COST EFFECTIVE METHOD FOR THE STUDY OF THE SHORT-CIRCUIT BEHAVIOUR OF AN ELECTRICAL RESISTOR

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1.- INTRODUCTION

Electrical power lines all over the world use electrical resistors for two main purposes: reduction of short-circuit currents and filtering. In the first case a Neutral Earthing Resistor is connected between the neutral conductor and the earth causing a reduction on current level for the same voltage load. In the second case, a filter composed by the resistor, capacitors and/or inductances is used to clean the electrical signal from undesired harmonics or noise. In both cases, the geometrical solution adopted to manufacture the resistor can be similar.

One of the most employed geometries consist on different flat steel plates connected in series or parallel and embedded in a resistant frame, such of the case exposed on Figure 1.

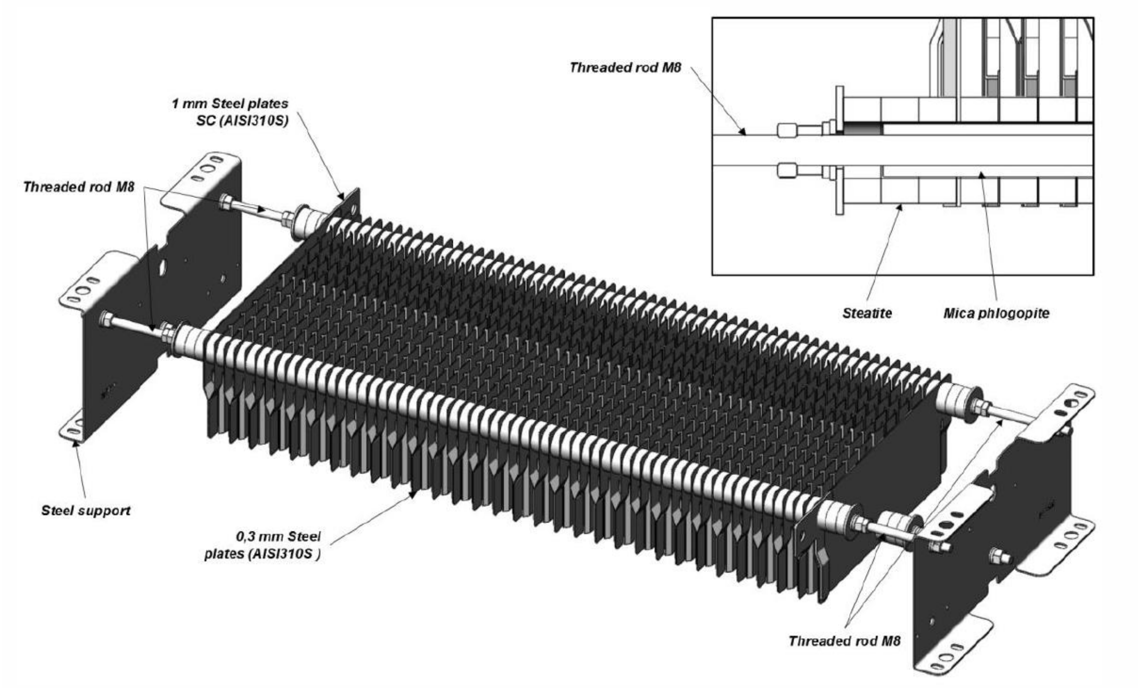


Fig 1. Part of a resistor with 59 plates block geometry.

Once the resistor is under load, the electrical current circulating across the plates heat up the steel causing variations on the resistivity of the material, which implies changes on the resistor ohmic value. The temperature level reached in the steel also modifies the mechanical properties of the material, so mechanical, thermal and electrical phenomena are coupled in this problem.

The mechanical resistance of the resistor must be certified in accordance with IEC 62001 standard [1] in order to guarantee the proper operation of the element. This can be done by means of experimental test under load and verifying the mechanical stress achieved in the resistor. Nevertheless this methodology requires experimental equipment and procedures which results in an expensive and time-consuming method.

With the evolution in last decades of different programs for Finite Elements Analysis (FEA), an alternative to verify the standard requirement appears. In the following sections the methodology proposed and its application to a case of study for the Ethiopia-Kenia Power Systems Interconnection is shown.

