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Electrical Engineering

PhD Thesis

– Summary –

Contributions on accelerated aging of electrical contacts

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INTRODUCTION

The approach of the subject related to the aging of electrical contacts is justified from several points of view:

- ✓ Phenomena in electrical fuses
- ✓ The growing trend of electricity consumers nationally and globally
- ✓ Reducing the negative effects on the national economy due to the aging of circuit breakers
- ✓ Studying the materials used
- ✓ Study of the Joule Lentz phenomenon in electrical fuses due to the short circuit phenomenon

These are just some of the reasons why the topic related to the phenomenon of aging electrical contacts is an important and topical issue.

Chapter 1 Electrical contacts

The electrical contact is the set of two pieces of metal material, the touch of which allows the conduction to be established in an electrical circuit. They fall into two main categories: separable and breaking, having the role of closing and periodically opening the circuit. The electromagnetic contactor is described as a mechanical switching equipment, which is not manually triggered, having a single rest position, being able to establish and withstand nominal currents, and can also interrupt currents higher than the nominal ones. It is designed to perform a high number of on-load switching and a higher number of on-load switching.

Electromagnetic devices operate on the principle of the action of the electromagnetic field on the polar parts of a ferromagnetic circuit. They are usually used in general connection and distribution boards, and can also perform circuit protection functions.

Normal operation is characterized by the rated current, below which value no heating, above the permissible limits, of the socket terminals must occur. It can be said that these protection devices are some of the most important categories of devices, due to their role in protecting equipment.

The low voltage circuit breaker is a mechanical switchgear designed to allow, close and open currents in rated operation and fault currents under previously established conditions. In all such AC equipment, the disconnection of the electric arc is carried out in extinguishing chambers, which operate according to the principle of the electrode effect together with the niche effect [3].

The rated current is the current below which the circuit breaker can operate permanently, without exceeding the permissible heating limits. The standard values of the rated current for the circuit breakers are conveniently chosen [10]. Low-voltage mechanical switching devices [3] that interrupt overload and short-circuit currents are equipped with sensors designed to transmit electrical or mechanical pulses in the event of abnormal currents. Sensors associated with an execution element are commonly referred to as either relays or triggers.

The shutter is sensitive to an abnormal current, consisting of a thermal sensor and a mechanical type system used to transmit a pulse to a mechanism to disconnect the device. The electrical quantities monitored are the current intensity and the voltage of the supply network. The rated short-circuit breaking capacity is the value of the short-circuit breaking capacity set by the manufacturer for this circuit breaker at the appropriate rated operating voltage [11]. The series contact resistance is determined by the existence of electrical contact.

Modern electronic theory of metals states that conduction must be understood as a measure of the actual number of free electrons, which travel an average free path without collisions [15].

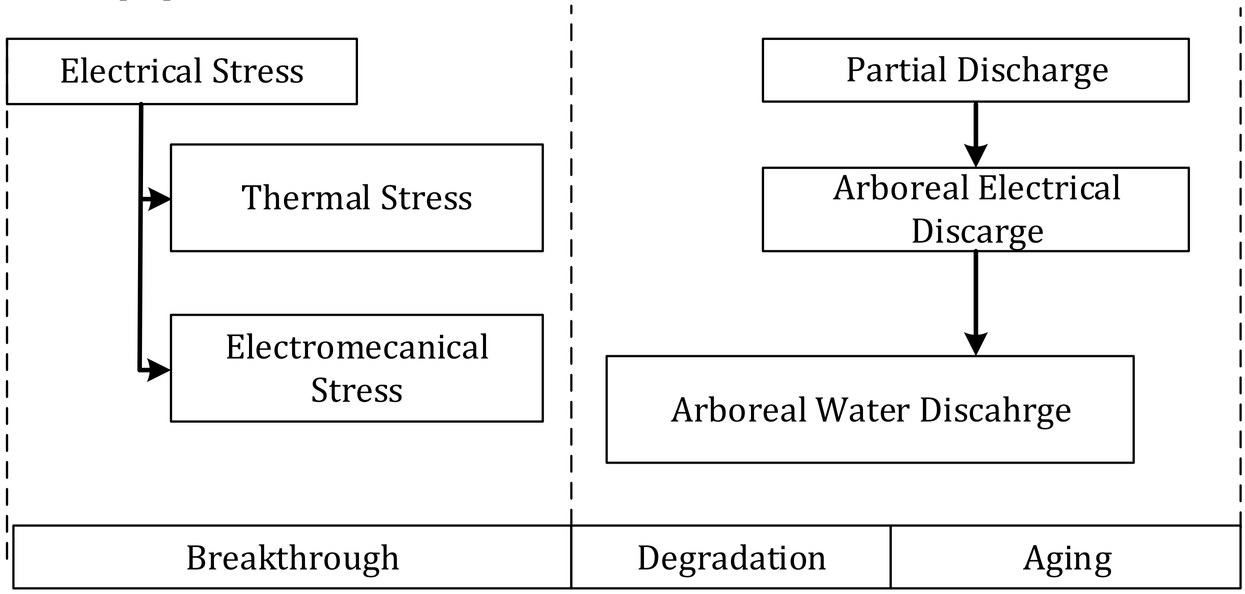

Figure 1.12 Breakthrough, degradation and aging processes depending on the intensity of the electrical stress [16]

During the operation of the electrical equipment, the system is subjected to different types of loads, which are dependent on the time and the value of the current intensity [16]

At high intensities of the current flowing through the circuit, an electrical breakdown phenomenon occurs through electrical stress. In general, at high demands, there is a process of degradation, respectively of aging of the components located inside. Electrical appliances are constantly evolving, transforming electromagnetic energy into thermal energy, all the heat released being given to the local environment [13]. During operation, the contacts are subject to wear and tear due to bumps, rolls and friction between the components. Wear is influenced by the number of closures and the width of the contact.

