Impact of Long-Term Thermal Stresses of Electrical Equipment on Climate Change

ALIN DRAGOMIR, MARICEL ADAM, MIHAI ANDRUŞCĂ, ADRIAN MUNTEANU
Faculty of Electrical Engineering
"Gheorghe Asachi" Technical University of Iasi
ROMANIA
alin_dragomir90@yahoo.com

Abstract: - The aim of the paper is to analyze the impact of long-term thermal stresses of electrical equipment on climate change. There were determined the steady-state overtemperatures and the thermal time constants for three different section size of a copper busbar system incorporated in a low voltage electric cabinet in order to compare the thermal stresses for each case. To see the influence of the long-term thermal stresses of electrical equipment over the climate change, it was performed an analysis in which electricity saved from reducing losses from Joule effect was converted into number of saved trees. This was achieved by equating the amount of electricity saved into emission in kg of CO_2 saved, and respectively the equivalent number of trees saved depending on the amount of CO_2 absorbed by them. For different scenarios, it was observed that the decrease of long-term thermal stresses of electrical equipment can result in benefits for limiting the climate change. Climate change awareness can lead us to solutions and adaptive measures to reduce the environmental impact of electrical equipment in order to follow a sustainable development.

Key-Words: - thermal stresses; copper bar; energy consumption; CO_2 emission.

1 Introduction

Global warming phenomena have always existed in our history. It is well known that global warming is due to solar activity and greenhouse gas effect due to natural phenomena on one hand and on the other hand to human activity. The temperature is the main parameter that defines the state of matter and it forms the underlie of the scientific progress [1], [4], [6]. Currently, the electric domain aims to have a better control on temperature of electrical equipment.

Technical condition of electrical equipment is optimal if they operate at allowable range of temperature defined by the manufacturer. An overheating (hyperthermia) jeopardize the proper functioning of equipment and it shortens the life (operation), and a low heating (hypothermia) leads to an oversized equipment which is economically irrational, but which can be considered as a contribution to the environment [2], [3].

Temperature θ, of the electrical equipment is determined by ambient temperature θ_a (where it is located), plus temperature rise ϑ due to the electro-caloric effect of the equipment heating:

$$\theta = \vartheta + \theta_a . \tag{1}$$

To ensure the safe operation of the equipment in long-term thermal stress, the actual standards require, for the materials used in electrical equipment and for its operating conditions, to not exceed maximum permissible temperatures in steady-state regime [5], [8]. When determining the temperature at which a landmark constructive work is a matter of knowing the ambient temperature θ_a, which in standards is 40 °C [4], [7].

Climate change leads to increased ambient temperature, which results in melting glaciers, hurricanes, catastrophic storms, floods, etc.

It is obvious that with increasing temperature a growing demand for electricity will occur in order to create a climate appropriate for living. By default temperature increase will reduce our ability to produce electricity in the condition we are making it today.

Increasing temperature leads to an increase in water evaporation thing that is defined by drought. So it had to use more energy intensive methods in order supplies water for irrigation and for drinking.

As the ambient temperature increases, the thermal stresses of the electrical equipment will be more pronounced, and thus it will be necessary for additional cooling installations which obviously have an additional consumption of electricity.

2 Long-Term Thermal Stresses of Electrical Equipment

Temperature is one of the most common indicator of the structural health of electrical equipment and its components.

Transformation of electromagnetic energy into heat occurs in active materials (conductive paths, ferromagnetic and insulating parts). The transfer is carried out by the heat transfer, the heat flow being always directed from areas with higher temperature to the areas with lower temperature, until the temperatures are equal. Thermal transmission is performed on known ways: conduction, convection and radiation. In the construction of electrical equipment, conductive paths are components that provide electrical conduction. When they are passed through the currents are subject to thermal stresses of variable intensity. Typically, the conductors are made of homogeneous busbar portions, subject to warming by electrocaloric effect produced under the action of current passing them.

