THERMAL LOSSES OF TRIPPING UNIT IN A CIRCUIT BREAKER

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Abstract: Protection devices help protect us against things that may go wrong with electricity. Increasing of the electricity consumption goes hand in hand with increasing of living standards. Therefore in the low voltage networks, there are increasing short-circuit currents. Novel technologies imply considerable demand on the performance, security and switching capacity of circuit breakers, respectively. This paper deals with an analysis of thermal losses of a new type low voltage circuit breaker. Thermal losses are computed using the finite element method (FEM).

Keywords: Circuit Breaker, Low Voltage, Joule Heat, Current Density, Thermal Trip Unit, Skin Effect, FEM

1. INTRODUCTION

Circuit breaker is one of the most important electrical switches. It provides automatic current interruption in case of an overcurrent in an electrical circuit.

According to the assessment methods point of view, molded case circuit breakers are distinguished as a thermomagnetic and an electronic. Thermomagnetic tripping unit includes a bimetal which trips a circuit breakers in case of an overcurrent (a low common multiple of the rated current) and an electromagnet which evaluates the short circuit (the higher multiples of the rated current). Electronic tripping units contain a microprocessor that monitors and evaluates the overcurrent.

2. STARTING POINT OF A DESIGN

Basic function of a tripping unit consists of generation of a tripping pulse when the circuit-breaker current exceeds the allowed positive deviation of the rated current. Model of the tripping unit used in the presented calculations is plotted in Fig. 1.

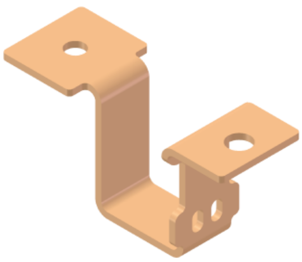

Figure 1: Model of tripping unit of a circuit breaker

The value of the material thickness can be parametrically varied either to the 2 or 3 mm. Common materials for the productions are: bronze, copper, brass and nickeline. Rated current passing through the model of the tripping unit is of 100, 160, 200 and 250 A. The simulation is aimed to the AC and DC overload with the power frequency. An effect of heating on specific electrical resistance and power losses will deal with in another paper.

3. THEORY

The thermal tripping unit provides tripping impulse in case of an overcurrent. An appropriate functionality of the bimetal is ensured due to Joule losses, which occurs during the current flow.

Heating of a material is caused by transferring part of electrons kinetic energy to particles, which do not contribute to the electric current (positive ions). The thermal motion of the particles is accelerating, and the material is heated. Joule losses are proportional to the RMS value of passing current. (Eq. 1)

$$P = R \cdot I^2 \qquad (W; \Omega, A) \tag{1}$$

The voltage drop is given by Ohm's law (Eq. 2).

$$\Delta U = R \cdot I \qquad (V; \Omega, A) \tag{2}$$

This equation describes the loss of the electrical voltage in the electrical current passing through the tripping unit with the electrical resistance of the material (R). Electrical resistance can be expressed by the following equation:

$$R = \rho \cdot \int \frac{dl}{S} \quad \left(\Omega; \Omega \frac{m^2}{m}, m, m^2 \right), \tag{3}$$

where ρ is the specific electrical resistance (resistivity of the material), which characterizes the electrical conductivity of the substance, depending on temperature. The higher specific electrical resistance the lower conductivity of the substance. The S is the conductor cross-section and l is the length of the material.

Alternating electric current creates a magnetic field around the thermal tripping unit and it will give rise to the skin effect. Skin effect is a tendency of an AC to distribute itself within a conductor with the current density being largest near the surface of the conductor, decreasing at greater depths. Skin effect is directly proportional to the value of:

- Frequency
- Cross-sectional area of the conductor
- Conductivity of the conductors material
- The relative permeability of the conductors material

Attenuation of the wave through the magnetic field in the conductor is given by the penetration depth δ according to the following equation:

$$\delta = \sqrt{\frac{2}{\omega \cdot \mu \cdot \gamma}} = \frac{1}{\sqrt{\pi \cdot f \cdot \mu \cdot \frac{1}{\rho_T}}}, \tag{4}$$

where f is frequency of the alternating current, μ is relative permeability, and ρ_T is resistivity of the conductor.