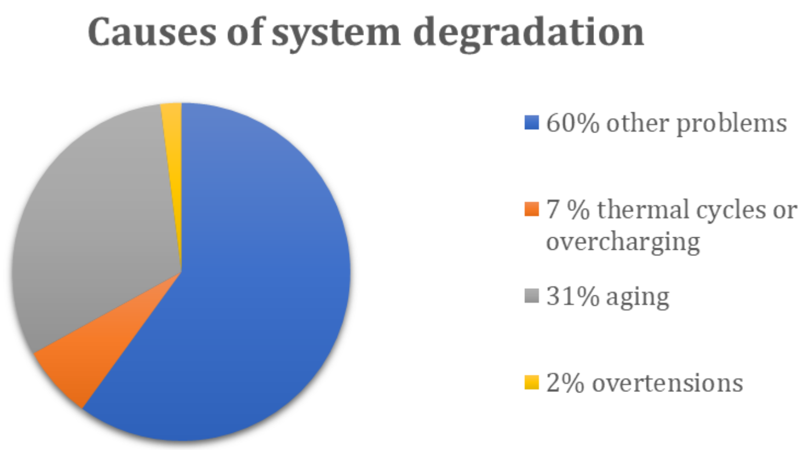

Figure 1.13 Causes of system damage

Thermographic analysis is performed using a system of transducers sensitive to infrared radiation, which produce an image based on the temperature gradient on the radiant surface. Thermal radiation, emitted by the target surface, is converted by the infrared radiation sensitive system into a thermal map image.

In general, contact defects that occur in electrical protection systems (fuses) are invisible to the human eye and therefore the use of a thermal imaging camera is welcome. Figure 1.21 shows the image of an electrical panel, respectively of an electrical contact obtained with the help of a thermal imaging camera. In this way the contact defects, the anomalies between the electrical components can be highlighted.

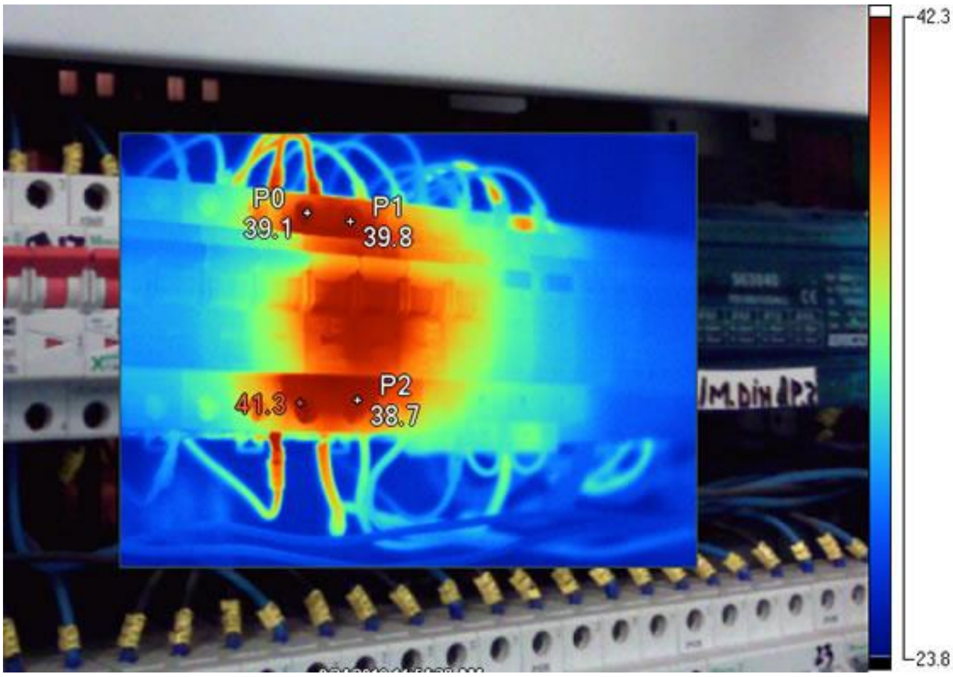

Figure 1.21 Thermographic image of an electrical panel [20]

The rapid rise in contact temperature leads to the evaporation of the metal from the surface. Burning of the contacts decreases the volume and mass of the parts [25]. The intensity of the electrical wear process is of major importance in the case of the contact life [25].

In the case of the required system with electrical voltages greater than or equal to the rated operating voltage, the characterization of the irreversible processes that take place during electrical aging can be represented by changing the dielectric strength.

Because the electric field strength is both an indicator of electrical life and a characteristic of the stress, the electrical aging curves of the size of the dielectric strength correspond to the constant or variable stress thresholds [26].

For the evaluation of the electrical life, a series of experimental techniques have been developed, more often being used the method of requesting the dielectric with constant voltage as amplitude, in which the breakthrough time is followed.

Erosion and oxidation of the base metal involves the evaporation of metal fractions and may involve spraying with metal liquid and expulsion of particles and / or pieces of material. Unlike pure silver contacts, silver-copper and silver-palladium alloys are also used, or some mixtures of silver with oxides of some metals (CdO) [15]. For materials obtained by pressing and sintering, the addition of additives could create brittle paths at the boundaries between the fine grains in the structure [15].

For metallic silver contacts, brittle phases may form at the boundary between the grains during oxidation of certain additives. For some of the oxidized materials, these fragile compounds undergo a process of segregation, which limits the plastic deformability [15]. Many of the materials can withstand the action of electric arcs without major cracks. Oxide grains from metal silver parts, obtained by internal oxidation after processing, are much larger than those from parts obtained by pressing, sintering and repression, or those obtained from mixtures with metal oxides.

Caloric effects differ because the amount of heat absorbed, or reflected, depends on the roughness and color of the radiation incidence surface. Variations in the intensity of thermal radiation can lead to variations in the expansion, or different shrinkage of the components [27].

The theory of thermal aging considers that the irreversible transformations that occur in the material, under the action of temperature, can be tracked and estimated.

The method of determining the service life, by aging tests, consists in maintaining the material at the aging temperature T = const. and the continuous, or discontinuous, recording of property values chosen as an indicator of thermal life.

The processing of experimental data consists in the calculation of the parameters α and K (T), in order to establish the analytical expression of the aging curves. For a given end-of-life criterion, then the lifetime corresponding to the given thermal stress is obtained. The degradation mechanism considered is of the Arrhenius type, where the evolution of the process depends exponentially on the operating temperature of the system.

Based on the Arrhenius type thermal life law, specific test methodologies have been developed to increase the extrapolation safety of data obtained in accelerated thermal tests and specific data processing methods have been introduced.

Thermal aging is a phenomenon encountered especially in dielectric materials of an organic nature, its evolution being determined by chemical or physical changes under the effect of heat. Chemical reactions are characterized by pure thermal degradation, thermo-oxidative reactions and the effect of hydrolysis [26].

