Analysis of Electrical and Thermal Characteristics of Thermal Cutoffs

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Abstract – **This paper presents the results of investigation of thermal cutoffs' characteristics in electrical and thermal domain by FEA. Radial S-type thermal cutoffs of two characteristic cut-off temperatures are simulated in steady state and transient regime. Dependences of rated functioning temperature, holding temperature, temperature rise and response time on different design parameters of cutoffs are analyzed. On the basis of the obtained simulation results optimization of geometry and dimensions of constitutive elements of thermal cutoffs is proposed.**

Keywords – **Thermal cutoffs, Electrical and thermal characteristics, FEA, Design optimization.**

I. Introduction

Reliable operation of different home appliances, electric industrial and office automation equipment demands their protection from the overheating. For that purposes thermal cutoffs are utilized. They detect abnormal temperature rise in the device caused by conducting current above the rated value or by excess surrounding temperature and permanently open the electrical circuit. These are non-reset device type and act as the last protection components.

Functioning of thermal cutoffs is based on the property of low-melting alloy that fuses conducting parts to melt at the specified temperature (*cutoff temperature* - T_{CUTOFF}) thus breaking the connection between them. The basic classification of thermal cutoffs is by construction, rated functioning temperature and electrical ratings [1]-[3]. Construction of thermal cutoffs depends on the design of temperature sensing part (with special shrinking resin or spring), shape and dimensions of the leads (axial, radial or strip) and type of the packaging (ceramic, plastic or metal). Rated functioning temperature is defined by melting temperature of fusing alloy and ranges from 70°C to 240°C. Electrical ratings include different values of AC or DC current and voltage which determine cutoffs' operating conditons.

Thermal ratings of one type of cutoffs specify values of cutoff temperature, rated functioning temperature and holding temperature, as well as their tolerances. *Rated functioning temperature* - T_F is the temperature at which thermal cutoff changes its state of conductivity to open a circuit with detection current as the only load. Tolerances of this value are from -10°C to +0°C and it is usually for a constant value (dependent on the packaging) higher then the cutoff temperature. *Holding temperature* - T_H is the maximum temperature at which thermal cutoff can be maintained while conducting rated current for 168 hours without functioning.

Beside thermal ratings which are crucial for appropriate implementation of thermal cutoffs, their quality and reliability are governed by performance data such as temperature rise due to *Joule* heating and response time [4]. Temperature rise is determined by properties of conducting parts and thermal properties of packaging. Response time is time for opening the cutoff after immersion into the silicon oil bath of specified temperature and is mainly dependent on thermal properties of constitutive elements.

Design and optimization of thermal cutoffs include determination of specified thermal and electrical ratings and performance data. For that purposes appropriate Finite Element Analysis (FEA) of electrical and thermal characteristics of cutoffs is employed.

In this paper results of electrical and thermal characteristics analysis of radial S-type thermal cutoffs by 3D numerical simulation are presented. Holding temperature and temperature rise for two types of cutoffs are determined by steady state simulation, while small displacement transient simulation is utilized for rated functioning temperature and response time investigations. Different geometries and dimensions of constitutive elements are considered. Optimization remarks from material consumption, manufacturing complexity and quality and reliability points of view are outlined.

II. Construction of Thermal Cutoffs

Analyzed thermal cutoffs are with spring (S type) and radial leads, placed in plastic package. They are aimed for operation at rated current of 12 A and voltage of 250 V AC. Mechanical connection with the device under protection is made by classical soldering at free ends of the leads. Construction and main constitutive elements of considered cutoffs are shown in Fig. 1.

Active parts of the cutoff are soldering sheets made from low melting alloy which connect contact heads of the leads with conducting strip inside the package. Spring placed inside the package cap is compressed and it presses the strip. At normal operating temperatures there is an electrical conducting path between the leads. When cutoff temperature is reached alloy melts at the soldering sheets and the spring pushes the strip into the space above the leads. This space is filled by insulation fluid (in this case it is air), so conducting path is permanently cut off.

