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Research Paper

Transient thermal modelling of substation connectors by means of dimensionality reduction

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HIGHLIGHTS

- This paper simulates the temperature rise test for substation connectors.
- A one-dimensional reduction method based on the finite difference method is proposed.
- It uses critical information of the three-dimensional geometry of the analyzed system.
- Tests done in a laboratory corroborate the results of the proposed simulation method.
- This simulation method can be extended to other power devices.

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ABSTRACT

This paper proposes a simple, fast and accurate simulation approach based on one-dimensional reduction and the application of the finite difference method (FDM) to determine the temperatures rise in substation connectors. The method discretizes the studied three-dimensional geometry in a finite number of one-dimensional elements or regions in which the energy rate balance is calculated. Although a one-dimensional reduction is applied, to ensure the accuracy of the proposed transient method, it takes into account the three-dimensional geometry of the analyzed system to determine for all analyzed elements and at each time step different parameters such as the incremental resistance of each element or the convective coefficient. The proposed approach allows fulfilling both accuracy and low computational burden criteria, providing similar accuracy than the three-dimensional finite element method but with much lower computational requirements. Experimental results conducted in a high-current laboratory validate the accuracy and effectiveness of the proposed method and its usefulness to design substation connectors and other power devices and components with an optimal thermal behavior.

1. Introduction

During the last years, the finite element method (FEM) has been widely applied to design electrical devices. Two- and three-dimensional (2D and 3D) multiphysics FEM simulations are recognized as a realistic means to predict the electromagnetic and thermal behavior of diverse type of electrical devices. Different authors have struggled to develop coupled electromagnetic-thermal 2D- and 3D-FEM formulations to predict the thermal behavior of diverse electrical components such as conductors, bus bars, cables, connectors or semiconductors among others [1–9]. Despite significant improvements in computer performance, 3D-FEM simulations are still time-consuming and memory-intensive due to the heavy computational resources involved to provide the required resolution for complex 3D multiphysic problems [10]. It can cause serious difficulties, particularly when applying recursive simulations during the design optimization stage [11]. The use of 3D-FEM simulation tools often requires the use of costly licenses and the implication of specialized engineers to carry out tedious and time-consuming tasks associated to the preparation of 3D geometries, generation of the 3D mesh, or settling of boundary conditions among others. Therefore the development of accurate fast models [12] which can be based on model reduction techniques [13] and are highly appealing to overcome the abovementioned drawbacks.

Different approaches have been applied to reduce the computational burden in complex 3D problems. For example in [14] a co-simulation strategy combining 1D finite difference and 3D finite volume codes are applied. In [15] a1D analytical model for simulating the response of piezoelectric transformers was compared

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Nomenclature

$i = 1,2,\ldots,I$	node index identifying the position along the x axis
$j = 1,2,\ldots,J$	time step index
cd	abbreviation of conductor
$conn$	abbreviation of connector
Δx	spatial step [m]
Δt	time step [s]
T	temperature [K]
T_i^j	temperature [K] at node $i \cdot \Delta x$ and time instant $j \cdot \Delta t$
T_o	reference temperature, 293.15 K
$T_{cd,\infty}$	conductor temperature far from the connector [K]
$T_{air,\infty}$	air temperature far from the conductor [K]
T_{film}	film temperature [K]
H_{sea}	conductor elevation above sea level [m]
$\dot{Q}$	rate of energy with respect to time [W]
D_{cd}	outer diameter of the conductor [m]
C_p	specific heat [J/(kg·K)]
k	coefficient of thermal conductivity [W/(m·K)]
ρ	mass density [kg/m^3]
ρ_e	electrical resistivity [Ω m]
α_e	temperature coefficient of the resistivity [1/K]
R	electrical resistance [Ω]
r	electrical resistance per unit length [Ω/m]
I_e	electric current [A]
S	cross sectional area perpendicular to the electric current [m^2]
P	convective/radiative heat transfer perimeter [m]
$P \cdot \Delta x$	convective/radiative heat transfer incremental area [m^2]
h	convective heat transfer coefficient [W/(m^2 K)]
ε	emissivity
σ	Stefan-Boltzmann constant [W/(m^2 K^4)]
μ	dynamic viscosity of air [Pa s]
β	thermal expansion coefficient of air [1/K]
g	gravity of Earth [m/s^2]
θ	angular coordinate [°]
L_c	characteristic length [m]
Nu	Nusselt dimensionless number
Pr	Prandtl dimensionless number
Gr	Grashof dimensionless number