Thermal life τ is the time interval in which the property p, called the thermal life indicator, reached the limit value pcr, called the end-of-life criterion, under the action of constant temperature thermal stress [26]:

The phenomenological theory of thermal aging considers that the irreversible transformations that occur in the material, under the action of temperature, can be traced by changes in the macroscopic quantities of material [26].

For homogeneous materials, at high temperatures, electrical degradation can be justified by the thermal effect of electrical stress, which causes degradation reactions similar to electrical aging [30].

The increase in temperature causes the particle speed between the anode and the cathode to increase, leading to an increase in the rate of evolution of physicochemical processes, according to the equation developed after the observations of the chemist and physicist Svante Arrhenius (1859-1927). This equation shows that the reaction rate increases exponentially with increasing temperature [31, 32].

For a material subject to thermal aging, the different characteristics do not have the same degree of degradation, but the thermal endurance is always determined for a certain property. Therefore, the reference material must have a satisfactory operating history and must have a known temperature index for a particular property [31, 32]. At high temperatures, processes can be described by the Arrhenius law, where the energy of molecules consistently determines the evolution of processes [33]. Arrhenius describes the effect of a change in temperature [33] on the rate coefficient.

Activation energy (Ea) is defined as the minimum amount of energy to trigger a fault mechanism that is influenced by the internal temperature of the device [24]. Fault phenomenon is defined as a physical phenomenon that can lead to device failure.
The value of the activation energy indicates the relative tendency of a failure mechanism to be accelerated by temperature, ie, the higher it is, the easier it is to trigger a failure phenomenon in relation to temperature [24].

At high temperatures, metals are more prone to oxidation. As the temperature increases, the speed of the aging process also increases, affecting more the thickness of the layer [34].

Collision ionization - In this case, the free electrons, in the space between two electrodes at a difference of electric potential, move towards the anode under the action of the electric field of intensity E [17]. In the case of contacts in the open atmosphere, the movement of electrons does not take place in a vacuum, but in a gaseous environment and as a result, the probability of the electron colliding with gas atoms occurs before it reaches the ionization energy [17]. In the case of metals, the increase in temperature causes an increase in the vibrational amplitude of the atoms in the crystal lattice, which leads to a more pronounced interaction between electrons. Collisions increase the electrical resistance of the propagation medium. [35].

The materials used in the electrical industry can be divided into construction materials: insulators, semiconductors, conductors and electrical resistors. A particular category of conductive materials is used to make non-permanent electrical contacts [35].

Chapter 2 Electrical and thermal stresses in switchgear

When the electrical circuits in charge are disconnected, an electric arc appears between the contact elements of the switching devices whose parameters (voltage, current density, duration) [1]. The existence of the electric arc leads to an additional stress, caused by the transfer of energy from the electric arc column to the conductive or insulating components of the appliance. This demand is manifested by overtemperatures that can require the contact elements until they reach vaporization.

The production of the cathodic potential drop is explained as follows: the positive ions moving at low speed towards the cathode have a low ionization effect and, as a result, the positive charge is predominant near the cathode, so that a large drop occurs between this area and the cathode. of potential.

The electric arc produced by the removal of the moving part of an electrical contact develops heat, the temperature of the contact parts increases favoring the thermal emission of electrons and electric field. Considered an autonomous discharge in which, as in any electric discharge in gas, shock ionization plays an important role in the multiplication of charge carriers.

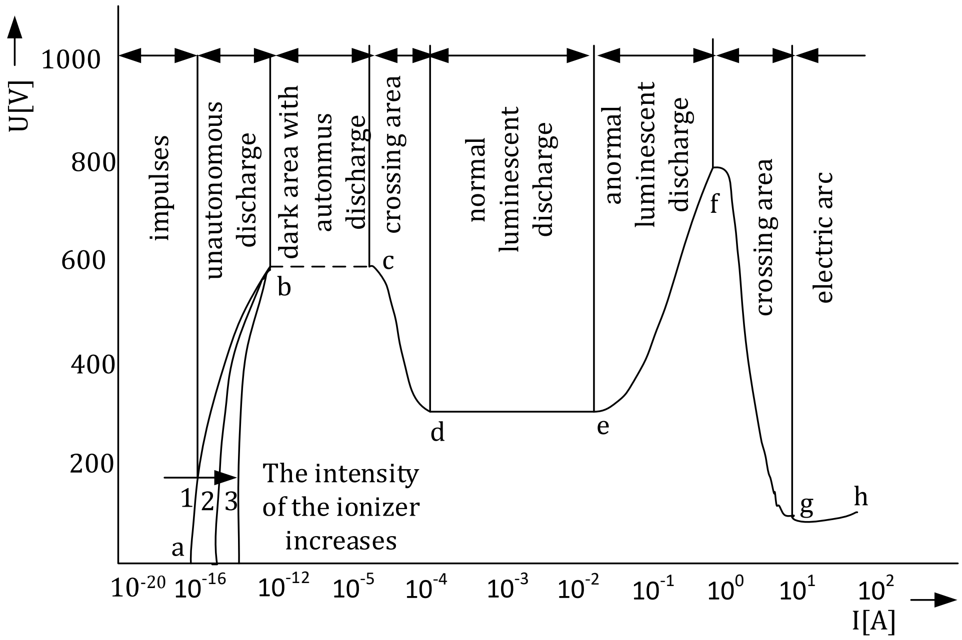

Figure 2.1 Electric arc [1]

The above-mentioned cathode electron generation processes (thermal emission, electric field emission, secondary emission), as well as gas column ionization processes (shock ionization, thermionionization, photoionization, ionization above the metastable level) cover the losses of charge carriers by recombination and loss of charge to the electrodes and ensures a high current density at the electrodes of the electric arc, of the order $1 \ldots 10^5$ A/mm^2 .

Electric arc in switchgear [1] as a phenomenon of electric discharge in a gas, is strongly influenced by local conditions in the extinguishing chamber such as arc length, heat transfer, current intensity and current mode (alternating, continuous).

In these situations it is interesting to extinguish the electric arc either by passing through the zero value of the current (alternating current), or by creating a combustion instability (direct current).

The change in the conductance of the electric arc is due to the change in temperature, which determines the degree of ionization, and the temperature cannot suffer arbitrarily fast fluctuations.