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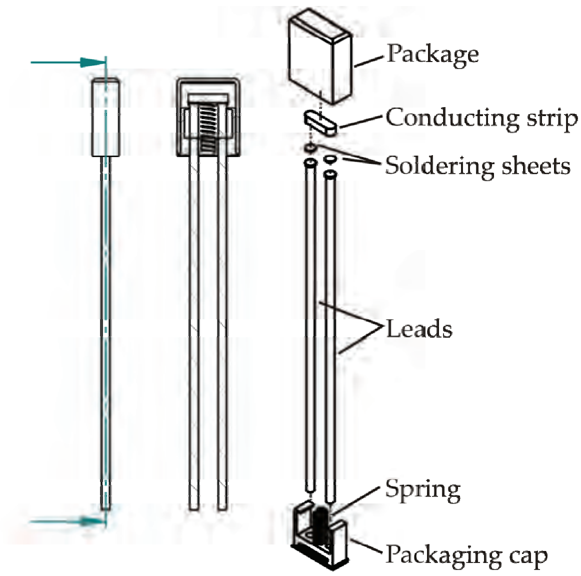

Fig. 1. Construction of thermal cutoffs

Values of characteristic dimensions of cutoff's elements, as well as materials they are made from, are listed in Table I.

TABLE I
CHARACTERISTIC DIMENSIONS AND MATERIALS OF CUTOFF'S ELEMENTS

Element	Material	Characteristic dimension	Value (mm)
Lead	Copper	Length	57
		Diameter	1,2
		Contact head diameter	1,6
		Contact head thickness	0,25
Conducting strip	Copper	Length	5,6
		Width	1,6
		Thickness	0,6; 0,9; 1,2
Soldering sheet	Low melting alloy	Diameter	1,2; 1,6
		Thickness	0,15
Packaging	Makrolon (poly-carbonate)	Height	11
		Width	8,8
		Depth	3,8
		Cap height	4
		Wall thickness	0,5; 1
Spring	Steel	Diameter	1
		Length	3

Two low melting alloys are considered as the soldering sheet material. The first one is 42%Sn-58%Bi with melting point of 138ºC. This is an eutectic alloy often used as Pb-free soldering material [5] and it is exploited in thermal cutoffs (S-138 type) for protection of power electric motors. The second is ternary eutectic alloy 52,5%Bi-15,5%Sn-32%Pb whose melting point is 95ºC. Thermal cutoffs operating with this alloy (S-95 type) are aimed for protection of water heating devices. Soldering sheets made from these alloys have microstructure with grater percentage of tin at the surface, which enables more efficient soldering of elements in cutoffs manufacturing processes [6].

Properties of cutoff elements' materials included in simulation incorporate their basic physical, electrical an thermal parameters [7], [8].

III. SIMULATION PROCEDURE

Simulation is performed with software that complex multiphysics problems solves numerically utilizing finite element analysis and multigrid approach [9]. It solves *Maxwell's* equations simultaneously with heat generation/transmission and elasticity equations. Through appropriate user interface geometry, dimensions and materials of cutoffs are given, load conditions are set and obtained solution is displayed graphically.

Load conditions define symmetry and degrees of freedom of cutoffs, values of conducting current, and method and areas of heat dissipation. Cutting plane from Fig. 1 presents symmetry boundary condition, while free ends of the leads are considered fixed. End of one lead is set to zero referent potential, while through second lead currents up to 15 A are applied. It is assumed that cutoffs are mounted in vertical position and heat exchange with bulk is by convection from free surfaces. Rated functioning temperatures, holding temperatures and temperature rise are determined for air as ambient fluid, while response time determination specifies silicon oil as surroundings. Values of convection coefficients in both cases are calculated according to [10] and assumed to depend on shape and orientation of the surface, thermal characteristics of the fluid and temperature difference between the surface and the bulk.

IV. RESULTS

Temperature of the soldering sheets under various operating conditions is of main interest in design and optimization processes of cutoffs. Its dependence on bulk temperature and applied current enables determination of rated functioning and holding temperatures important for cutoffs' implementation specifications. Distribution of temperature in S-138 cutoff at 12 A rated current and with bulk temperature 27°C is shown in Fig. 2. Vector presentation of current density distribution under the same condition is shown in Fig. 3. From these figures it is evident that maximum current density and consequently maximum temperature due to *Joule's* heating, exists at the boundary of conducting strip and soldering sheets. High thermal conductivity of leads, conducting strip and soldering sheets, as well as low thermal conductivity of package and air inside it, result that generated heat is mainly dissipated by convection from free surfaces of the leads. Also, range of temperature of conducting parts is only 1,5°C. The same qualitative distribution of temperature and current density exists in S-95 cutoffs, with slightly different maximum values [11].

