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ESTIMATION OF THE MAXIMUM APPLICABLE VOLTAGE LEVEL OF ALUMINIUM ELECTROLYTIC CAPACITORS BY AUTOMATED SPARK-DETECTION MEASUREMENT

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The paper deals with the presentation of a complete Measurement Automation System (MAS) implemented in an Aluminium Electrolytic Capacitor Development Laboratory at EPCOS Hungary. The main function of the MAS is to facilitate electrolyte and capacitor research and development by automation of the related measurement tasks and to provide a powerful database system background for data retrieval and decision support. The presentation focuses on the architecture of the spark-detection measurement system and introduces a reliable estimation procedure for determining the maximum level of the voltage which can be applied to the capacitor without damage. For the design engineers it is often impossible to determine the exact maximum voltage which will never be exceeded in the application. With the presented spark detection measurement a good estimation of the allowable maximum voltage can be given.

Keywords: measurement automation, test automation, passive electronic components, electrolytic capacitor

Introduction

There are many different kinds of capacitors (ceramic, foil, electrolytic and tantalum capacitors). The most widely used type is the aluminium electrolytic capacitor which can be found in many electrical systems like energy storage, power conditioning in power supply, power factor correction in electric power distribution, etc. The lifetime of electronic systems depend significantly on the lifetime of the capacitor, so they use this type of capacitors because reliability is very important in these systems. The aluminium electrolytic capacitor has many really important properties: capacity (1 μF – 3 F), operational voltage (from a few Volts up to 700 V), operational temperature (from -55 °C to 125 °C), loss factor, size and shape.

The design engineer must determine the exact maximum operating voltage. It is not an easy task, in contrast with the other parameters, because the capacity of the capacitor is specified by the surface capacitance of the anode foil. The spark-detection measurement system presents a good estimation procedure for determining the maximum level of the voltage which can be applied to the capacitor without damage. In addition to that, the paper deals with the basic construction of the wet aluminium electrolytic capacitor and introduces a measurement automation system (MAS) of an Electrolytic Capacitor Development Laboratory at an international company in Hungary.

Aluminium Electrolytic Capacitor

The winding of aluminium electrolytic capacitors contains two foils (anode and cathode foil) with an impregnated paper. They are rolled together tightly into a winding [1] as shown in *Fig. 1*.

The positive foil is made from pure aluminium (the purity is higher than 99.9 %). The foil has been etched to increase the effective surface area (and the capacitance of the capacitor). It is typically 30–100 times larger than the plain area of the foil. On the etched surface of the foil an aluminium oxide layer has been formed electrochemically. The voltage of the etched foil is 30–40 % higher than the rated voltage [2] of the capacitor. The cathode foil is made from pure aluminium, too, and it has a thin oxide film (only a few Volts, regardless of rated voltage). It is typically etched to increase the surface area slightly. The function of the aluminium cathode foil is to reduce the series resistance of the capacitor by making contact with the paper over a wide area. The positive pole of the capacitor is the anode foil. The other pole is a combination of high-absorption paper impregnated with an electrolyte, in contact with the cathode foil. The electrolyte is there to make good contact with the anode, by permeating its etched structure, and also to repair any flaws in the oxide layer when the capacitor is polarized.

The anode and the cathode foils are contacted by aluminium tabs which are extended from the winding and are riveted to the aluminium terminals of the cover disk. The tab foils are not etched but they also feature an oxide film made by electrochemical oxidization.

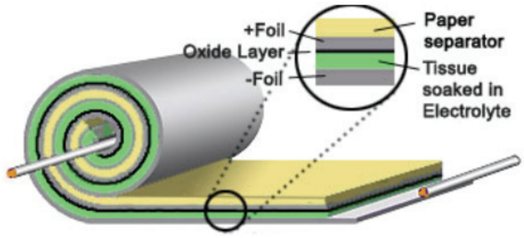

Figure 1: Winding of Aluminium Electrolytic Capacitor

Before being housed in a suitable container, the complete winding is impregnated with electrolyte. After housing the edges of the can are curled back. Before being sleeved and packed, capacitors are first aged. The purpose of this stage is to repair any damage in the oxide layer and thus reduce the leakage current to very low levels.