The general equation of thermal conductive path has the expression:

(2)

where ρ_0, and γ are the resistivity and the conductor material density at 0 °C, α_R is the coefficient of the resistivity variation with the temperature, J is the current density, c is the specific heat, α_t is the global thermal transmissivity, ℓ_p is the length of the perimeter corresponding to the transversal section s, $\vartheta(t)$ is the conductive path's overtemperature.

Table 1 Admissible temperature values for different type of material

No.	Material	Constructive type	θ_{ad}, [°C]	θ_{kad}, [°C]
1	Copper	Busbar without insulation / painted	90	200
		Busbar with insulation	105	170
2	Aluminum	Busbar without insulation / painted	85	190
		Busbar with insulation	100	160

In order to ensure thermal stability of electrical equipment [2], [6], it is required that the final value θ_k of the temperature, at the moment t_k, to be under the rated limit for the nominal currents θ_{ad} and under θ_{kad} for fault currents, as in Table 1.

The study transient heating of path conductors for long-term thermal stresses is performed on the following simplifying assumptions: the conductor path is homogeneous, the overall thermal transmissivity and specific are considered invariable with temperature, temperature variation along the conductor is null and ambient temperature has a constant value. In order to determine steady-state overtemperature ϑ_p and thermal time constant T, was use equations (3), according to [2]:

$$\vartheta_p = \frac{\rho_0 J^2 s\left(1+\alpha_R\theta_a\right)}{\alpha_t\ell_p-\rho_0 J^2 s\alpha_R}, \qquad T=\frac{\gamma c s}{\alpha_t\ell_p-\rho_0 J^2 s\alpha_R}. \qquad (3)$$

It was considered two hypotheses of the critical current density to determine the transient overtemperature equation.

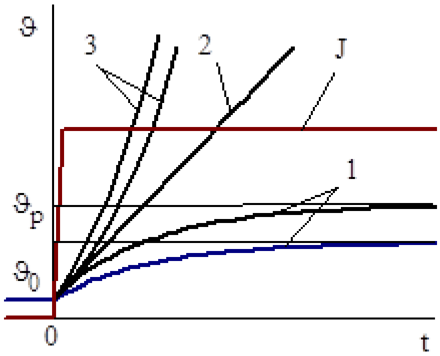

Fig. 1 Overtemperature transient state
1- the conductive path's steady-state overtemperature for long-term thermal stresses; 2, 3- the conductive path's overtemperature for short-term thermal stresses; J- current density

On hypothesis of that the critic value of the current density is:

(4)

equation (2) has the solution:

(5)

On hypothesis of $J \neq Jcr$, for equation (2) the solution is:

$$\vartheta(t)=\vartheta_p\left(1-e^{\frac{-t}{T}}\right)+\vartheta_0 e^{\frac{-t}{T}}. \qquad (6)$$

Corresponding to equation (6), in Fig. 1 there are presented the $\vartheta(t)$ of the transient heating state of the conductor path for long-term continuous stresses. The curves 1 s how the time evolution of the overtemperature corresponding to $J_1<J_2<J_{cr}$ for which it results $\vartheta_p>0$; $T>0$; the curve 2 corresponds to the solution (5) taking into account (4); the curves 3 presents the transient state time-varying of the overtemperature for $J>J_{cr}$ which corresponds to the fault regime. This last case, is characterized by unlimited growth of overtemperature in time, this warming occur under the action of short-circuit currents.

3 Electrical Equipment in a New Environment Temperature

Currently ambient temperature is on an upward slope [9], [10] mainly due to the activities of generation, transmission, distribution and consumption of electricity.

Until the electricity is used by smart phones, computers and many other electronics, it goes through three main stages: generation, transmission and distribution.

In electrical equipment the heat develops in a continuous fashion due to conversion of a part of the electromagnetic energy into heat. The main sources of heat from electrical equipment are covered conductors of electricity, iron cores crossed by time-varying magnetic fluxes, electric arc (open contact between tracks), active power losses from insulators and mechanical collisions. The other elements of the device, which are not sources of heat, can be strongly thermal stressed by heat propagation from one body to another through heat conduction. The heat that is developed in various parts of electrical equipment makes the temperatures to rise over time until a stationary value (corresponding steady-state), when the entire device is dissipating heat produced by convection to environment.