2.- MATERIALS AND METHODS

Although it has not been found in the literature an application of multiphysics analysis to the structural behavior of an electrical resistor, some authors have done similar things for inductive devices [2] or thermoelectric generators [3]. More recently, Keyvani and Shayegani [4] have optimized the size of neutral resistors when used in high inductance-earthed network for reducing the overvolatages caused by inductive current interruption. The authors used a model developed under the PSCAD/EMTDC. From the experimental point of view, Mohamad et al. [5] analyzed the experimental performance of earthing systems with 2, 3 or 4 electrodes, concluding that more experimental studies are necessary to fill the gap between models and obtained results.

An alternative to the multiphysics analysis with FEA can be the use of a reduced-order circuit, which has been validated in transformers [6].

The FEA code used throughout the analysis is ANSYS Mechanical Enterprise (release 19.0), provided by ANSYS, Inc. (USA). Two models have been used to evaluate both the electro-thermal and the structural behavior of the filter resistor blocks. The element types employed to model the resistor blocks are described in the following paragraphs.

2.1 Description of elements used

BEAM189 [7] element is used to simulate the threaded rods that support the plates. It is suitable for analyzing slender to moderately stubby/thick beam structures. This element is based on Timoshenko beam theory and shear deformation effects are included. This element is a quadratic (3-node) beam element in 3-D. It has six or seven degrees of freedom at each node, being the default six degrees of freedom. These include translations in the x, y, and z directions and rotations about the x, y, and z axes. A seventh degree of freedom (warping magnitude) is also considered. This element is well-suited for linear, large rotation, and/or large strain nonlinear applications.

The element type SHELL157 [7] is used to model the steel plates that form the filter resistor for the electro-thermal analysis. This is a 3-D element having in-plane thermal and electrical conduction capability. The element has four nodes with two degrees of freedom, temperature and voltage, at each node. The element applies to a 3-D, steady-state or transient thermal analysis, although the element includes no transient electrical capacitance or inductance effects. It requires an iterative solution to include the Joule heating effect in the thermal solution. If the model containing the thermal-electrical element is also to be structurally analysed, it can be replaced with an equivalent structural element, such as SHELL181.

The element type SHELL181 [7] is used to model the steel plates that form the filter resistor for the structural analysis. This element is suitable for analyzing thin to moderately-thick shell structures. It is a four-node element with six degrees of freedom at each node: translations in the x, y, and z directions, and rotations about the x, y, and z-axes. It is well-suited for linear, large rotation, and/or large strain nonlinear applications. Change in shell thickness is accounted for in nonlinear analyses. In the element domain, both full and reduced integration schemes are supported. SHELL181 accounts for follower (load stiffness) effects of distributed pressures.

The element formulation is based on logarithmic strain and true stress measures, and element kinematics allow for finite membrane strains (stretching). However, the curvature changes within a time increment are assumed to be small.

Elements CONTA175 and TARGE170 [7] are used to connect the resistor plates (shell elements) to the threaded bars (beam elements). Both elements define what ANSYS calls a "force-distributed constraint": In this type of constraint, forces or displacements applied on the pilot node are distributed to contact nodes (in an average sense) through shape functions.

2.2 Procedure

The Multiphysics simulation is performed according to the schematic flow drawing of Figure 2. In a first step, a transient electro-thermal analysis is performed in order to obtain the temperature distribution in the resistor plates over time. No energy dissipation is considered in the resistor plates (adiabatic system) and consequently all the generated energy by the Joule effect is stored by the resistor plates as internal energy. After this, a static structural analysis is performed every 0.1 seconds using as input the resulting temperature distributions from the electro-thermal analysis, obtaining the efforts produced when the thermal expansion of the resistor plates is constrained by the supporting threaded bars. The maximum stress values obtained from the structural analysis are evaluated according to the material properties of the different components. In the following figure.