The characteristics of the electric arc (electrical conductivity depends on thermal conductivity) are: electric field strength, electric power developed per unit length (temperature field).

The interruption of the electric arc in alternating current [1] is facilitated by the passage of the current through the value of zero, moment in which the ionization in the column of the arc has the lowest value. The interruption of the electric arc in the extinguishing chamber is dependent on the network parameters (reset voltage and short circuit current) and on the device parameters (holding voltage and arc voltage) which means the restoration of dielectric strength in the electric arc column (fig.2.6).

The electric arc that appears at disconnection is an autonomous discharge through which the space between the electrical contacts becomes a good conductor of electricity, being characterized, in the space between the contacts, by the current density (fig.2.7 and 2.8) [36].

The physical model of the electric arc is characterized by a series of particular aspects that result from the distribution of electric charges, [37].

The produced electric arc can be assimilated with a mobile conductor that can move under the influence of the magnetic field. Shock ionization (collision) is the energy given by an ion or electron to the environment (fig. 2.10).

The gas column is surrounded by a thicker, brighter layer, which is called the halo. The conductivity of the gas forming the halo is lower than that of the central column (fig.2.11) [17].

The spring column has a variable length, its properties depending on the type of electric spring, the nature of the electrodes, the combustion medium and the cooling mode. The column, in terms of electronic load distribution, behaves quasi-neutral [17]. The dependence of the voltage drop, depending on the current flowing through the arc, is the voltammetric characteristic of Herta Ayrton [17].

The electrons, extracted from the cathode surface, are accelerated (in the electric field) towards the anode producing collision ionizations, which causes an avalanche increase in the number of carriers. This allows a puncture to appear, in the form of an electric shock, which takes the form of a blue spark [14].

Chapter 3 Solutions, experiments, results

A circuit breaker is a mechanical switching device, capable of allowing, closing and opening currents in nominal operating conditions and fault currents (short circuit, prolonged overload) under predetermined conditions [3]. The circuit breaker is also a protection device, as it is equipped with fault-sensitive trip units (low voltage overload, short circuit) which cause the circuit to be interrupted in a relatively short time.

In all these alternating current devices, the electric arc is interrupted in extinguishing chambers, which operate according to the principle of the electrode effect combined with the niche effect.

The design of data acquisition and processing algorithms were developed in the Arduino environment and the monitoring data developed in Microsoft (Excel). In terms of user interface and connectivity, the communication module transmits the information obtained through the SD CARD protocol.

In order to make the necessary determinations to study the evolution of contact degradation over time, a complex measurement circuit was created containing electrical circuits and analog and digital electronic circuits. For the acquisition and recording of information, both hardware and software components were designed, a system with microcontroller of “data logger” type, whose block diagram is represented in figure 3.16. Along with this system, a series of applications was created necessary for the further processing of the acquired information.

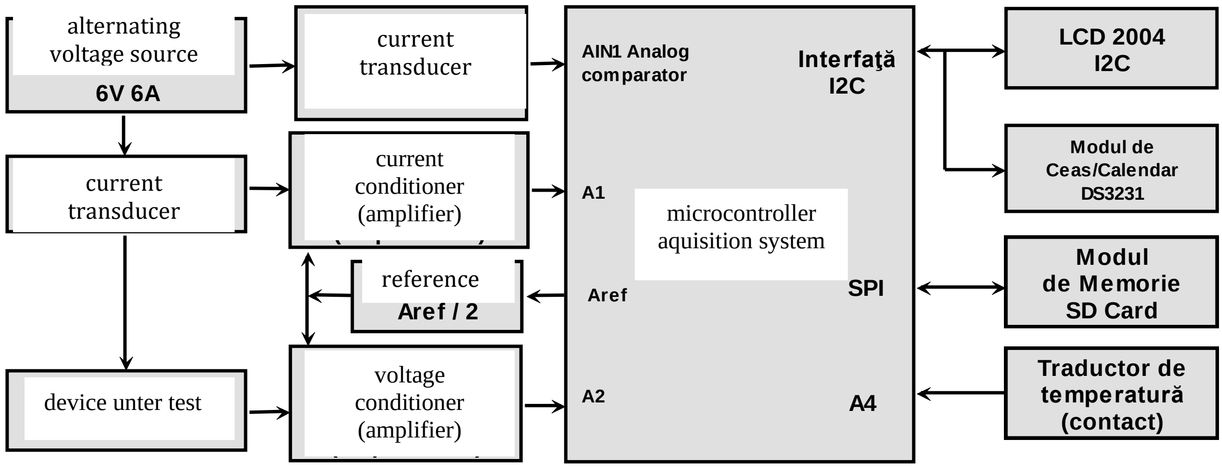

Figure 3.16 Block diagram of the purchasing system

Detector de trecere prin 0 – detector for passing through 0
Interfata –interface
Modul ceas /calendar = clock/calendar module
Modul de memorie SD card – SD card memory module
Traductor de temperatura (contact) –contact temperature transducer

The switching device (contact) with a rated value of 2A under test is supplied by an alternating voltage source capable of discharging a current with an actual value of approx. 6A, resulting in accelerated degradation of the contact to be analyzed.

By measuring the instantaneous values of voltage and current, parameters can be determined (impedance, dissipated power, harmonic components, etc.) that allow the detection of phenomena associated with degradation processes.

The simplified wiring diagram of the measuring and conditioning circuit, designed for the purpose presented above, can be seen in Figure 3.17.