Leakage Current of Capacitors

The leakage current is the most important parameter of capacitors. Real capacitors have failure places on the oxide layer of the anode foil. Damage to the layer can occur due to the failure of the oxide layer's structure or mechanical breakdown, e.g. slitting of the anode foil (foil manufacturers produce the anode foil in rolls), riveting the tabs to the anode foil, or minor mechanical damage caused during winding. Numerous effects depend on the magnitude of the leakage current, for example the time, the ambient temperature and the voltage of the capacitor. The time-function of the leakage current [3] is shown by *Fig. 2*. At the initial stage, the current has a peak, and then decreases by time until it reaches a low, almost constant value (I_{RB}).

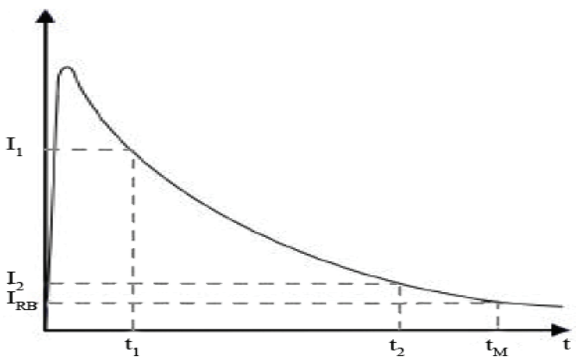

Figure 2: Characteristic of Leakage Current

According to Fig. 2, decreasing of the leakage current is exponential. The decreasing can be written down by a simple relation:

$$I_2 = I_1\left(\frac{t_1}{t_2}\right)^a \text{ or } I_1 = I_2\left(\frac{t_2}{t_1}\right)^a \quad (1)$$

where:

I_1 – the leakage current value at the t_1 time
I_2 – the leakage current value at the t_2 time
t_1 and t_2 – time of the leakage current's measurement
a – constant.

A well-operating capacitor's *a* index value is equal to 0.5. As a result of *a* = 0.5, the previous figure changes to:

$$I_2 = I_1\sqrt{\frac{t_1}{t_2}} \text{ or } I_1 = I_2\sqrt{\frac{t_2}{t_1}} \quad (2)$$

For the calculation of the leakage current, t_1 and I_1 assets are needed. However, the value of the leakage current is affected not only by the time but the ambient temperature, too. Its characteristic can be seen on *Fig. 3*.

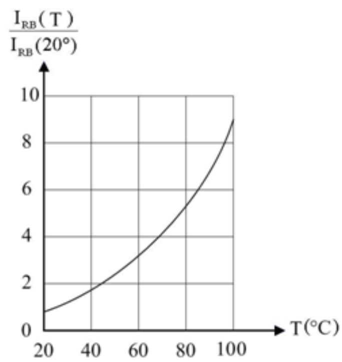

Figure 3: Ratio of leakage current increasing dependence on ambient temperature

The figure above shows the ratio of the increasing current caused by the ambient temperature and the I_{RB} value at 20 °C. The higher the ambient temperature the higher the leakage current. Moreover, the capacitor's leakage current depends on the operating voltage, too, shown by *Fig. 4*.

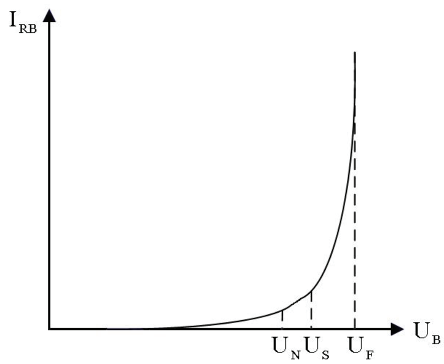

Figure 4: Leakage Current dependence on voltage of Aluminium Electrolytic Capacitors

It can be seen that the I_{RB} leakage current increases by U_B operating voltage. After reaching the U_N rated voltage, the gradation of the current curve increases. The closer the voltage level to the U_F forming voltage, the bigger the gradation of the current curve becomes. Between U_S surge voltage and U_F forming voltage the leakage current does not regenerate the capacitor's oxide layer but starts damaging procedures, e.g. heating of the capacitor, gas emission, electrolyte decay, formation of imperfect oxide layer. When devising the capacitor's construction, design engineers must set the optimal operating voltage. It is important not to cause too high current during operation because that can lead to the breakdown of the capacitor.