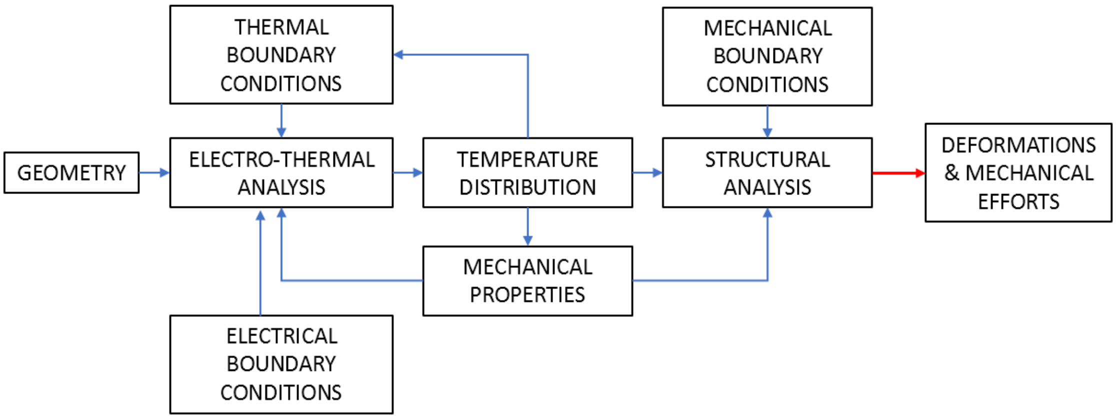


Fig 2. Schematic flow chart for Multiphysics procedure.

3.- APPLICATION OF THE METHODOLOGY TO THE ETHIOPIA-KENYA POWER SYSTEMS INTERCONNECTION

The methodology exposed in section 2 has been applied to the analysis of a resistor that has been designed for the Ethiopia-Kenia Power Systems Interconnection.

3.1 Description of the resistor

The resistor, manufactured by KLK ELECTRO MATERIALES SLU, is configured in 4 columns of blocks connected in series. The blocks consist of steel plates welded together forming groups of 56 or 59 of serial connected plates with two cold plates (SC) at both ends. These blocks of plates are supported by three M8 horizontal threaded rods which are electrically isolated from the plates by cylindrical isolators made of mica and steatite. Resistor is made from AISI 310 stainless steel plates of 0.3 mm thickness, resulting in an ohmic value of 477 Ω.

3.2 Material properties

The physical and mechanical properties of the electrical plates' material are summarized in Table 1. It can be observed that thermal influence has been considered.

Temp. (K)	Young's Modulus (Pax10^{11})	Yield Strength (Pax10^{8})	Thermal Conductivity (J/s·m·K)	Electrical Resistivity (Ωmx10^{-7})	Coefficient of Thermal Expansion (K^{-1}x10^{-5})
293	2.00	2.00	13.13	7.90	1.585
373	1.92	1.76	14.73	8.49	1.590
473	1.84	1.52	16.73	9.24	1.604
573	1.76	1.42	18.73	9.99	1.615
673	1.68	1.32	20.73	1.07	1.650
773	1.60	1.26	22.72	1.14	1.686
873	1.52	1.22	25.04	1.22	1.734
973	1.42	1.02	27.55	1.22	1.783

Table 1. Mechanical and physical properties of Stainless Steel AISI310 (Electrical Plates).

3.3 Mesh main features

The Finite Element Model was performed using the elements cited in section 2. For the thermo-electrical model 863307 elements SHELL157 were used, with almost 950000 nodes and more than 1.8 million of degrees of freedom.

In the case of the structural model 863307 elements SHELL181 were used as well as 1170 elements BEAM189, 6588 elements CONTA175 and 183 elements TARGE170. Thus, the mesh of the structural model contains more than 870000 nodes and 5.2 million of degrees of freedom.

To be on the safe side, the strength and stiffness of the isolators are not considered in the model, just their weight simulated by increasing the threaded bars density. In addition, no thermal energy is stored in the isolators, thus, all the heat generated by the Joule effect is used in the simulation to increase the plates temperature.

All elements have been checked regarding their aspect ratio, parallel deviation, maximum corner angle, Jacobian ratio and warping factor.