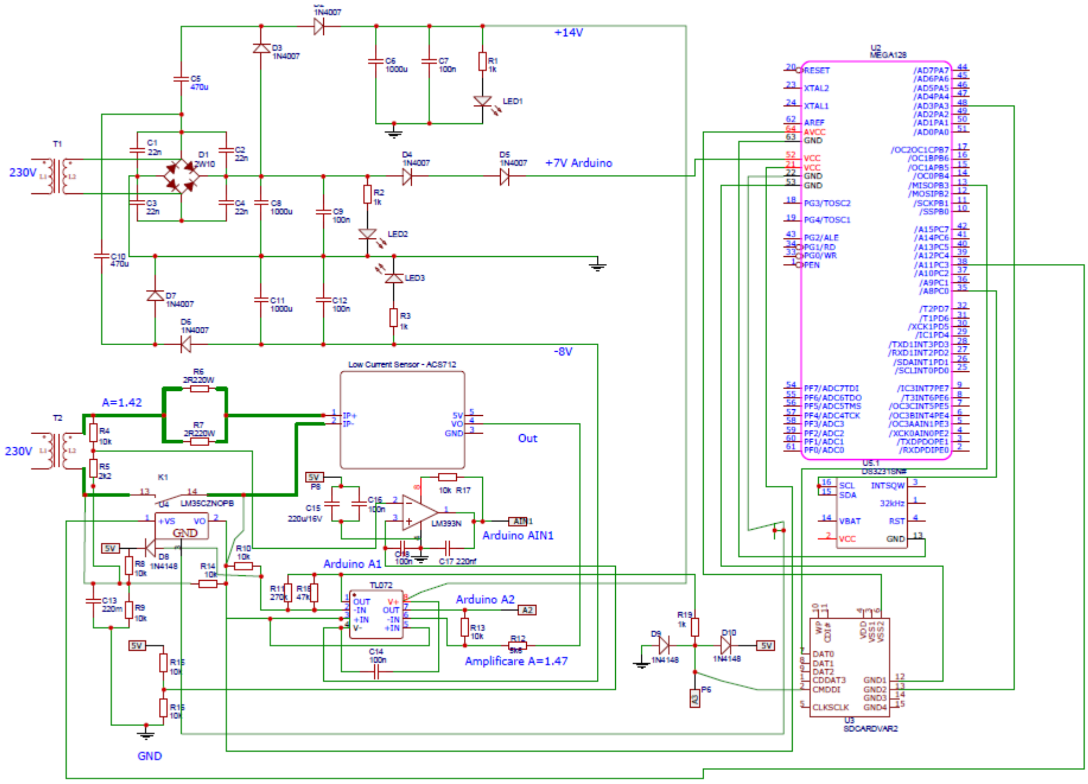

Figure 3.17 Electric schematic

The microcontroller acquisition system uses a software application designed and developed for this analysis. Routines use functions based on external and internal interrupts for synchronous acquisition, which allows for more accurate, predictable, and consistent sampling of data strings. The acquisition process is triggered when the voltage supplied by the power supply is zeroed, the samples being then taken in equal time intervals, precisely controlled by using the internal timers of the microcontroller.

The pairs of voltage and intensity samples are taken at an interval of 10 minutes, ie 144 in one day. After each sampling sequence, the strings are saved together with time information (Date, hour, minute, second), number of samples per cycle, type of variable purchased and average value of each string, very useful information in numerical processing and subsequent statistics.

The validation of the data obtained was confirmed following checks based on statistical methods using concordance tests. The graphical representation of a set of acquired values, over a period, of the current intensity signal, is represented in figure 3.20.

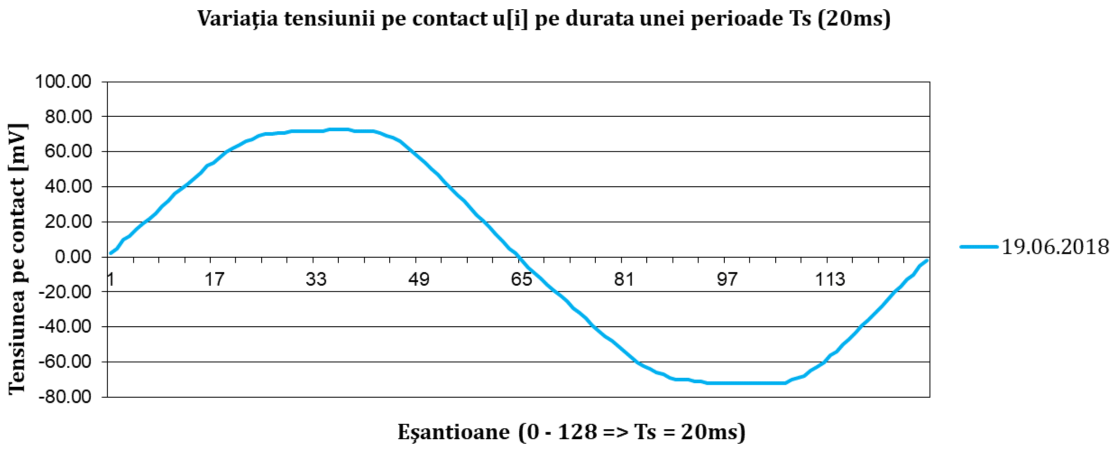

Figure 3.20 Graphical representation of the acquired natural values, for voltage

Tensiunea pe contact – contact voltage
Esantioane –samples
Variatia tensiunii pe contact ui pe durata unei perioade ts = variation of contact voltage on duration of a ts period

It is expected that the degradation of the surfaces of the parts in contact and a possible decrease in the pressure between them will lead, at some points, to the appearance of electric arc discharges. This phenomenon can lead to a change in the total harmonic distortion factor and therefore, a harmonic analysis of the voltage signals can highlight these phenomena.

The measurement of the average temperature in the contact area can be done using different types of parametric transducers. The presence in the contact area, of the voltage and implicitly of the test current, makes necessary the galvanic (electrical) insulation of the temperature measuring circuit compared to the other circuits.

An integrated semiconductor parametric transducer was chosen for temperature measurement, with an output voltage proportional to the measured parameter, which allows easy numerical acquisition and processing of temperature information. The temperature transducer was placed inside the device under test in the immediate vicinity of the contact.
Simultaneously, the ambient temperature was also measured using the temperature transducer of the clock module (DS3231), arranged in the same enclosure with the device being tested outside it and with the purchasing system.