Electricity production has an obvious footprint on the climate change, due mainly to greenhouse gases [8], [14] emitted into the atmosphere, especially CO_2. Although at present we have alternative electricity production methods that are less polluting, and which implicitly affects less the environment, still vast majority of the global quantity of electricity is produced from burning fossil fuels [11], [12]. Referring to Fig. 2 we can see that the highest emission of the most predominant greenhouse gas, CO_2, comes from the generation of electricity and heat [16], [18].

To reduce the impact of greenhouse gas effect we have to find as many ways as possible to reduce emissions and where we can't we must find ways to increase their absorption. CO_2 is used by plants in photosynthesis process. But massive deforestation doesn't help to reduce emissions on the contrary. Thus, an increase in ambient temperature results in a decrease in the difference between ambient temperature and combustion temperature, reducing the efficiency of Diesel groups, boilers and turbines belonging to conventional power plants. In the case of gas turbines, the output power reduction is proportional to the temperature rise, for example, if it is estimated that a 5.5 °C increase in ambient temperature, this can reduce the production of electricity by about 3% to 4%.

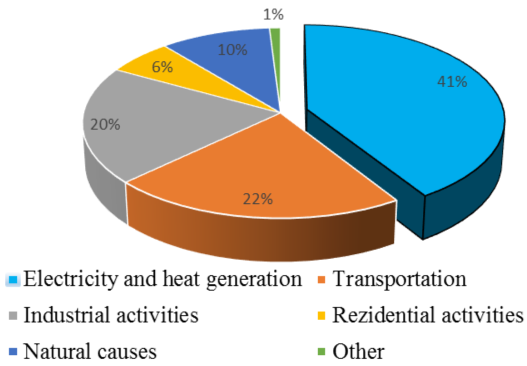

Fig. 2 CO_2 emissions from combustion of fossil fuels

Transmission and distribution of electricity have a life span of 30 to 50 years and together they represent approximately 40% of the total assets of electro-energetic system [8], [17]. Electricity transport networks are very important and must be managed and used optimally. For example, if one power plant fails, others can fill the gap of power, but if a line fails, other alternative transport network routes are not often available. From this point of view the supply and demand must be balanced, avoiding excessive voltage and frequency fluctuations, and electrogen systems should not pose a threat to people health and safety or to the environment.

Transmission and distribution networks can be sustainable if operating temperatures are maintained at safe levels, networks are not interrupted, and the distances from trees, people and buildings are kept safe [13], [19].

High temperature limits the rated overhead lines, underground cables and transformers but causing no immediate defects [18]. Network losses may increase by 1% if the temperature rises by 3 °C, in a network with an initial loss of 8% [8], [16]. So overloaded operation of transmission and distribution networks lead to an increase in energy losses by Joule effect, and implicitly contribute to global warming. With increasing ambient temperature, the electricity consumption will be higher due to the need for cooling in the spring season and especially in the summer [15]. To make a contribution to environment protection, the devices that use electricity must become more efficient and at the same time users have to become more efficient and to eliminate energy waste.

In some studies [21], [22], [23] it was presented that, theoretically, would result that if implemented globally, the best solution available to improve passive systems (almost independent of electricity) of residential buildings, factories and vehicles will reduce global electricity demand by up t o 73%. To which can be added an additional gain of more efficient production systems, transport and distribution of electricity, it can lead to a decrease in demand for electricity by 85%. But because of political and economic barriers those can't be achieved. Thus the only solution remains to adapt to climate change and find solutions that involve less investment and which do not depend on political decisions.

Adapting to meet electricity demand with increasing temperature there are three directions:

- increasing the electricity production (MWh);
- optimizing energy supplied (improving the efficiency of generation, transmission and distribution of electricity);
- improving the efficiency of the end use of electricity.