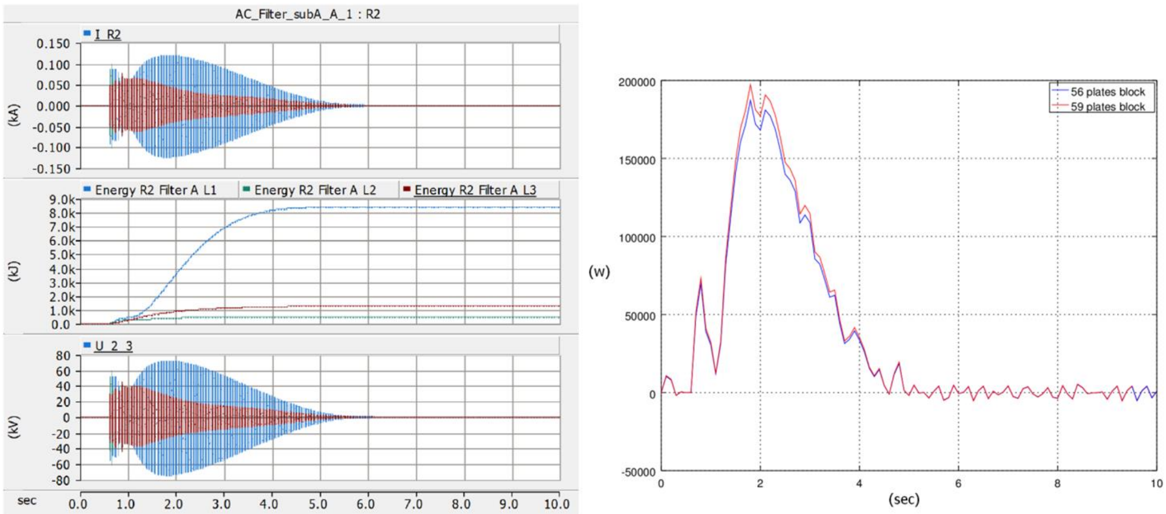
3.4 Boundary conditions

The boundary conditions applied to the electro-thermal and structural models are described in the following sections.

Electro-thermal analysis

An initial ambient temperature of 293 K is applied to all the elements of the finite element model. To be on the safe side, the system is considered adiabatic, so no convection or radiation condition is applied to the plates' surface.

The electrical load applied to the resistor is based on the worst case scenario provided by the customer and the energization stress on the resistor is shown in Figure 3a. Based on this energy curves and the internal block configuration the dissipated instantaneous power for each block is calculated and applied to the model (Figure 3b).



a b

Fig 3. a)Transformer Energization Stress on Resistor –R2; b) *Power dissipated by resistor during transformer energization.*

In order to properly evaluate the thermal effect of the resistance, an iterative transient analysis is performed, in which the voltage difference between contacts is recalculated each step time, taking into account the power dissipated by the resistor and its temperature. The calculated voltage difference is applied as a voltage magnitude at the inlet contact, a value of 0V is applied at the outlet contact.

Structural analysis

Displacements in all directions and the rotation around the Z axis are constrained at the nodes where the threaded bars connect with the steel supports. The nodal temperature distribution obtained from the electro-thermal analysis is imposed to the plate nodes.

The resistor plates displacement and X and Y rotation are connected to the threaded bars at the drills position by means of CONTA-TARGE elements. The SC plates are considered not to be in contact with the threaded bars in X direction since there is a gap between the plates and the bars in this direction.

Self-weight of the block is considered by applying a vertical acceleration of 9.81 m/s^2. The threaded bars density is adjusted to consider the isolators weight.

3.5 Results

Figure 4a shows the temperature distribution in the 59 plates resistor block at time 3.3 s (model and time at which maximum displacements and efforts were obtained from the structural analysis). Each plate has similar temperature distribution each other, with hot spots on the edges of the cuttings, where current density load is higher and thus the Joule effect is also higher in those areas, as it can be seen in Figure 4b.

