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Zonal thermal model of the ventilation of underground transformer substations: Development and parametric study

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HIGHLIGHTS

- A zonal model of ventilation of underground transformer substations is presented.
- The development of the zonal model is based on a CFD model.
- A good correlation between the results of the model and the experiments is obtained.
- The model is implemented as a simulation tool for design and optimisation purposes.

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ABSTRACT

An algebraic thermal zonal model of the ventilation of underground transformer substations during a standardised temperature rise test is presented in this paper. The development and adjustment of the proposed model rely on the analysis of the air flow pattern and temperature distributions obtained by a more complex model numerically solved by means of CFD techniques. The flow domain of the model represents a section of the substations divided into several interrelated zones where the mass and the energy conservation equations are formulated and the generated system of nonlinear algebraic equations is solved. The model is validated by comparing its results with the ones obtained by the CFD model and with the experimental results of eight temperature rise tests under different conditions. A parametric analysis was carried out on the model to prove its utility as an efficient tool to improve and optimise the thermal performance of transformer substations during the design process. From the parametric study it has been inferred that the main parameters affecting the ventilation of the substations are the pass area between the LV–MV zone and the transformer zone, the surface area of the ventilation grilles in the substation with horizontal ventilation, and the perimeter of the protruding ventilation vents in the substation with vertical ventilation.

1. Introduction

Underground transformer substations are used to convert electrical energy from medium to low voltage in electrical power distribution networks. These buildings are usually made of pre-fabricated concrete and their main components are the ventilation grilles, one or two distribution transformers, the Low Voltage (LV) boards and the Medium Voltage (MV) cubicles. Because of the power losses occurring in the electrical conversion that takes place in the transformers and the LV boards, heat is generated. This heat is dissipated by the air circulating by natural convection through the substation and by the radiation exchanges with the walls of the enclosure.

The maximum temperature reached by the top-oil of the transformer is established by International Standards [1,2] as the main criterion for evaluating the performance of a transformer substation. This temperature must be limited in order to extend the operating life of the transformer. Obtaining a temperature that is over the limit during the experimental tests run on a real substation would invalidate the design and new casts would be required. This is a slow and expensive design procedure that could be avoided by using a mathematical model of the ventilation in the substation to perform a simulation to determine the temperatures in the design stage prior to the experimental tests.

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Nomenclature

Latin letters

A	surface area, [m^2]
$\bar{c}_p$	average specific heat, [J/kg K]
C	fitting coefficient, [−]
e	thickness of the wall, [m]
faces	number of faces of the zone under consideration, [−]
g	gravity acceleration, [9.81 m/s^2]
h	height of the middle point of the zone with respect to the floor of the substation, [m]
K	enclosure class of the substation, [K]
k	thermal conductivity, [W/m K]
$\dot{m}$	air mass flow rate, [kg/s]
Nu	Nusselt number, [−]
p	pressure, [Pa]
Pr	Prandtl number, [−]
q	heat transfer, [W]
Ra	Rayleigh number, [−]
T	temperature, [K or °C]

Greek letters

ΔT	temperature rise over ambient temperature, [K]
ε	emissivity, [−]
σ	Stefan−Boltzmann constant, [5.67·10^{-8} W/m^2 K^4]
ρ	density, [kg/m^3]

Subscripts

amb	ambient air
base	base of the transformer
cond	conduction heat transfer
conv	convection heat transfer
fins	transformer fins
grilles	ventilation grilles
hor	horizontal face
i	zone under consideration
in	internal surface
inflow	inflow air
j	neighbouring zone
lid	lid of the transformer
L	characteristic length
max	maximum
out	external surface
outflow	outflow air
rad	radiative heat transfer
source	relative to the transformer or to the Low Voltage boards
transf	transformer
upwind	relative to the zone where the mass flow rate comes from
ver	vertical face
w	each wall of the zone under consideration
wall	walls of the substation

Superscripts

r	level of iteration on pressure
s	level of iteration on temperature

One of the first models of the ventilation of transformer substations was presented by Menheere in Ref. [3]. It is a very simplified model that uses one equation for the heat transferred to the ventilation air and another equation for the heat dissipated through the walls of the substation. The main inputs of the model are the power dissipated by the transformer, the dimensions of the transformer and the substation, and the heights, surface areas and resistance coefficients of the inlet and outlet ventilation grilles. The outputs of the model are estimations of the outflow air and of the transformer mean temperature rises over the ambient temperature.

The next step in the modelling of the ventilation of transformer substations is the transient equivalent thermal circuit model used by Radakovic and Maksimovic [4,5] and Iskender and Mamizadeh [6]. This type of model can be used to obtain the transformer top-oil temperature and an average or characteristic internal air temperature of experimentally checked substations, but as the parameters affecting the ventilation are lumped, it is more difficult to perform an optimisation or a parametric analysis of a transformer substation in the design stage.

If the objective is to use the model in the design stage of the substation and with the objective of optimising the ventilation, a more detailed type of mathematical model must be developed. The principal effort in this direction is by means of numerically solved models based on the Navier−Stokes and the energy conservation equations.

In this sense three works stand out in the literature. The first one corresponds to Loucaides et al. [7], who 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. 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 two works correspond to the research group led by Ramos et al., who present a preliminary version of their model in Ref. [8] and the final version in Ref. [9]. In this last paper they present a CFD model of the ventilation (air circulation and heat transfer) of two underground transformer substations solved by means of the Finite Volume Method (FVM). The model is 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 steady-state simulations serve to analyse the air flow pattern and the air temperature distributions inside the substation. Moreover, two important parameters related to the ventilation performance of the substation that are very difficult to determine experimentally are obtained from the simulations of the model: a correlation for the air mass flow rate as a function of the ventilation conditions and the heat dissipated by the transformer, and correlations for the heat transfer coefficients on the surfaces of the transformer and the walls of the enclosure.

On the one hand, these CFD models permit design parameters (size of the substation, dimensions of the walls, and dimensions, location and types of ventilation grilles, among others) that directly affect the ventilation of the substation to be taken into account. But on the other hand, they have huge computational requirements and consume a great deal of CPU time to perform a single simulation. These characteristics therefore invalidate the use of these models for design and optimisation purposes.

Nevertheless, the information obtained in the simulation of the CFD model can be used to develop an intermediate level model, an approach known as zonal modelling [10,11], which requires fewer computational resources and less simulation time, thus allowing its