Developing Process of Capacitor

Development of aluminium electrolyte capacitors is a complex process. The ideal flow-chart is shown by *Fig. 5*.

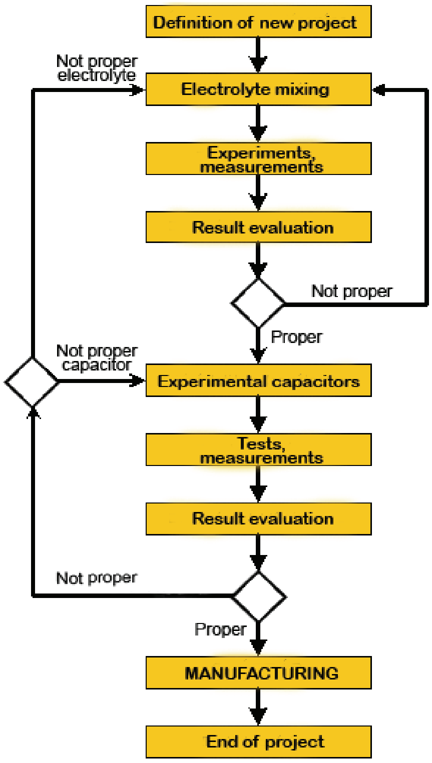

Figure 5: Flowchart of Capacitor Development

The flowchart shown on Fig. 5 consists of two parts: the first part is electrolyte development, and the second part is capacitor construction development. Both sections include measurements and experiments. Measurements of and experiments on electrolyte last for a short time while measurements of and experiments on capacitor construction can last for thousands of hours. The stages of development are determined by the purpose of the development project: there are cases when the only object is developing a new construction so measurements of and experiments on electrolyte are irrelevant. Regarding measurements of electrolyte, this article only deals with spark measurement which helps design engineers in determining the optimal operation voltage. The automation of multi-operating, data-registering, mid-long and long measurements and experiments was optimal, increasing the efficiency and speed of capacitor development. The automation has been realized by creating an Information Technological system which studies every aspect of capacitor development.

Measurement Automation System (MAS)

The main purpose of MAS [4] is to help capacitor development, which is a time-consuming and really complicated task. The base of the whole software system is a framework originally designed to provide a common user interface for different measurements and registry programs. The measurement system includes at least 30 different measurements and software modules. The whole system can not be presented here we only focus on the software modules related to the estimation of the maximum voltage level.

The main structure has two different parts. The first one contains the measurements, while the second one contains the data evaluation modules, concluding data management and data visualization modules that can display all the results of measurements, tests and experiments. The "class" of measurements has two sub-groups involving the electrolyte and the capacitor measurements. The electrolyte experiments are controlled by a NI-PXI which is connected to the database. The structure of the measurements is shown by *Fig. 6*. The graphical interfaces of electrolyte measurements have two pages. The first one contains the settings of the measurements and equipments (e.g. number of serial port, cell voltage of conductivity equipment, file path of saved data, etc.). This page is used before the measurement. The second one shows the status of the experiment. It displays the measurement results with numeric indicators and graph, the elapsed and remaining time, etc. The software can store the results into a file and the global database.

