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The influence of gravel on the ambient temperature of power substations

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ABSTRACT

This paper examines the role of gravel in the heating process of substation environments. The choice of the material applied to the electric energy substation surface level can influence temperature changes in equipment. Ambient temperature is an important parameter used to define how many years a transformer will last when subjected to a load curve, under normal and emergency operation conditions. This paper shows that the ambient temperature of 30 °C, suggested in IEEE C 57.91 standard for calculating transformer's loading depending on the desired equipment life span is underestimated. There are differences in ambient temperature on surfaces when applying different rocks on the soil surface substations. In terms of the resistivity, some rocks have higher values than others when the drain systems fail to drain all the rainwater to the soil. Two field tests were performed, one in the 345 kV/138 kV Jacarepagua Substation in Rio de Janeiro, and the other in the Substation of Foz do Iguaçu in the state of Paraná, where measurements were performed at three locations: switchyard of 600 kV direct current – DC, 500 kV and 750 kV alternating current – AC. Laboratory tests of thermal and electrical properties of rocks typically used to cover the ground of substations were also performed. This paper presents some consideration of drainage properties.

1. Introduction

Temperatures generated during system operation conditions in the environment of substations may have important consequences for the durability of expensive equipment like transformers and reactors. The analysis most commonly used to determine the transformer life expectancy is the hot-spot temperature (HST) value analysis as presented in [1,2]. Very few academic articles present quantitative data of air and surface temperatures, wind speed or relative humidity of the microclimates existing near electric equipment in open spaces [3,4]. Optimization models are often used for temperature and load substations forecasting, such as [5]. Additionally, most studies do not focus on the thermal properties of the materials used on the soil surface in substations yards.

In general, the energy efficiency of material applied on the ground is not considered by designers of electric substations in Brazil, because gravel rock is an inexpensive and effective isolator.

The aim of this study is to determine whether there are differences in the thermal performances of different types of rocks, and which rocks have desirable properties like high resistivity, inert material, and easy drainage, with the aim of making recommendations for the type of rock that should be used as a first layer in substations yards. Recent research presented in [6] discusses the materials used (soil moisture) for grounding focusing on power distribution systems.

Often, all of the equipment in a substation yard can operate under high temperatures. Equipment is usually remotely monitored by thermometers installed internally, or else is controlled by visual inspection. This visual verification is performed systematically by employees in an open environment that is densely occupied by equipment that produces heat and hot air gusts. Rock can retain heat, increasing employees' health risks [7]. The infrared technology can be used to monitor the substation as described in [8,9].

Some studies describe methods of grounding mesh design, as presented in [10–20]. Temperature evaluation of substations switchgear is described in papers related to preventive maintenance using infrared technology in the diagnosis of substation equipment, as reported by Cao [12].

Some studies outline the use of specific tools, such as the MATLAB computational tool, used to identify the most economical designs of grounding systems [13], and new communication networks for on-line monitoring of the main parameters of substations [14–16].

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A paper by Chen et al. [17] discusses the modeling and calculation of temperature limits for urban distribution substations (DSS), but it does not provide references for tests. Other interesting research is related to use derivative methods to support topology grounding grids analysis [21].

The present study will demonstrate that it is important to consider the thermal parameters of surface materials in the initial phases of a project. As shown in [20] the temperature is one of the initial parameters referenced in grounding systems projects in substations, but sometimes the critical analysis of the material used in the grounding system is not considered in most current projects models.

An electric substation grounding project in Brazil must follow Brazilian standard NBR15571/2009 and observe ANSI/IEEE 80-2000 [19] recommendations. The ground grid has the function to: maintain the ground resistance at minimum values, in order to drain fault and lightning current safely to ground. In this way, it is possible to keep the potential produced by the fault current flowing to the ground within safe limits and eliminate static discharge generated by the equipment housing.

Thus, it is desirable that the surface material of the substation have high resistivity and a good ability to drain the rainwater. However, few recommendations exist regarding the temperature rise of the environment and its effect on the equipment aging.

From this point of view, the evaluation of thermal emissions from the substation's surfacing is important. This paper describes a series of tests made in the field and in the LETD, the Transmission and Distribution Laboratory of Federal Fluminense University, in Niterói, Brazil. Some important recommendations are made based on the analysis of the overall results.