By following these directions during the history, it was recorded a relative steady improvement in efficiency since 1980 and this improvement can continue even without political interference [6], although the electricity consumption is considerable growing. However, measures to adapt to climate change may have a su bstantial impact. Assuming a scenario in which is taken into account an average warming by year 2100, and with modelling the energy consumption of cities in southern Europe in this period, will result an increasing demand for cooling, while the heating demand will decrease, this resulting in a net increase in electricity consumption [10].

4 Case Study

To see how much influence has the value of long-term thermal stresses of electrical equipment on climate change, it was taken for analysis a busbar system from a l ow-voltage switchboard, serving to drive a forging press.

In Fig. 3 is shown to internal view of switchboard, it can be identify the main circuit breaker Q1, busbar system, command and control equipment, soft starter U1 and its protective equipment.

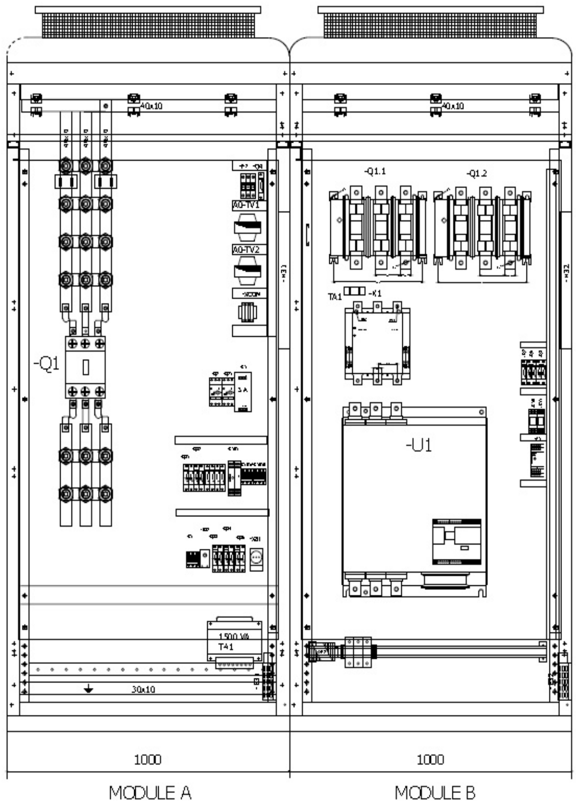

Fig. 3 Electrical switchboard under analysis

The busbar system for the switchboard of Fig. 3 consists of three copper bars associated with each phase, with protective earth system TN-C. Copper bar size is 40x10 mm and have a total length of 8.4 meters.

Functional parameters of switchboard are: nominal voltage 400 V, rated current of 690 A. The voltage of command and control circuits was 230 V.

To optimize the production, companies that produce electrical switchboards, often choose predetermined patterns when they have to size copper bars for low voltage switchboards. Also the copper bar mills have catalogues that offer standardized sizes of copper bars in accordance with IEC 60947-1 standard. Any other different size from those offered in catalogues has an additional cost.

Thus for switchboard taken for analysis, we see that for the rated current of 690 A is recommended to use a copper bar with a section between 350 ÷ 450 mm^2. In our case, the size is 40x10 mm, resulting a 400 mm^2 section area.

To determine which is the steady-state overtemperature rise and thermal time constant related to the copper bar was used equations (3), resulting, ϑ_{p1}= 31.74 °C and T= 2296.2 s.

This value ϑp_1 represents how much temperature will increase copper bar over ambient temperature after reaching permanent regime.

At first glance we can say that the bar undergoes a consistent heating, but in terms of the limits imposed by standards the temperature is acceptable. Maximum allowable temperature is 90 °C for this scenario, according to [18]. It is obvious that for this warming will have a loss of energy through proper Joule effect. To reduce energy loss and implicitly overtemperature value we must to increase the bar section.

Calculations have been performed to determine the steady-state overtemperature and thermal time constant for two other types of copper bars with different dimensions, namely 50x10 m m and respectively 60x10 mm. Overtemperature of steady-state and thermal time constant of copper bar 50x10 mm are ϑ_{p2}= 21.16 °C and T= 2391.8 s, respectively overtemperature of steady-state and thermal time constant of copper bar 60x10 mm are ϑ_{p3}= 15.16 °C and T= 2460.2 s.