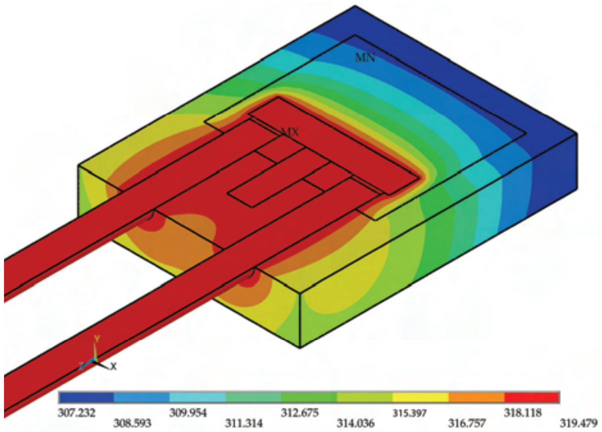

Fig. 2. Distribution of temperature (in K) in S-138 cutoff at rated current 12 A at bulk temperature of 27°C

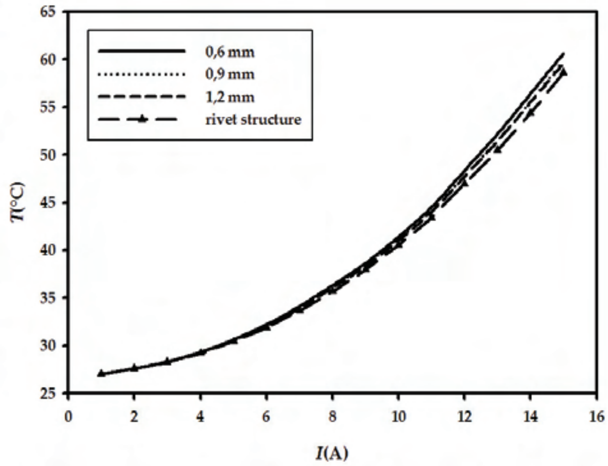

Fig. 4. Temperature rise in S-95 cutoff for different conducting strip thicknesses at bulk temperature of 27 °C

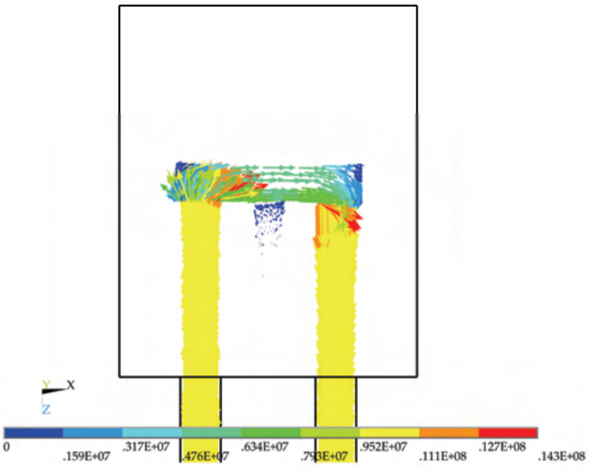

Fig. 3. Distribution of current density in S-138 cutoff at rated current 12 A at bulk temperature of 27°C

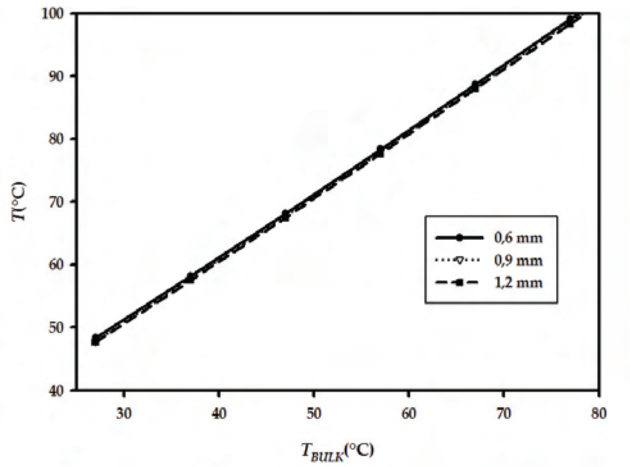

Fig. 5. Dependence of soldering sheets temperature on bulk temperature in S-95 cutoff with applied current 12 A for different conducting strip thicknesses

Temperature of soldering sheets in S-95 thermal cutoffs for different applied current at bulk temperature of 27°C is shown in Fig. 4. Temperature rise due to electro-thermal effects is less than 35°C even for currents 20% above rated 12 A. Simulation of S-138 thermal cutoffs gave similar dependence, with little lower temperature values due to higher conducting properties of applied alloy.