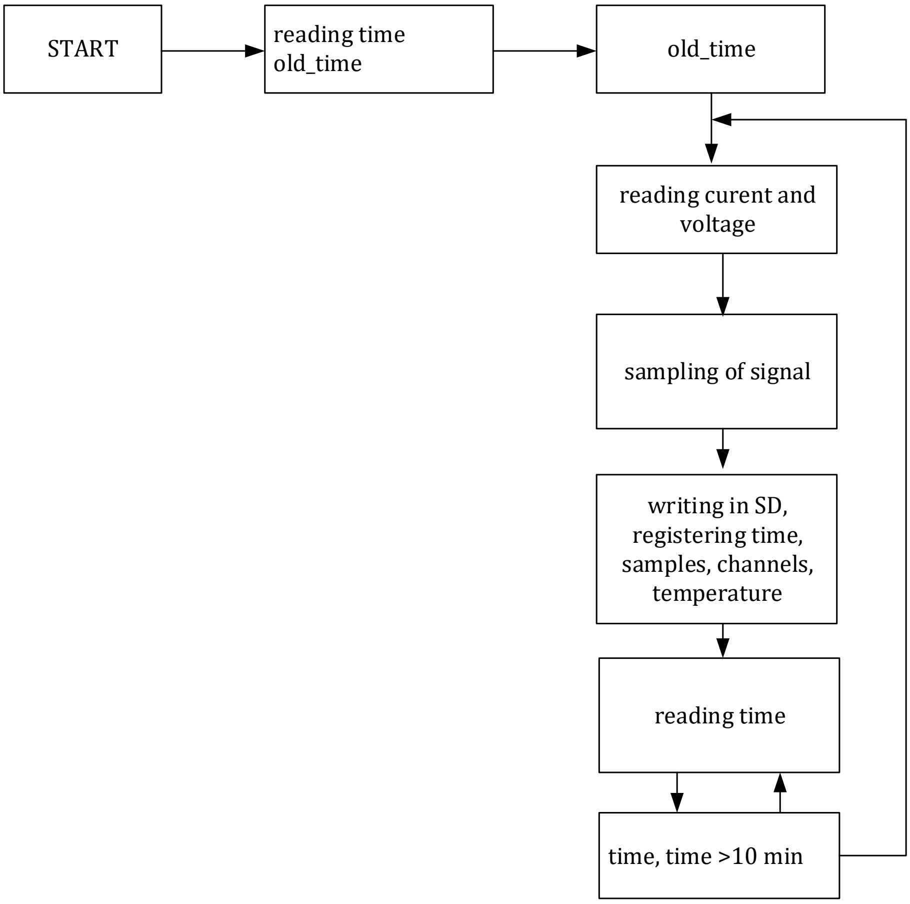

Figure 3.25 Logical scheme for implementing the acquisition program

Figure 3.25 shows the block diagram of the implemented system. Each step of the block diagram is detailed below:
Start - the acquisition process begins, by reading the time information.
Moment of reading - compares the current time of Time with Time_Old and when the condition of Interval_Acquisition is met - the reading starts.
However, the reading of the voltage and current data is conditioned by the "zeroing" of the supply voltage. The actual acquisition is triggered by two routines based on external interruptions (zero ISR (INT2_vect) {}) and internal interrupts (using timers for the 128 samples over a period of about 20ms ISR (TIMER1_COMPx_vect) {}, transfer analog values being provided by ISR (ADC_vect) {})
Temperature measurements are performed separately for the ambient and core temperature of the monitored device.
The data is transferred to the memory card after a complete set of information has been collected.
Time - return to Start position and expect to meet purchase conditions.
The acquisition is made for each of the two analog channels of the microcontroller system, by using the ADMUX configuration register, for channel 0 (ADMUX = 0x41), and for channel 1 (ADMUX = 0x42). The values of the purchased samples are stored in two string variables, one for each channel:
```
if (channel == 0) xu_r [smpl_Nmbr] = ADC;
if (channel == 1) xi_r [smpl_Nmbr] = ADC;
```

The acquisition of the parameters with the help of current transducers, the time of purchase and the temperature of the external environment is made only after the fulfillment of the condition given by the prescribed period (10 min).
The processing of the energy parameters is done, with the help of numerical calculation programs, using the purchased values, being correlated with the time at which the purchase was made, the temperature of the external environment and the contact.
The acquisition starts from the moment when time_flag = 1, at a time interval Interval_Acquisition = 10 min, the acquisition of signals 128 samples in an interval of 20 ms, for each channel: Channel 0 representing Voltage and Channel 1 representing Current.

Figure 3.26 Acquisition signal check

Figure 3.26 shows the practical part of the system that verifies whether the acquisition signal complies with the INT 2 structures regarding the acquisition.

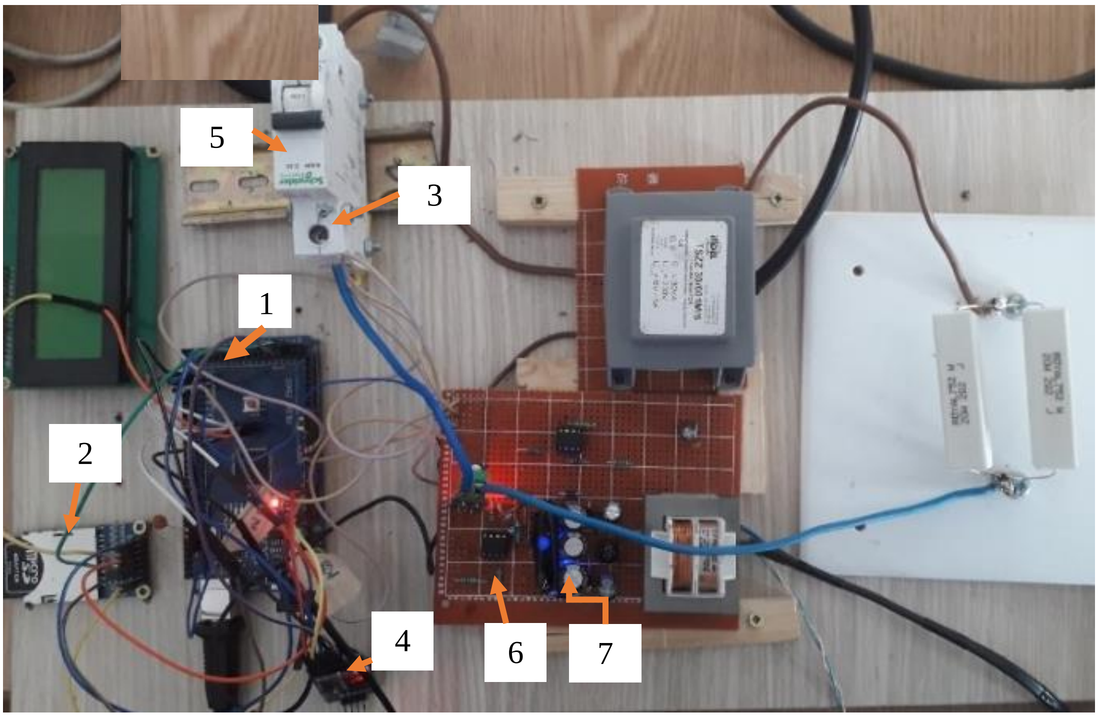

Figure 3.27 Practical implementation of the procurement system

Figure 3.27 shows the practical implementation for the signal acquisition in the mentioned interval, in which we have the following components: 1-Microcontroller (Arduino Mega); 2-Sd Card; 3-LM 35; 4- DS1307; 5- circuit breaker; 6-voltage division; 7-ACS 712

In order to transform the standard (dimensionless) values of the samples into natural values of voltage and current, the relationships presented in the paragraph describing the principle on the basis of which the procurement system was implemented were applied.

