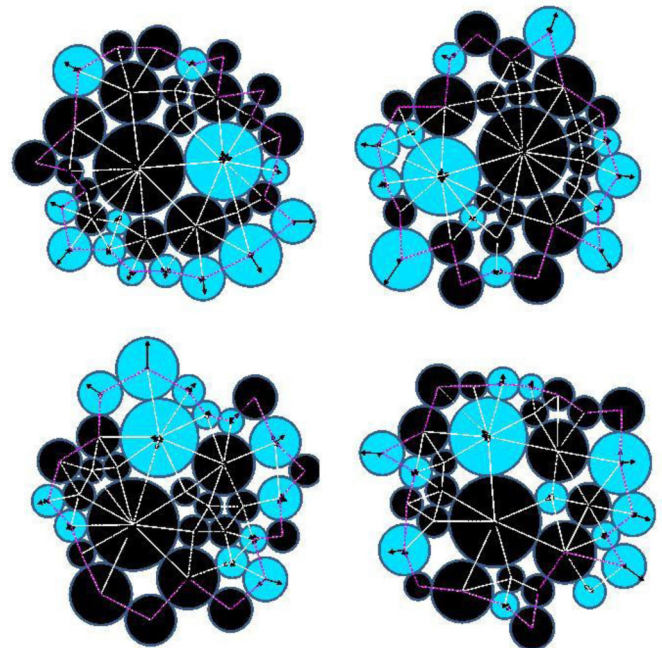


Figure 1. Examples of different wire bundle configurations for a given current profile (blue: wire conducting a current)

wire temperature, one gets a temperature distribution, allowing a much more precise analysis compared to a simple worst-case calculation [1]. The same method is applied to the undetermined current profiles, which also are generated randomly and then simulated. The results are temperature distributions for each wire as a function of a normalized total bundle current. So, if the mean bundle current can be estimated, the finding is that this method using statistics allows a very good thermal assessment despite unknown bundle configurations and current profiles.

THEORY

The thermal behavior of a single wire can be described with a straightforward approach using fundamental laws of physics (Eq. 1), where p is the power per volume, T the temperature, λ and c the specific thermal conductivity and capacity, R the radius, I the electrical current, ρ_0 the specific electrical resistance and β its thermal coefficient [1]:

$$p_c = p_{el} - p_\lambda \rightarrow c \frac{\partial T}{\partial t} = \frac{I^2 \rho_0 (1 + \beta(T - T_0))}{\pi^2 R^4} + \lambda \left(\frac{\partial^2}{\partial z^2} + \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial}{\partial r} \right) \right) T \quad (1)$$

$$-\lambda_i \frac{\partial T}{\partial r} \Big|_{r=R_i} = \alpha (T - T_A) \quad , \quad \alpha = \alpha(T_{r=R_i}, T_A, R_i, \dots) \quad (2)$$

Equation 2 shows the most important boundary condition, which is the thermal transition between the insulation and air based on radiation and convection [3] and represented by the coefficient α (T_A : ambient temperature, i : index for insulation).

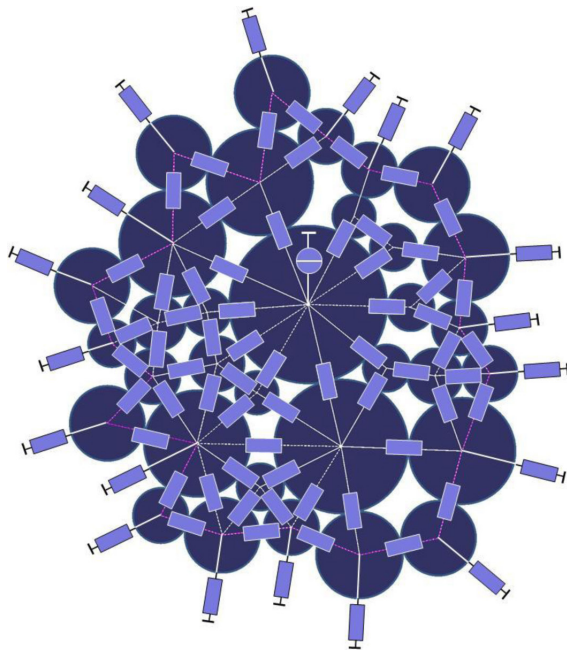


Figure 2. Example of a linear network for a given wire bundle. Here, only one wire (center) is conducting a current.

For the examination of wire bundles, however, the local temperature distribution within the wire can be ignored. Furthermore, since the static behavior represents the worst case and also for simplicity, the time dependency of the temperature is not considered. Thus, as a first approximation, the thermal model of a wire bundle can be described by a simple linear network of thermal conductances and sources (Fig. 2).

Thus, the energy balance for a wire i is as follows:

$$P_i = R_{E,i} I_i^2 = G_{a,i} T_i + \sum_{j(\text{neighbors})} G_{w,ij} (T_i - T_j) \quad (3)$$

with $G_{w,ij}$ the conductances between wires and $G_{a,i}$ those between wires and the environment, j the wire index of the adjacent wires, T_i the wire (core) temperature rise with respect to the ambient temperature, I_i the electrical current, and $R_{E,i}$ the electrical resistance.

Obviously, the problem is the determination of the conductances $G_{w,ij}$ and $G_{a,i}$. Based on geometrical considerations (see Fig. 3), the following equations were derived,

$$r_i + r_j - \varepsilon = \sqrt{r_i^2 - h^2} + \sqrt{r_j^2 - h^2} \quad (4a)$$

$$G'_{w,ij} \approx \frac{2h\lambda_i}{(d_v + d_k)} \approx \frac{2\lambda_i}{(d_i + d_j)} \sqrt{2\varepsilon \frac{r_i r_j}{r_i + r_j}} \quad (4b)$$

$$G'_{a,i} \approx \alpha \gamma_i r_i$$

where the ' indicates values per length (longitudinal-specific values).

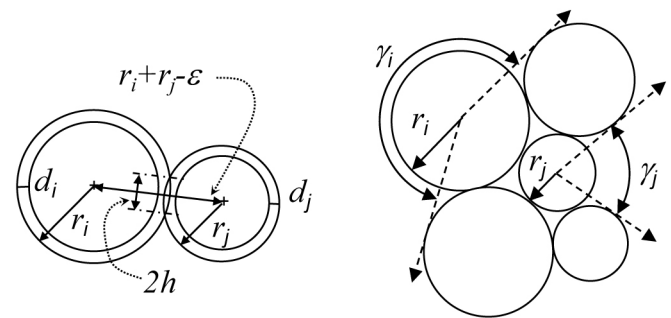


Figure 3. Left: Thermal conductance between two wires. Right: thermal conductance between wire and environment.

Indeed, the values of ε and γ vary for a single wire and depend on various parameters such as the bending radii or the forces between wires. However, as shown in the next section, these local variations can be ignored, as only the mean values are relevant for the thermal balance.