Dependence of soldering sheets temperature on bulk temperature for applied rated current of 12 A for S-95 thermal cutoff is shown in Fig. 5. From this figure holding temperature T_H is determined as the temperature of bulk at which cutoff temperature is reached and it is 78°C. Also, for S-138 thermal cutoffs this temperature is determined as 115°C.

For optimization purposes thermal cutoffs with different conducting strip thicknesses and changed contact heads of leads are simulated. Initial strip thickness value of 1,2 mm is decreased to 0,9 mm and 0,6 mm and dependencies of soldering sheets temperatures are analyzed. From Fig. 4 it is evident that decrease of strip thickness to 0,9 mm does not affect temperature rise, while for thickness of 0,6 mm it is slightly increased. Also, dependencies from Fig. 5 show that holding temperature remains unchanged in all cases. On the basis of the above considerations decrease of strip thickness to 0,9 mm is justified since thermal cutoffs performances remain unchanged, while better manufacturing capabilities and less material consumption are achieved.

In the second analysis contacting heads of leads are formed in rivet shape whose dimensions are listed in Table I and soldering sheets are adjusted appropriately. Riveted contact heads enable better mechanical characteristics of soldered joints. Considering electro-thermal characteristics, from Fig. 4 it is evident that temperature rise is decreased about 1°C for rated current value (for the second type of cutoffs it is about 0,5°C). These improvements are minimal and change of initial design is not justified since it involves additional manufacturing steps.

Rated functioning temperature and response time determination of thermal cutoffs demand transient analysis. Standards prescribe rated functioning temperature as the temperature at which cutoff is opened when operating in ambient whose temperature is set to 20°C bellow cutoff temperature and afterward gradually raised by 1°C/min. Simulation results for such boundary conditions of soldering sheets temperature in time for both cutoff types are presented in Fig. 6. Rated functioning temperatures determined from this figure are 1°C above cutoff temperatures (T_F=96°C for S-95 and T_F=139°C for S-138 type), due to high thermal conductivity of cutoff's elements.

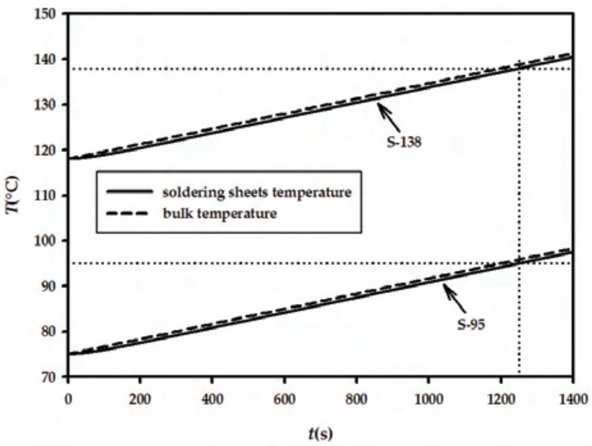

Fig. 6. Dependence of soldering sheets temperature for rated functioning temperature determination

Simulation results of soldering sheets temperature after immersion of S-95 cutoff maintained at 27°C into silicon oil bath whose temperature is ΔT above cutoff temperature is shown in Fig. 7. Similar dependencies are obtained for S-138 cutoff type. Response times determined on the basis of these curves for both types are plotted in Fig. 8 which could be used for quality verification of cutoffs with different constructions. It is evident that response time is strongly dependent on cutoff temperature and temperature of the silicon oil bath.

Also, cutoffs with reduced package wall thickness (0,5 mm) are investigated and no changes in rated functioning temperature and response time are observed. Therefore, since mechanical characteristics of cutoffs depend on this thickness, greater value is preferable.