The Fig. 4 illustrates transient state heating of copper bar for the 3 different sections taken for analysis.

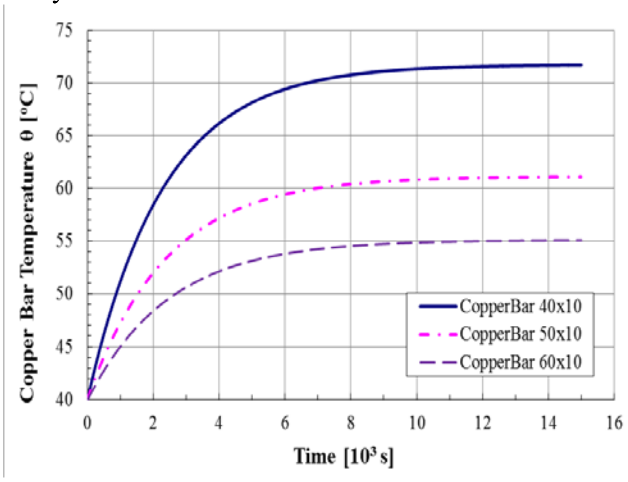

Fig. 4 Transient state heating regime for three copper bars with different sections until achieve continuous operating temperature

In Fig. 4 ambient temperature was considered 40°C, which represent the temperature inside the electrical cabinet. In case that the ambient temperature changes upward to 1 °C, the heating curves will shift one degree, according to the relationship (1). From this graph it can be seen that when the bar section is increased by 25% we get a temperature reduction of approx. 10 °C, and if the section is increased by 50%, we get a temperature reduction of approx. 15 °C. If it is chosen a higher section of the bar, the value of long-term thermal stresses will be lower. Increasing section of copper bar will drive up its costs, but still we will analyze whether this increase is justified in terms of protecting the environment.

The most pronounced environmental footprint is obvious comes from smallest section bar size, due to a higher temperature. To see how much the environment temperature is influenced by different sizes of copper bar was made an analysis for each bar size separately.

Influence on the environment has been equated by the emission quantity in kg of CO_2 which reduces with increasing copper bar section.

On the one hand we have a CO_2 reduction which will come from reducing energy demand in the power plant produced due to decrease energy losses. On the other hand we have an increase of CO_2 emission resulting from energy consumed to produce additional quantities of copper to for the new sections (50x10 mm or 60x10 mm).

It was considered both, the energy consumed by the electric switchboard and the energy needed to manufacture extra copper weight, energy produced exclusively from burning fossil fuels.

In the first phase, in Table 2, were determined energy losses by Joule effect for switchboard analyzed for the three sections considered.

Table 2 Total energy lost Joule effect for the sections considered

Copper bar size [mm]	Total energy losses [Wh]
40x10	846
50x10	812
60x10	785

Basically these losses of energy represent the heat source inside the switchboard. Switchboard must dissipate this heat all over the surface of metal cabinet.

With the growth of the section we will have a reduction of energy lost through heat comparing to the copper bar with size of 40x10 mm.

Table 2 shows this reduction is 34 Wh for new bar size of 50x10 mm and respectively 57 Wh for new bar size of 60x10 mm.

It was extrapolated this energy lost through to 1 year and have achieved a reduction of energy lost by 297.84 kWh for the 50x10 mm size and an energy lost reduction of 499.43 kWh for the 50x10 m m size.

At the same time was calculated the amount of copper required for larger sections. So for the 8.4 m of copper bar were required 7.76 kg for copper bar size 50x10 mm and respectively 15.08 kg for copper bar size 60x10 mm. From research reports [19], was determine the energy required to produce 1 kg of copper from sulfur copper ores.

Were obtained values between 16 ÷ 34.7 kWh per each kg of cooper manufactured, the variation of electricity consumed depends on copper quantity in a ton of rock, ranging between 0.5% ÷ 2%.