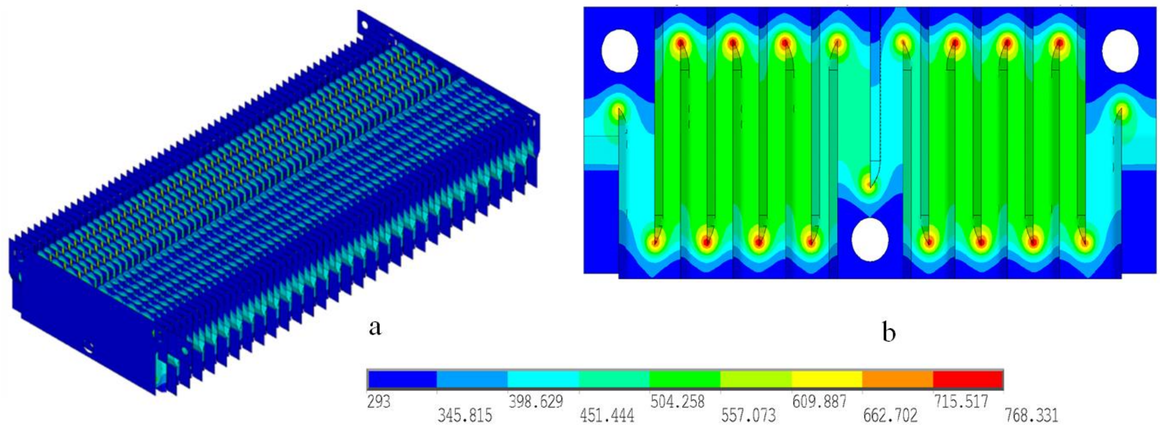


Fig 4. Temperature distribution at time 3.3 s: a) Resistor block; b) Resistor plate (Temperature in Kelvin).

With regard to the mechanical stress, Figure 5 shows the Von Misses equivalent stresses obtained in the model under load.

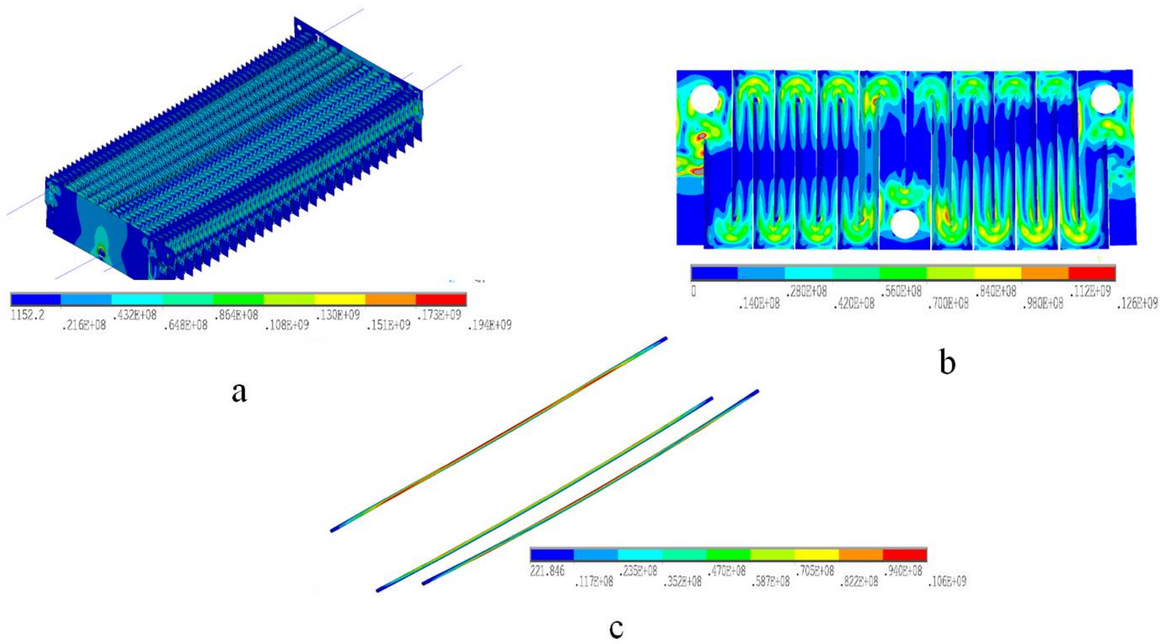


Fig 5. Von Mises Equivalent Stress (Pa). a) Resistor Plates; b) First resistor plate; c) Threaded bars.

Since the maximum temperature obtained in the steel plates is 769 K, the minimum yield strength considered for the plates material is 126 MPa. This value is only exceeded at stress concentration points that are highly localized. These are considered negligible as stress will redistribute after yielding and the overall strength of the block structure will not be affected. The maximum stress value obtained in the threaded bars from the structural analysis is 106 MPa. This value does not exceed the yield strength of the material (200 MPa). Consequently, the support system is suitable to hold the resistor steel plates and the isolators.

Figure 6 illustrate the distribution of total displacements at time 3.3 s, when the maximum thermal stress occurs. It can be observed that no contact between resistor plates is produced. Consequently, the support system is suitable to hold the resistor steel plates and the isolators.