V. Conclusion

On the basis of finite element analysis of electrical and thermal characteristics for two types thermal cutoffs, their rated functioning and holding temperatures are determined. Response time dependencies of thermal cutoffs for their quality specification are obtained. Change of conducting strip thickness is proposed as an optimization result, with minimization of material consumption and simplicity of manufacturing processes being design goals. On the other hand, it is concluded that rivet shape of contact heads of the leads introduces minor improvements into thermal characteristics of cutoffs and initial flat shape is optimal. Moreover, simulation showed that reduction of packaging wall thickness does not influence on time dependent parameters of cutoffs (rated functioning temperature and response time).

Acknowledgement

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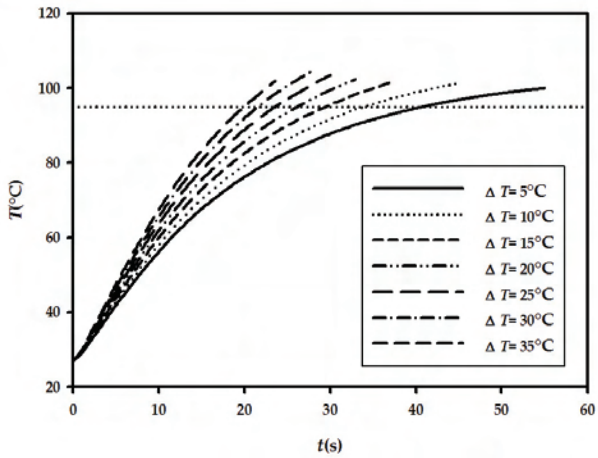

Fig. 7. Change of soldering sheets temperature with time in S-95 cutoff for different silicon oil temperatures

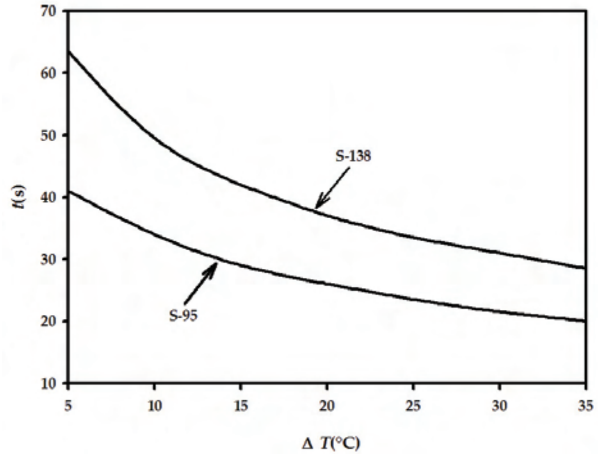

Fig. 8. Response time of cutoffs

References

[1] "Thermal cutoffs", World Thermo Corp., Taiwan, 1995.

[2] http://www.us-electronics.com/files/Thermalcutofffuses.pdf.

[3] PANASONIC-Thermal Cutoffs – Data sheet.

[4] NEC-Thermal Cutoff SEFUSE – Data sheet, 1996.

[5] F. Hua, Z. Mei, and J. Glazer, „Eutectic Sn-Bi as an Alternative to Pb-Free Solders", in *Proc. of Electronic Component and Technology Conference,* pp. 277-283, 1998.

[6] A. Prijić, B. Pešić, Z. Prijić, „Karakterizacija niskotopivih legura za primenu u termičkim prekidačima", Zbornik radova L konferencije ETRAN, IV sveska, pp. 119-122, Beograd, Srbija i Crna Gora, Jun, 2006.

[7] http://www.indium.com/products/tableofalloys.xls.

[8] J. Rigdeon, *Macmillan Encyclopedia of Physics.* Simon & Schuster, 1996.

[9] ANSYS 8.0 Inc.

[10] C. Popiel, J. Wojtkoviak, „Experiments on free convective heat transfer from side walls of a vertical square cylinder in air", Experimental thermal and fluid science, Vol. 29, No. 1, pp. 1-8, 2004.

[11] A. Prijić, B. Pešić, Z. Prijić, D. Pantić, S. Ristić, „Analiza karakteristika termičkih prekidača 3-D numeričkom simulacijom", Zbornik radova VI simpozijuma o industrijskoj elektronici INDEL 2006, pp. 48-52, Banja Luka, Republika Srpska, Novembar, 2006.