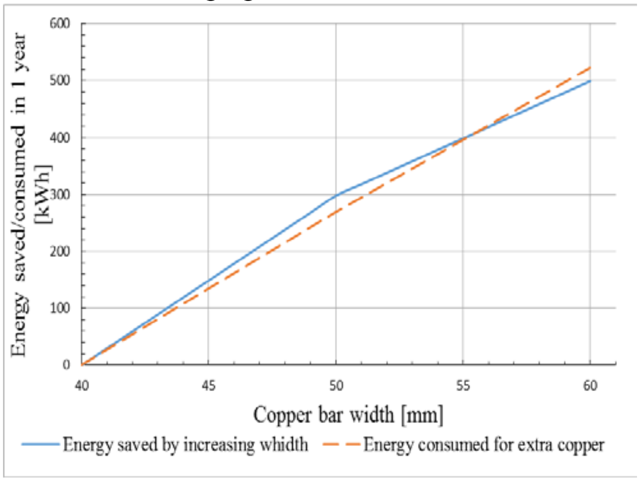

Fig. 5 Energy saved/consumed by increasing the copper bar size

If the amount of copper in the ore will be higher, the amount of energy consumed to produce 1 kg of copper will be lower. Rare times the amount of copper exceeds 2% in tone of rock. If is below 0.5% is not profitable to exploit the ore.

Therefore, considering the worst case (34.7 kWh energy consumption per manufacturing 1 kg of copper), were calculated quantities of electricity consumed for the additional amount of copper for each new size. It was obtained value of 269.27 kWh for copper bar with size 50x10 mm and 523.28 kWh for copper bar size 60x10 mm.

For switchboard analyzed, in Fig. 5 it is illustrated the electricity saved in one year, respectively electricity consumed to produce the amount of additional copper based on c opper bar width increasing. It can be noted that around 55 mm width of the cooper bar is the intersection of the two lines which indicate that the electricity saved is equal to electricity consumed.

Referring to Fig. 6 by withdrawing the energy needed to produce the additional weight of copper from the amount of energy saved from increased copper bar size, we can see that for a period of 1 year, can have a gain of 28.56 kWh for the bar size 50x10 mm. For bar size 60x10 mm will be nothing left of the initial electricity save, because by raising the copper bar the whole amount of energy gained plus 23.9 kWh will be needed for the production of extra copper.

When it is considered the power consumption of 34.7 kWh to manufacture 1 kg copper, in Fig. 6 it is illustrated the fact that for switchboard taken for analysis it is optimal in terms of reducing energy losses if the width of copper bar is increased up to 50 mm, where the maximum reduction is obtained. If will further increase copper bar width the gain energy lost decreases linearly up to a width of 55 mm, after which it becomes negative.

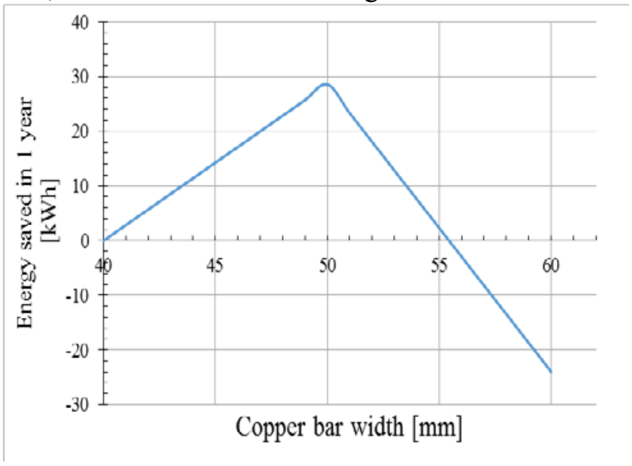

Fig. 6 The net gain in energy lost in a year for different values of copper bar width

To perform the analysis in terms of CO_2 emissions will be equivalent the energy saved as [12]. Table 3 centralize the equivalence for 1 kWh produced in kg CO_2 emitted.