Penetration depth for the materials used at the power frequency of the rated current I_n:

The frequency of electrical current *In*	Penetration depth δ [mm]			
	copper	brass	bronze	nickeline
50 [Hz]	9,47	18,97	26,16	45,03

Table 1: Penetration depth according to the material and the frequency of the electrical current.

4. FINITE ELEMENT METHOD

The principle of this method consists in a discretization of the continuum into a finite number of concrete elements.

Three dimensional element SOLID69 is enables simulation of heat and electric field conduction. Joule losses are generated by the electric current passing throw this element. The heat is divided into an accumulated and a disbursed.

Three dimensional element SOLID97 allows to simulate magnetic, electric and heat field conduction. This element is used for the surrounding environment (air) and thermal tripping unit in the simulation of AC. The flux lines of the magnetic induction flow are enveloped around this thermal tripping unit. Part of this flow passes through the conductor thus skin effect appears.

The value of the magnetic field intensity on the surface of the thermal tripping unit is based on the Ampere's law:

$$\oint_l \underline{\mathbf{H}} \cdot d\mathbf{l} \approx \underline{H}_o 2b \approx \underline{I} \Rightarrow \underline{H}_o = \frac{\underline{I}}{2b} \tag{5}$$

Subsequent treatment of the Eqn. (5) leads to the expression of the current density - Eqn. (6)

$$\underline{J} = \frac{\underline{k}\underline{I}}{2b} \cdot \frac{\cos \underline{k}x}{\sin \underline{k}a}, \tag{6}$$

where $\underline{J}$ is the current density, $\underline{k}$ is the wave vector, $\underline{I}$ is the harmonic current, $\underline{a}$, $\underline{b}$ are the dimensions of the cross-section of the thermal tripping unit and $\underline{H_o}$ is the intensity of magnetic field on the surface of the thermal tripping unit.

In case that b >> 2a, influence of the thickness thermal tripping unit on the magnetic field is neglected.

The following equation describes the thermal equilibrium of the element, where the vector $\vec{\phi}$ characterizes the disbursed flow of heat from the solid element Ω_A, across its border $\partial\Omega_A$. The surface of the solid element Ω_A is accounted for by the vector $\vec{n}$. The heat of the solid element Q is a scalar value and it contains the Joule losses.

$$\forall \Omega_A, \int_{\Omega_A} Q dv = \int_{\partial\Omega_A} \vec{\phi} \cdot \vec{n} ds \tag{7}$$

5. SIMULATION RESULTS

Graphical illustration of the Eqn. 2 is presented in Fig. 2 - the voltage drop in the tripping unit of circuit-breaker made from bronze, with a thickness of 3 mm and the resistance R.

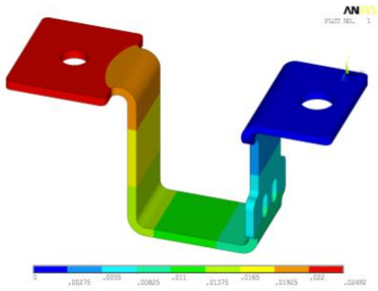

Figure 2: Voltage drop [V] with a rated current of DC 100 A, material bronze - 3 mm.

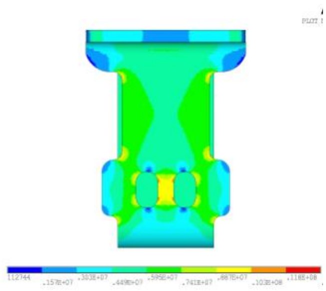

Figure 3: Current density [A/m^2] with a rated current of DC 100 A, material bronze - 3 mm

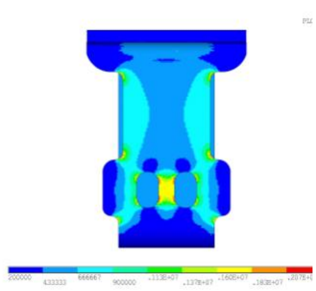

Figure 4: Joule losses [W/m^3] with a rated current of DC 100 A, material bronze - 3 mm

In Fig. 3, the density of electric current is plotted. Increasing density of the electric current between holes, which are used to fix bimetal, can be seen. These holes have rounded corners to eliminate the concentration of the density of electric current. For this reason, there was created a parallel path on the outer side of these holes.