2. The importance of the ambient temperature in the definition of a transformer maximum operation load

According to IEEE standard C57.91 – IEEE Guide for Loading Mineral-Oil Immersed Transformers [22], a transformer's loss of life in hours, with hottest-spot temperature for a 65 °C rise insulation system, due to a load curve, can be calculated as:

$$\%\text{Loss of Life} = \frac{F_{\text{EQA}} \cdot t \cdot 100}{\text{Normal Insulation Life}} \tag{1}$$

Normal Insulation Life – (former IEEE Std C57.91-1981 criterion) = 180,000 h.

$$F_{\text{EQUA}} = \frac{\sum_{n=1}^{N} F_{\text{AA},n} - \Delta t_n}{\sum_{n=1}^{N} \Delta t_n} \tag{2}$$

where F_{EQA} is the equivalent aging factor for the total time period; n is the index of the time interval, t; N is the total number of time intervals; $F_{\text{AA},n}$ is the aging acceleration factor for the temperature that exists during the time interval Δt_n and Δt_n is the time interval, in hours.

$$F_{\text{AA}} = \mathrm{e}^{\left(\frac{15000}{383} - \frac{15000}{\theta_{\text{H}}+273}\right)}; \tag{3}$$

$$\theta_{\text{H}} = \theta_{\text{A}} + \Delta\theta_{\text{TO}} + \Delta\theta_{\text{H}} \tag{4}$$

where θ_{H} is the winding hottest-spot temperature, in °C; θ_{A} is the average ambient temperature during the load cycle to be studied, in °C; $\Delta\theta_{\text{TO}}$ is the top-oil rise over ambient temperature, in °C and $\Delta\theta_{\text{H}}$ is the winding hottest-spot rise over top-oil temperature, in °C.

Transformers that make use of thermally upgraded paper treated chemically improve the cellulose structure stability are standardized, so that, a temperature rise of 110 °C in the isolation will cause an 65 °C average increase in the windings. These equipments are known as transformers of insulation class of 65 °C.

Table 1
Power values as a function of cooling and temperature required to supply a 1 pu flat load curve for 40 years.

Amb. temp. (°C)	OA	OA/FA	OA/FA/FA	Non-directed FOA or FOW	Directed FOA or FOW
14	1.000	1.000	1.000	1.000	1.000
16	1.003	1.003	1.003	1.003	1.002
18	1.022	1.020	1.019	1.018	1.016
20	1.043	1.038	1.036	1.034	1.031
22	1.065	1.057	1.054	1.050	1.046
24	1.087	1.076	1.073	1.068	1.062
26	1.111	1.098	1.093	1.087	1.079
28	1.136	1.120	1.114	1.106	1.095
30	1.164	1.143	1.135	1.126	1.114
32	1.193	1.168	1.159	1.148	1.133
34	1.224	1.195	1.182	1.171	1.153
36	1.256	1.222	1.208	1.195	1.175
38	1.292	1.253	1.236	1.221	1.198
40	1.332	1.285	1.264	1.247	1.221

For standard conditions such as 30 °C of ambient temperature, 1 pu of load, 110 °C of hot spot and 180,000 h of normal insulation life, FAA and FEQA are equal to 1. So, 100% of life loss will occur in 20.55 years, not in 40 years.

The hottest-spot temperature depends on the type of cooling and on constructive characteristics. To emphasize the importance of the ambient temperature, Table 1 shows the additional power required by a transformer of the insulation class of 65 °C with nominal power of 1 pu, to supply a flat load curve of 1 pu during a period of 40 years, according to the ambient temperature.

Using the information in Table 1 as an example, if temperature is considered to be the only aging agent, a directed forced-oil cooled transformer with a nominal power rating of more than 122 MVA would be required to supply a load of 100 MVA for 40 years at 40 °C. If the ambient temperature was 20 °C, only 103 MVA would be necessary for the same period of time. To reach 40 years of life the transformer's hot spot value must be lower, 103.59 °C. This happens when subjected to a lower load than 1 pu, that is 0.8591 pu for a natural cooling transformer of Table 1. So, if the transformer needs to feed a load with nominal power, during 40 years, it will be to install a 1.164 pu transformer (1/0.8591 pu).

The IEEE standard C57.91 [22] adopts 30 °C as the ambient temperature for calculation purposes. The field test described in Section 3 will demonstrate that higher temperatures happen more frequently, because gravel retains more the heat.

3. Materials used in a high voltage switchyard

A rock is a naturally occurring aggregate of minerals and mineral-like substances called mineraloids. Rocks are classified as igneous, sedimentary, and metamorphic, based on their mineral and chemical composition, the texture of the constituent particles, and the processes that formed them. In the present study, only rocks used to produce commercially available gravels will be considered.

Basalt a magmatic or igneous rock that is usually grainy and predominantly black in color, but may be gray or chestnut; it is always melanocratic. Basalt has high mechanical resistance and, according to its durability, suffers alteration in external environmental conditions and is less wear-resistant than granite [23].

Granite is a composed supersaturated plutonic rock consisting mainly of quartz and feldspar, which are often associated with small amounts with mafic minerals such as biotite, felsic, or muscovite. The origin of this color variation lies in the proportion of feldspar in the granite. Granite is the most common rock found in Brazilian soil. It exists in conjunction with the composition of the gneiss basement, which is the substrate of the sialic crust on the continental blocks.