After centralizing the acquired information over an accelerated test period of the researched device, relevant information was obtained which is summarized below.

From the total recorded data, sets were taken, at intervals of one week, on the same day, taking values mediated over a period of 24 hours. Thus, for each set of information acquired every 10 minutes, the actual values of voltage and current were determined, with which the impedance (approximated with the contact resistance) and the dissipated power were determined. The ambient temperature and the temperature inside the circuit breaker were measured directly. For each of these parameters, the average values in 24 hours were determined (populations with a population of 144 terms).

When establishing the conditions for carrying out the tests, it was desired that the current intensity through the circuit be kept constant so that the aging phenomena evolve constantly over time, and the parameters voltage on contact, its resistance and temperature inside the device reflect as suggestively as possible the evolution of these. processes.

The thermal demands were made within the department of Materials Science and Engineering. The figures below show the experimental temperature stand (Fig. 3.39 a, b, c).

Throughout the thermal aging period, the oven must maintain a certain temperature in the useful space or where the test tubes are placed. The circulation of the air through the oven as well as the change of the air content must be correlated with a constant temperature distribution for both the drying process and the heating.

Aging should be performed in an oven that operates in a normal laboratory atmosphere.

Figure 3.39 Experimental stand for temperature

The practical experiment, in which the electrical circuit breaker was tested, complied with the standard SR EN 60068-2-2 / environmental tests part 2-2 Tests B dry heat.

Artificial aging is a process that takes place in a shorter time than natural aging due to the influence of temperature, the acceleration being influenced by the composition of the material. As a rule, the materials are subjected to temperatures above normal operating temperature during testing to accelerate aging. In accelerated service life testing at high temperatures, the mode of failure depends on migration. These types of faults are usually found in electrical components or other types of products or materials.

The value of the activation energy indicates the relative tendency of a failure mechanism to be accelerated by temperature, ie, the higher it is, the easier it is to trigger a failure phenomenon in relation to temperature.

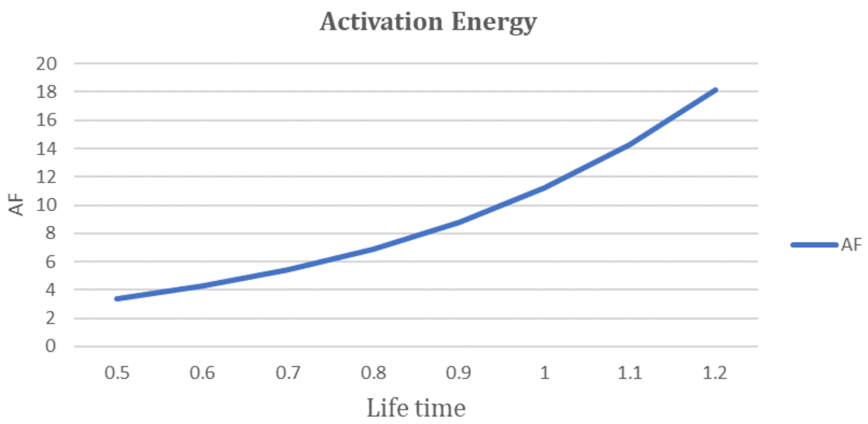

Figure 3.50 Electromigration lifetime during accelerated test duration

Figure 3.50 shows the lifetime subjected to electromigration during the accelerated test. As can be seen, as the energy of accelerating the migration of electrons between the anode and the cathode increases, the activation energy increases and it is found that we have an accelerated aging of the material that is located in the furnace.

4 Numerical modelling

This chapter presents aspects regarding the implementation and analysis in the Comsol / Solidworks work environment in the study of the accelerated aging of the electrical circuit breaker, which validates the results obtained within the practical experiment.
Losses due to the film effect and the proximity effect are not in question due to the frequency used.

The desired performance is explicitly or implicitly dependent on the value of the electromagnetic field. The range of modeled devices can be extremely diverse and covers both cases in the field of strong currents (electromagnetism, electrothermal, electrochemical, etc.) and in the field of low currents. The determination of the demands arising in the electrical equipment is made by the full use of the computing facilities of the COMSOL 5.4 software environment (finite element analysis software on multiple platforms, simulation software) and SOLIDWORKS (offers design, simulation and analysis possibilities).

In order to be able to observe the simulation conditions so as to get as close as possible to the experimental part, the following modeling steps were followed:
Following the data entered in the modeling program, the following information was obtained:
Figure 4.7 shows the distribution of the electrical potential inside the electrical contact.

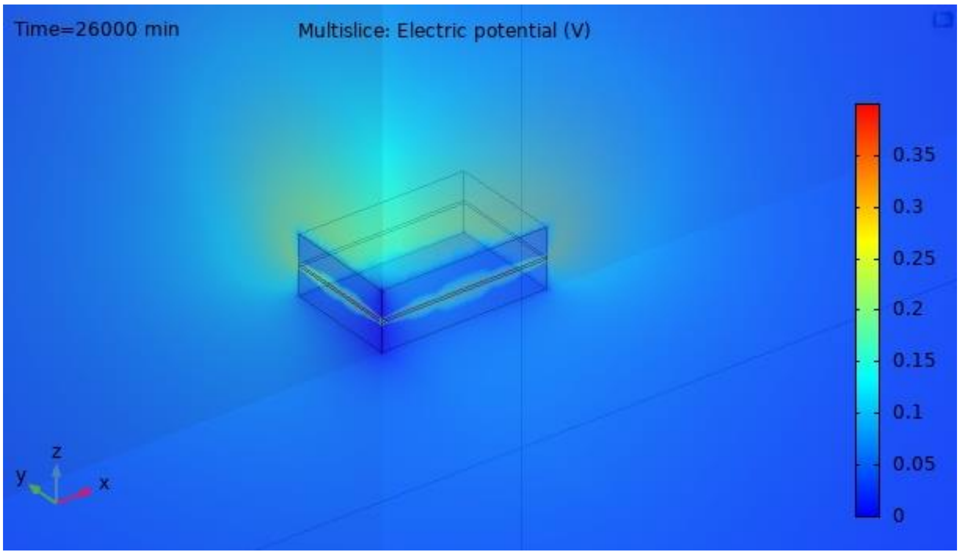

Figure 4.7 Distribution of electrical potential in contacts

Due to the contact of a constant current for a long time, a heat accumulation occurs due to the Joule Lenz effect. As the temperature increases, some characteristics of the material change, including electrical resistivity, which leads to changes in resistance and changes in voltage between the 2 contacts.

