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Numerical modelling of the natural ventilation of underground transformer substations

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HIGHLIGHTS

- ► A model of natural ventilation of underground transformer substations is developed.
- ► Simulations serve to analyse air flow patterns and temperature distributions.
- ► There is a component of reverse flow in the outflow grilles.
- ► There is a mass of static warm air at the top part of the switchboards zone.
- ► Correlations for air mass flow rate and heat transfer coefficients are proposed.

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ABSTRACT

Ventilation by natural convection of two underground transformer substations has been numerically modelled. The model has been verified in terms of discretization errors and it has been validated with the experimental results of eight temperature rise tests carried out under different conditions of ventilation and transformer power losses. The results of the simulations serve to analyse the air flow pattern and the air temperature distributions inside the substation. A correlation for the air mass flow rate as a function of the ventilation conditions (discharge coefficient and area of the grilles) and the heat dissipated by the transformer has been fitted. The heat transfer coefficients on the surfaces of the transformer and the walls of the enclosure can also be obtained from the simulations of the model. All this information will be used in a future paper to develop a zonal thermal model of the ventilation of the substations that can be employed as a design and optimisation tool.

1. Introduction

Underground transformer substations are used for electrical power distribution in public networks and private installation load-centres. These buildings are usually made of prefabricated concrete and have a personnel access point and some ventilation grilles. Inside of the enclosure there are one or two distribution transformers with their Low Voltage (LV) boards, Medium Voltage (MV) cubicles, and interconnecting and auxiliary devices. In the transformer and the LV boards the generation of heat is due to power losses occurring in the conversion of the distributed electrical energy from medium voltage to low voltage for domestic and industrial applications. This heat must be removed by the natural convection flow of air that enters and leaves the substation through the ventilation grilles and by the radiation exchanges with the walls of the substation.

International Standards [1,2] state that the criterion for good performance in a transformer substation is given by the maximum temperature reached by the top-oil of the transformer. This temperature must be limited in order to extend the operating life of the transformer. As experimental tests must be run on a real substation, obtaining a temperature that is over the limit would invalidate the built substation, requiring a new design and new casts. In order to avoid this slow and expensive design procedure, it would be very useful to have a mathematical model of ventilation in the substation and to perform a simulation of this model to determine the temperatures in the design stage prior to the experimental tests.

One of the first models of ventilation in transformer substations that can be found in the literature is the one by Menheere [3]. This

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Nomenclature

Latin letters

$A_{grilles}$	surface area of the ventilation grilles [m^2]
c_p	specific heat [J/kg K]
$C_{d,grilles}$	discharge coefficient of the ventilation grilles [m/s Pa$^{0.5}$]
g	gravity acceleration [m/s^2]
GCI	Grid Convergence Index [%]
k	turbulent kinetic energy [m^2/s^2]
$\dot{m}_{air}$	air mass flow rate [kg/s]
Nu_z	Nusselt number [−]
p	pressure [Pa]
P	transformer power losses [W]
$q_{conv,transf}$	transformer convection heat losses [W]
Ra_z	Rayleigh number [−]
S_h	source term in energy equation [W/m^3]
T	temperature [K or °C]
u_i	velocity components [m/s]
x_i	Cartesian coordinates [m]
$y+$	dimensionless distance to the nearest wall [−]

Greek letters

δ_{ij}	Kronecker delta [−]
ΔT	temperature rise over ambient temperature [K]
ε	dissipation rate of k [m^2/s^3]
λ	thermal molecular conductivity [W/m K]
λ_T	turbulent thermal conductivity [W/m K]
μ	dynamic molecular viscosity [kg/m s]
μ_T	turbulent eddy viscosity [kg/m s]
ρ	density [kg/m^3]

is a very simplified model that uses one equation for the heat transferred to the ventilation air and another equation to the heat dissipated through the walls of the substation. The inputs of the model are the power dissipated by the transformer, the dimensions of the transformer and the substation, the thermal conductivity of the walls, and the heights, surface areas and resistance coefficients of the inlet and outlet ventilation grilles. The outputs of the model are estimations of the outlet air and of the transformer's mean temperature rises over the ambient temperature. Although the model takes into account the main parameters involved in the ventilation performance of the substations (the transformer power and the surface area and the resistance coefficient of the ventilation grilles) the results can be used only as a "rule of thumb" in the design stage of a transformer substation because the model does not give the enclosure class of the substation required by IEC Standard [2].

Another possible approach to the thermal modelling of transformer substations is the transient equivalent thermal circuit model developed by Radakovic and Maksimovic in [4]. This model is based on a small number of characteristic temperatures inside the transformer substation, and it relies on some parameters whose values have to be determined through experimentation for each new design. The same authors in [5] present an improvement of the model by including solar irradiation and wind velocity.

Iskender and Mamizadeh in [6] use the same methodology as the dynamic thermal circuit model. They improve the previous models by taking into consideration the variation over time of the thermal resistances and capacitances of the top-oil, of the ventilation air and of the different components of the substation enclosure.

A common characteristic of these dynamic network models is that they can be used to simulate the load capability and ageing of a specific and experimentally checked system using discrete temperature measurements, but they are not able to analyse and optimise the performance of a transformer substation in the design stage in order to determine the enclosure class.

Thus, in order to deal with design and optimisation objectives, the use of other types of mathematical models with a more exhaustive treatment of the physical phenomena that is taking place in the transformer substation is required.

Hence, there is the type of model based on the description, by means of differential equations, of the mass and heat transfer phenomena taking place in a flow domain under the restriction of some conditions imposed at its boundaries. To solve these differential equations there are different numerical techniques that can be employed.

As far as the authors are aware, there are only two attempts in the specialized literature. Loucaides et al. [7] use the Finite Element Method (FEM) to solve the energy and the Navier–Stokes equations in a flow domain corresponding to the air inside a transformer substation. They assume that the flow is under a laminar regime and the buoyancy forces are modelled by means of the Boussinesq hypothesis. As main boundary conditions, they impose the ambient temperature on the external surface of the walls, the ventilation grilles are geometrically modelled with their effective area, and the transformer losses are imposed as a uniform heat flux on the surface of the transformer. The model is used to analyse the influence of the aperture of the ventilation grills, the transformer load and the ambient temperature in the air temperature distribution inside the substation.

The other work addressing the issue of modelling the ventilation in substations by means of differential equations is the one by Ramos et al. in [8], where they develop a differential model of the ventilation (air circulation and heat transfer) of a half-buried transformer substation solved by means of the Finite Volume Method (FVM). Taking a more realistic approach than the previous authors, they assumed the flow is turbulent and used the Standard k–ε model to model it. The walls of the enclosure are modelled as solids with one-dimensional heat conduction and external convection. The ventilation grilles are modelled as boundaries where the air flow suffers a pressure loss, and the corresponding loss coefficients are calculated numerically. A vertical temperature distribution is imposed on the transformer casing and the oil-filled hollow fins are modelled as solids by means of an equivalent thermal conductivity. The model allows the enclosure class of the substation to be determined and for the analysis of the air velocity and temperature distributions.

On the one hand, the principal handicap of these differential models is the high computational cost of performing a single simulation and the long time period that is required to obtain results. On the other hand, they provide results that cannot be obtained either experimentally or with other types of models, namely, the air flow pattern and temperature distributions, the air mass flow rate and the heat transfer coefficients on the transformer surfaces.

Nevertheless, all this information obtained in the simulation of the differential model can be used to develop an intermediate level model, an approach known as zonal modelling [9,10], which requires fewer computational resources and less simulation time, so as to allow its implementation in a software tool oriented toward designing and optimizing the thermal performance of transformer substations.