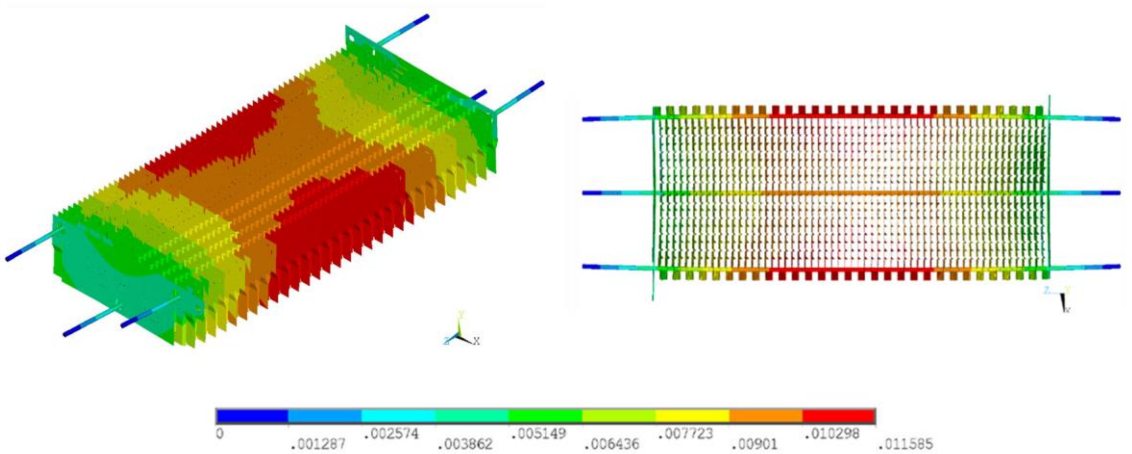


Fig 6. Total displacements at time 3.3 s (m).

4.- CONCLUSIONS

A cost effective procedure to analysis the thermal and electro-mechanical performance of an electrical resistor has been proposed using Multiphysics Finite Element Analysis. The procedure described has been satisfactorily applied to the case-study of a filtering resistor for the Ethiopia-Kenia Power Systems Interconnection.

The results of the analysis show that the resistor blocks perform properly under the indicated load conditions. The yield strength values of the materials stated on chapter 3.2 are only exceeded at very localized areas in the resistor plates. These peak stresses are considered negligible as stress will redistribute after yielding and the overall strength of the block structure will not be affected. The deformation of the resistor plates is compatible with the resistor block operation.

The results obtained in the present analysis show that the stress is lower than admissible stress, ensuring the suitable behavior of the studied components, according to IEC 62001 requirements.

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SUPPLEMENTARY MATERIAL

a b c

Fig 7. Electrical resistor: a)External view; b) Internal view; c) Detail of plates connection.

The following graph shows the free body (unconstrained) thermal expansion of one plate in X direction. As it can be seen, the maximum displacement, and thus the maximum thermal stresses occur at a time value of 3.3 s.

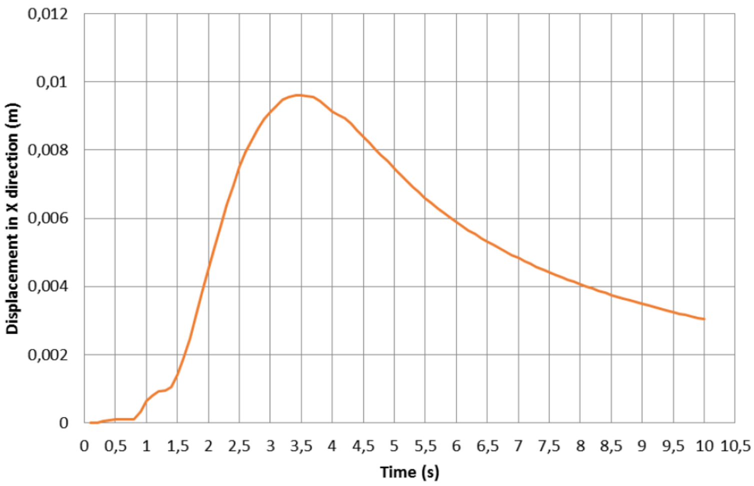

Fig 8. Resistor plate free body thermal expansion.