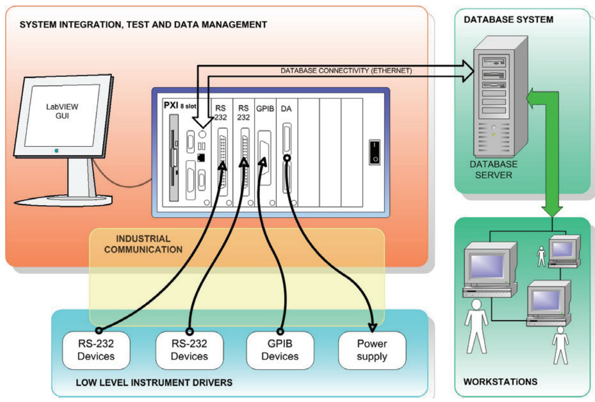

Figure 6: Structure of the electrolyte measurements

The most important electrolyte measurements are the following:

- *"Conductivity(T)"*: measuring temperature dependence of conductivity. In this experiment the temperature of the solution is regulated and after the stabilization time the conductivity value is measured with the controlled equipment.
- *"Ph(T)"*: measuring pH value as a function of temperature. The structure of the program is the same as that of the above-mentioned one, with the only difference that a pH meter is used instead of conductivity meter. The measurement is important because the pH value of the electrolyte used in the electrolytic-capacitor must be within a specified range.

- *"Mixing(pH with single temperature)"*: measuring pH value as a function of the concentration of an electrolyte composition at a specified temperature. As a matter of fact, we use this measurement in order to set up the pH value of the electrolyte.
- *"Spark detector":* measuring the breakdown potential of the electrolyte. This measurement is one of the most important tasks, and will be presented in detail in the next section.

The second subgroup contains the capacitance management modules which simplify the electrical measurements and data registration. In addition, it includes the registration interface of the capacitor experiments for qualification approval.

The most important measurements in this group are the following:

- *Capacitor Registration:* This module simplifies the registration of the properties (anode, cathode foil, type of can, cover disk, etc.) of the capacitor.
- *"ESR (Equivalent Serial Resistance) - Matrix":* This measurement is mostly used in order to determine the resistance of the capacitor at different frequencies and temperatures.
- *"Gas pressure":* measuring the internal gas pressure of the capacitor in various operating conditions.
- *Electrical measurement:* measuring the electrical parameters (Capacitance, Impedance, ESR) of the capacitor by an *Agilent LCR* equipment at different frequencies.
- *Leakage measurement:* The oxide layer of the capacitor's anode foil is not flawless, so DC current is flowing through the capacitor if voltage is applied to it. This current is the leakage current. Its value depends on the applied voltage, the duration of the charging period and the capacitor's temperature.

The last part of the system has been developed for data management. This software module contains really useful tools, which facilitate the representation and evaluation of the stored data. For example: the *Report Generate* module can make a standard report in less than one minute.

This module contains the following software:

- *Report Generate:* for composing a standard report about the specified experiment (e.g. endurance, surge test, etc.)
- *Search:* for constructing several SQL commands that can build "ad hoc" queries.
- *Documentation Library:* for handling the reports on experiments.

The software package facilitates electrolyte and capacitor development because these tools accelerate the experiments and make work easier.

The most important measurement is the *"Spark detector"* experiment, which helps estimate the maximum applicable voltage of aluminium electrolytic capacitors.

Spark Measurement

During a spark measurement the breakdown voltage of the tab foil's oxide layer is measured. Breakdown voltage is the voltage where the dielectric starts to conduct. A spark can occur because of the electric field. This phenomenon happens by growing of the polarization bias. The field strength is increasing. If the increase is adequate, the neutral corpuscles become polarized and the insulator starts to conduct. Such spark phenomenon occurs too if the dielectric loss heats up the insulator. Above a specified heat level the insulating attribute no longer exists. A spark is featured by its time interval, which can extend from a few nanoseconds to seconds. Spark is affected by the pressure, the humidity, the temperature and the material purity. Because of the spark phenomenon's sensitive nature, small voltage changes in short time intervals must be detected. The equipment built for this purpose detects spark the following way: Damages of the dipped tab are repaired by the current. The oxide layer becomes thicker, so voltage is increasing. During etching a limited oxide layer with limited sturdiness can be produced. Above this critical voltage level spark happens, accompanied by a hissing and crackling sound. The current of the circuit is momentarily increasing. Instead of voltage generator mode, the system's power supply works in current generator mode. By this method a sufficient layer of insulating material can be produced on the freshly cut edges on the influence of the electrolyte's limited current level. After reaching a critical voltage level, the voltage is no longer increasing and spark happens. The oxide layer starts to conduct and the power supply's voltage falls. This voltage can easily be detected.