Figure 4.17 shows the graph of temperature evolution during the simulation. In order to obtain these purchased values, a temperature measuring probe was introduced within the Comsol program, resulting in a table with temperature values. These values were subsequently checked and plotted. It can be seen in the figure that the simulated values follow a linear growth curve.

In this part he compares the results obtained by simulation with those obtained in the experimental part. Table 4.15 shows the contact temperature obtained from simulations at different time intervals (approximately at one day intervals) over a period of 18 days.

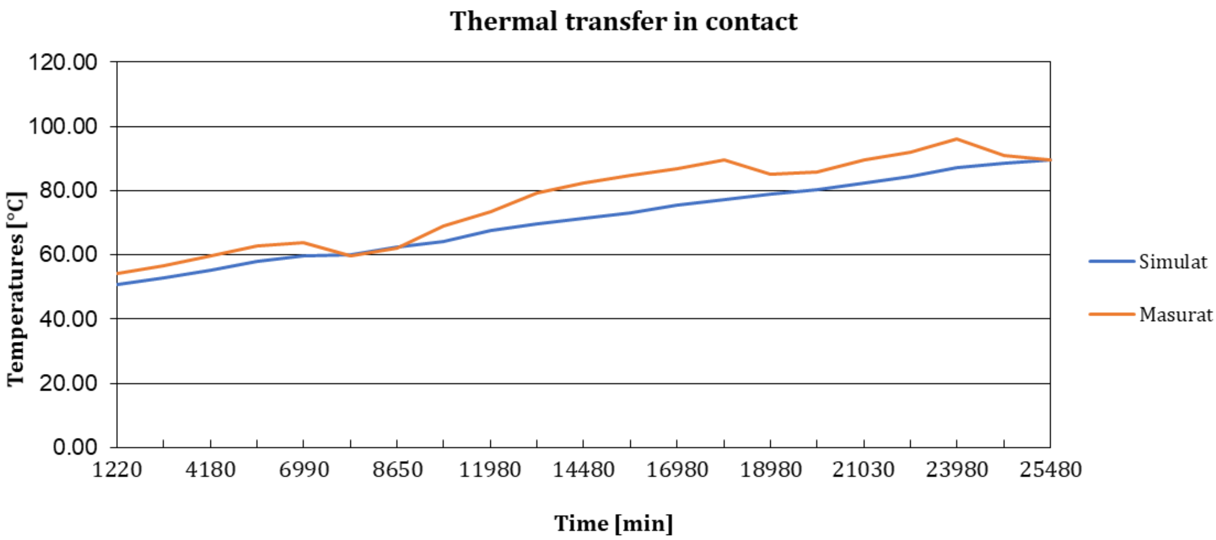

Figure 4.18 Thermal transfer in contact comparative analysis

Figure 4.18 shows the heat transfer in the electrical contact depending on the temperature variation, according to table 4.15. There is a good correspondence between simulation and experiment.

With the help of the Solidworks modeling program, in this subchapter we presented the thermal distribution of temperature due to the Joule Lentz phenomenon.

The following were used as input data:

- Creating an electrical circuit breaker;
- Creating an electrical panel;
- Switching the current through the circuit breaker.

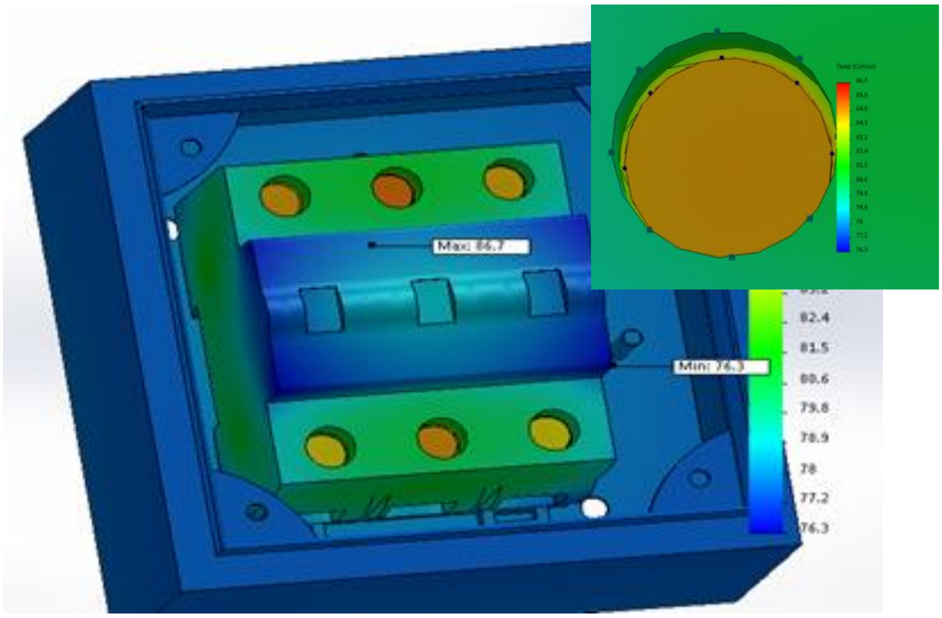

Figure 4.19 Temperature distribution in the electrical panel

Figure 4.19 shows the temperature distribution in the electrical circuit breaker, where you can see the heat diffusion and the temperature distribution in the electrical panel, where the maximum temperature is 86.7 ° C and the minimum 76.1 ° C. In general, these problems are caused by loose electrical contacts that can affect its proper operation.