against 3D-FEM simulations. In [16] a 1D finite difference approach to model mass conservation in ducts of an internal combustion engine was studied. Cerfontaine et al. [17] proposed a 1D-finite element formulation to model the grouting and field temperatures of borehole heat exchangers.

This paper proposes a one-dimensional fast method based on nodal equations and finite differences formulation to accurately predict the temperature evolution in substation connectors during the standard temperature rise test. This is a multiphysics electromagnetic-thermal problem since the main heat source is the Joule loss due to the electric current whose time-profile is known, although there is a minor contribution due to the induced eddy currents. The proposed method discretizes the analyzed domain in finite one-dimensional regions in which the energy rate balance due to the flow of heat is calculated. To accurately predict the temperature profile along the connector and the surrounding conductors, the proposed transient model takes into account the three-dimensional geometry of the analyzed system to determine for each discretized element and at each time step different parameters such as the incremental electrical resistance or the convective coefficient. It is worth noting that the proposed approach can also be applied to simulate the temperature rise of other power devices.

To evaluate the accuracy of the proposed system, two substation connectors are evaluated and the standardized temperature rise test according to the ANSI/NEMA CC1-2009 standard [18] is simulated and checked against experimental tests. According to this standard, the connector passes the test if its temperature is below the temperature of the conductors at with which the connector is associated. This test is very useful since it allows evaluating the thermal behavior of the substation connectors under both transitory and stationary conditions. Temperature rise tests are expensive since they last for long time, and consume large amounts of electrical power. As a result, to obtain designs with optimal thermal performance [19], substation connectors' manufacturers require fast, easy-to-use and accurate simulation tools to anticipate the results of the mandatory standard temperature rise tests.

The finite difference method (FDM) is a recognized tool to approximate the solutions of systems governed by differential equations by means of finite differences calculated at the grid points of a discretized geometry. The FDM method has been widely applied in the technical bibliography, for example to model the heat transfer in solar cells by applying the conservation principle [20], calculate the natural convection heat transfer in a cavity filled with a nanofluid [21,22], determine the temperature rise of a surgical drilling machine [23], model the transient thermal performance of machining processes [24], predict the temperature distribution of ball-screw mechanical systems [25] or to perform vibrational analysis in elastic media [26].

Most of the works are based on two- or three-dimensional FDM approaches. In this paper it is shown that by using an one-dimensional FDM reduction by considering the whole three-dimensional geometry in calculating key parameters for the energy conservation laws it is possible to obtain very accurate results, similar to those attained with 3D-FEM, which is the current way to solve this kind of problems [27], but with much less computational burden. As a consequence, the method here proposed can be very useful to optimize in an economical and fast manner the design of different power devices including substation connectors, power conductors, busbars or fittings used in power lines among others to ensure an improved thermal behavior.

2. The model bases on nodal equations and finite difference formulation

2.1. Problem discretization

The temperature of the connector is directly related to the temperature of the reference conductors at which it is connected. Due to the longitudinal geometry and heat conduction of the considered problem, the thermal analysis can be reduced to a one-dimensional problem by formulating suitable assumptions. To this end the whole domain is divided into several discrete elements called nodes, along the axial and main dimension of the geometry, as shown in Fig. 1. The axial dimension is selected to solve the heat transfer problem because it is the dimension where almost all heat conduction occurs. It is assumed that the temperature of the central point of the any node is the average temperature of this node. This assumption is accurate since connectors are made of good conductor materials such as copper and aluminum and because a small enough spatial step Δx is selected.