Joule losses in the tripping unit of circuit-breaker are plotted in Fig. 4. The highest losses arise in the areas with the highest density of the electric current - see Fig. 3.

These losses ensure the correct function of bimetal. Appropriate combination of material and the thickness of the tripping unit ensure the circuit breaker tripping by low multiple of the rated current I_n (striking of pin (placed on the end of the bimetal) onto the thermal access strip).

Total sum of all of these losses is of 2,49 W (3mm bronze).

The results of simulations are summarized in the Table 2.

Material od TTU	Rated current *In* [A]	Thickness of TTU					
		2 mm ΔU [mV]	3 mm ΔU [mV]	2 mm Pz [W]	3 mm Pz [W]	2 mm ΔPz [%]	3 mm ΔPz [%]
Copper	100	4,81	3,44	0,48	0,34	0,03	0,04
	160	7,69	5,50	1,23	0,88	0,03	0,04
	200	9,61	6,87	1,92	1,37	0,03	0,04
	250	12,03	8,59	3,01	2,15	0,03	0,04
Bronze	100	35,28	24,92	3,53	2,49	0,00	0,00
	160	56,45	39,88	9,03	6,38	0,00	0,00
	200	70,56	49,85	14,11	9,97	0,00	0,00
	250	88,20	62,30	22,05	15,58	0,00	0,00
Nickeline	100	102,85	72,53	10,29	7,25	0,00	0,00
	160	164,55	116,05	26,33	18,57	0,00	0,00
	200	205,68	145,10	41,14	29,02	0,00	0,00
	250	257,10	181,33	64,28	45,33	0,00	0,00
Brass	100	18,79	13,20	1,88	1,32	0,00	0,01
	160	29,89	21,12	4,78	3,38	0,00	0,01
	200	37,36	26,40	7,47	5,28	0,00	0,01
	250	46,70	32,98	11,68	8,25	0,00	0,01

Table 2: The voltage drops, power losses and the influence of skin effect for materials with different thickness of thermomagnetic tripping unit.

Power losses of the tripping unit for different materials and thicknesses (2 to 3 mm) are graphically illustrated in Fig. 5. The power losses are increasing with the square of the current (Eq. 1). Based on practical measurements, one can see that the average value of the power losses is between 3 and 5 W. These values are suitable for the function of the bimetal.

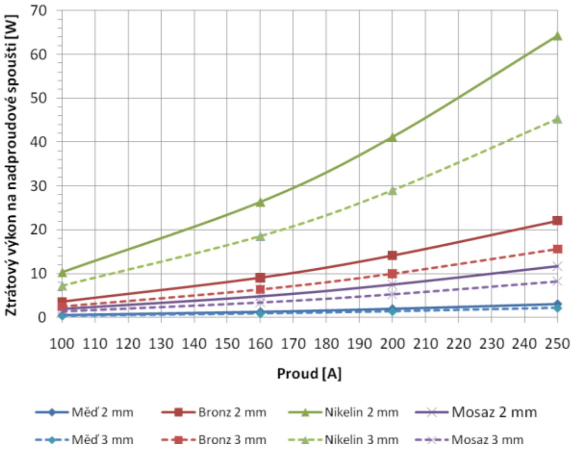

Figure 5: Power loss of the thermomagnetic tripping unit for different materials and thicknesses

Rated current *In*	Recommended materials and thicknesses thermomagnetic tripping unit	
[A]	[-]	[mm]
100	Bronz	2
160	Mosaz	2 to 3
200	Mosaz	3
250	Měď	2

Table 3: Recommended material and thicknesses thermomagnetic tripping unit.

6. CONCLUSION

Three-dimensional model of tripping unit enables to take advantage of modern numerical methods, such as FEM, for control of the devices, already used in the industry or for the assessment of the critical areas during the development of new devices. Critical area of the tripping unit model is located between the holes used for the fixation of the bimetal.

Conclusion drawn from the simulations:

a) Parallel path for the electric current in the critical area was designed correctly.

b) Material nickeline is not suitable for this tripping unit, because of high losses.

c) There is no influence of the skin effect on the geometry of this model.

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