Table 3 CO_2 emissions depending on the fossil fuel use per kWh

Fossil fuels		kg of CO_2 per kWh
Natural gas		0.56
Coil	bituminous	0.94
	subbituminous	0.97
	lignite	0.98
Oil	distillate	0.74
	residual	0.8

Was considered the worst case scenario, the electricity is produced from burning lignite, and meanwhile the electricity needed to produce extra weight of copper is at maximum rate, then the amount of CO_2 reduced in a year will be as much as 28 kg for the bar size 50x10 mm.

For the same scenario if the bar has the size 60x10 mm, we will not save anything even more emissions will occur according to additional 23 kg of CO_2 emitted by manufacturing extra weight of copper.

Considering that a mature tree can absorb in a year around 23 kg of CO_2, [20]. For the given scenario, we can say that replacing the initial copper bar of the switchboard with copper bar size of 50x10 mm in 1 year the environment can be protected from emission of CO_2 quantities that normally would be absorbed by one mature tree.

If the section size of the copper bar becomes 60x10 mm, it will not be beneficial either in terms of protecting the environment, because the amount of electricity needed for manufacturing the additional copper weight will be that high that can be equivalent to CO_2 emission corresponding to an additional cutting of one mature tree.

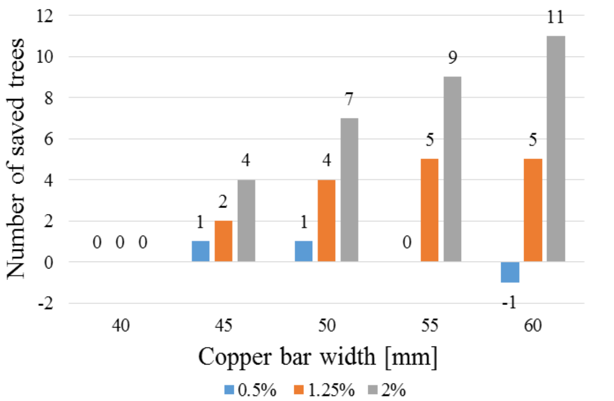

Fig. 7 The number of saved trees depending on copper bar width for different percentages of existing copper in 1 ton of exploited rock

In Fig. 7 is shown the number of saved trees depending on the increasing the width of copper bar, for switchboard analyzed, when varying the percentage of existing copper in 1 ton of exploited rock. For this comparative analysis CO_2 emission equivalence was made for energy produced from burning lignite as Table 3. Copper bar with a width of 40 mm was taken as a r eference for calculating over the benefits of other bar widths.

Thus in Fig. 7 it is observed that by increasing copper bar dimensions it can be reduced the environmental impact. As copper percentage in ore mined will be higher, as much environmental benefits will be greater due to the increase width bars. But, for the analyzed case, when the copper percentage in minimal in 1 ton rock exploited, the optimal bar size in terms of protecting the environment is only the bar with the width of 50 mm.

5 Conclusions

As the ambient temperature is higher the energy lost by Joule effect will be higher. Constantly is needed to find new measures to protect the environment because either the ambient temperature increase or decrease this leads to an increase in electricity consumption.

From the case study it was observed that the size of the long-term thermal stresses of electrical equipment values decreases with increasing copper bar section. Meanwhile it occurs a reduction of energy lost by Joule effect leading to reduction of electricity produced.

From the analysis of increasing copper bar section were obtained interested benefit in the environment protection that may be brought by this solution. Thus by replacing copper bars from initial size of 40x10 mm with a size of 50x10 mm, for switchboard with 2 modules taken for analysis, it has achieved a r eduction of emission of CO_2 in a year, regardless of the percentage of existing copper in ore mined. Even in the worst case scenario by increasing the copper bar size to 50x10 mm, was reduced CO_2 emissions equivalent to the amount absorbed by one mature tree. As percentage of existing copper in the ore is higher, the higher will be the environmental benefits by increasing the size of the bars.

Even if, in the analyzed case, over sizing the copper bar at first glance appears to be an uneconomic solution, it can bring significant benefit in fighting climate change and can support sustainable development.

Taking in account the positive environmental influence brought by only one electrical switchboard, in the analyzed case, it can say that if the solution is applied to all existing electrical switchboard from electrical installations it can be saved a whole forests of mature trees.

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