The complete measurement system can be seen on *Fig. 7*. The system includes the power supply, the thermostat, the thermostated beaker and the spark detector.

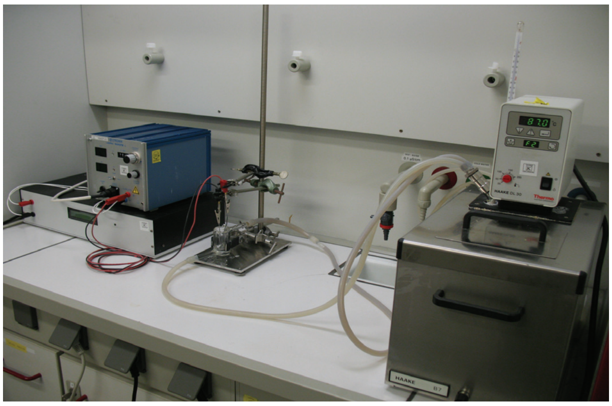

Figure 7: The Spark measurement system

For collecting, registering and handling measurement results a suitable software has been developed. The user's interface of the software is shown in *Fig. 8*.

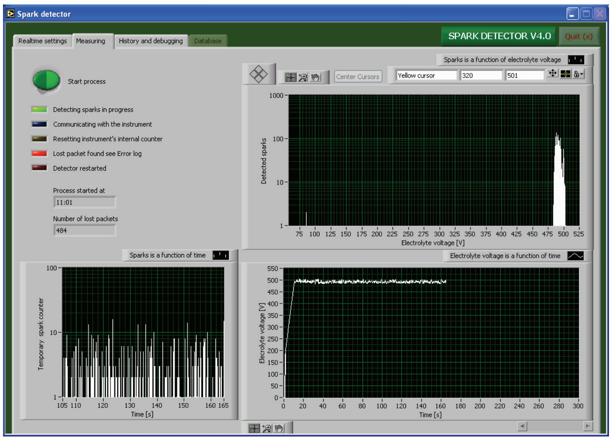

Figure 8: Graphical interface of Spark measurement

The equipment and the measuring PXI communicate through an RS-232 port. The software can set the properties of the equipment and control the entire experiment. The users just have to start the experiment.

There are two graphs on Fig. 8. The upper one shows the number of sparks while the lower one shows the voltage level. After the experiment, the measured results can be saved into the database or exported into MS EXCEL.

Results

Many experiments were performed with the equipment and the data on voltage and sparking density of the electrolytes were stored. The Spark phenomenon was measured at the maximum temperature of the climatic category of capacitors (As previously discussed, breakdown voltage is influenced by the temperature). The results showed (*Fig. 9*) that the peak of the Gauss-curve of spark density specifies a voltage, which is approximately the maximum voltage level of the electrolyte. The applicable voltage is determined by the paper construction of the capacitor: Spark voltage of the electrolyte has grown by about 5 to 10 percent. By this method, the capacitor's maximum applicable voltage can be approximately evaluated. This voltage level is not used during the usage of the capacitor. The actual voltage levels in practice are 400 V, 450 V, 500 V, etc. International standards determine certain experiments to be performed for qualification approval. The capacitor's selected rated voltage must withstand a defined voltage level. For example, a capacitor with a 450 V rated voltage must withstand a 495 V voltage level, which is determined by the surge test.

In practice, first the spark voltage of the capacitor must be measured (the experimental electrolyte's spark voltage is 479 V), and after that a RAMP test is recommended.

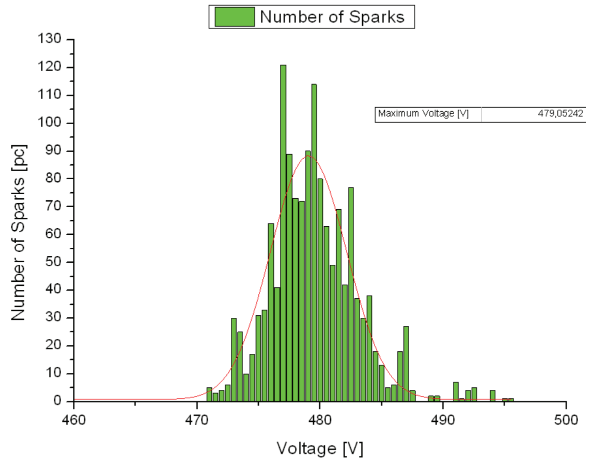

Figure 9: Spark voltage of the electrolyte

In the RAMP test the voltage level is continuously increased until the failure of the capacitor.

The experimental electrolyte was tested with capacitors of different paper construction. (With a thinner paper during the first, and with a thicker paper during the second test). The first test's current curves can be seen on *Fig. 10* and the second test's current curves can be seen of *Fig. 11*.

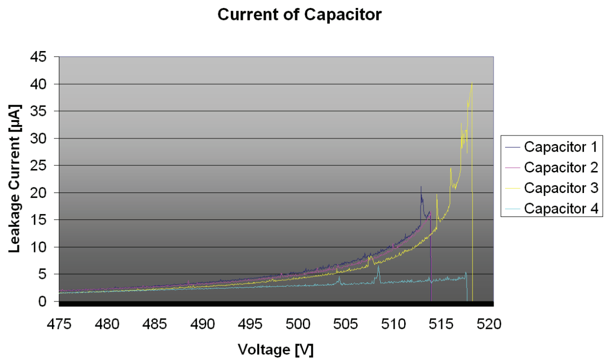

Figure 10: The current, with the first paper construction

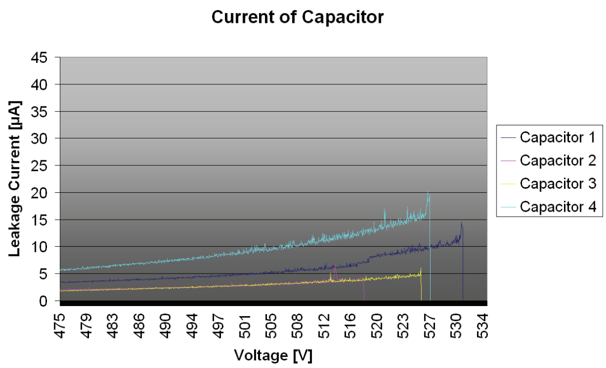

Figure 11: The current, with the second paper construction

The breakdown voltage of the capacitor is 516 V and 525 V. The first one is 107.7 % while the second one is 109.6 % of spark voltage. This proves that the paper's thickness influences the spark voltage. The capacitor's rated voltage is 450 V. The CECC standard defines a surge test, where the capacitor must endure 110 % of the rated voltage, in this case 495 V.

Conclusion

This paper presents the measurement automation system of an Electrolytic Capacitor Development Laboratory at EPCOS Hungary that contains more than 30 modules, including measurements on electrolytes and capacitors and data visualization software. All measurements have been implemented in a similar manner. First, the user initializes the measurement, sets the measurement parameters, launches the execution and leaves the program to run on its own, sending the results of the measurements to a database system, from where the data can be retrieved in a predefined or non-predefined way. The data acquisition system increases the efficiency of work (by decreasing the possibility of failures and assisting the developer engineer), and accelerates the process of development. These advantages are due to the automation of the measurements and the effective data visualization tools.

The paper presents in detail an important and very useful method, the Spark measurement which helps determining the maximum applicable capacitor voltage level by measuring the electrolyte's breakdown voltage. This voltage level is 90–95 % of the capacitor's operating voltage. For defining the maximum voltage level, a RAMP test must be executed after the Spark measurement where the voltage of the capacitor is continuously increasing. The voltage measured this way is the capacitor's maximum voltage. The executed tests prove the accuracy and adaptability of the measurement.

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