An analysis on analogue ESR-meter

C M Dinis, G N Popa, C D Cunțan and A Iagăr

Politehnica University of Timisoara, Department of Electrical Engineering and Industrial Informatics, 5 Revolution Street, Hunedoara, 331128, Romania

E-mail: corina.dinis@fih.upt.ro

Abstract. The paper presents an analogue ESR meter, made with a JFET integrated circuit, which can be used to identify defective electrolytic capacitors. It is powered by continuous voltage and consists of a differential voltage source, a 100 kHz oscillator, a Wheatstone bridge with resistors supplied with alternating voltage, in a connecting arm of bridge being connected the electrolytic capacitors to be checked, a voltage amplifier-comparator with optical warning, a high-pass filter and a voltage-current converter. At the output of voltage-current converter is a milliammeter pointing out the ESR value (up to 20 Ω). Measurements were made on a batch of electrolytic capacitors (new and used) and a comparative analysis was performed between the measured values with an analogue ESR-meter and a digital one.

1. Introduction

In present day, electrolytic capacitors are widely used in power electronics circuits and are the main sensitive components with the shortest life. Usually, the main functions in power sources of electrolytic capacitors are in power sources, bus voltage, stabilization, etc. [1-5]. Primary wear-out mechanism in electrolytic capacitors failures are deterioration of the electrolyte between electrodes and loss of electrolyte by vapours (dry-up).

The electrolytic capacitors have series internals resistances (ESR – equivalent series resistance) that increase with operating time, temperature and voltage [6-9]. Increasing of ESR conducts to heating of electrolytic capacitor and decreasing of capacitor value and increasing of tangent of loss angle (tan δ) [10]. Today, to fix the problems in electronic circuit must be used an oscilloscope, an analogue multimeter, a digital multimeter, and an ESR meter to verify electrolytic capacitors life.

2. Electrolytic capacitors. Design, using, and electrical models

Aluminum electrolytic capacitor is widely used in power electronics circuits. The main functions are: bus voltage, stabilization, etc. Most of electrolytic capacitors have maximum temperature ratings: 85 °C and 105 °C, and a few rated 125 °C [11], [12]. The aluminum electrolytic capacitor consists of (Figure 1): plastic insulation, aluminum, metal plate, dielectric, positive and negative charge connections.

There are different types of capacitors (Figure 2): ceramic capacitors, plastic capacitors, aluminum electrolytic capacitors, power capacitors, tantalum capacitors, double-layer capacitors and supercapacitors [13].

The electrolytic capacitors life is finite depending on electrolyte evaporation (dry-up of electrolytic capacitors). E.g.: at 35 °C, the electrolytic capacitors life is 16 years [10]. The electric conductivity depends of the type of capacitors (Figure 3).
Figure 1. Design of electrolytic capacitor

Figure 2. Typical capacitors used in practice

Capacitor life is defined as the time laps to the point when the capacitance value is decreased to 70% of the initial value. Usually, the capacitors users could not determine when should replace fault capacitors before they fail completely. Capacitor capacity decreases and $\tan \delta$ increases after approximately 10000 hours of operation.

Electrolytic capacitors are sensible to: especially temperature and voltage, and humidity, temperature gradients, shocks and vibrations [11], [14], [15].

Figure 3. Electric conductivity depending on capacitors type

For switch mode power sources, the fault rate is [12]:
- 59% for electrolytic capacitors;
- 30% MOSFET;
- 5% coils;
- 2% diodes.
- 4% others.

Capacitors have equivalent series internal resistance ESR that conduct to heating when ripple current flows [16]. The failure mechanisms and modes in aluminum electrolytic capacitor is presented in Figure 4 [17].

![Figure 4](image)

**Figure 4.** Failure mechanisms and modes in aluminum electrolytic capacitor [17]

Primary wear-out mechanisms in electrolytic capacitors is mainly due the loss of electrolyte by vapor diffusion and deterioration of the electrolyte. Typically, lowering the mass of the electrolyte leads to ESR growth (sometimes even 20 times), and capacitor capacity decreases by up to 40%. The detailed electrical model for electrolytic capacitor is presented in Figure 5.

![Figure 5](image)

**Figure 5.** Detailed electrical model for electrolytic capacitor [4]
In Figure 5: \( C_{AK} \) is ideal anode-cathode capacitance (main element of the capacitor), \( R_p \) is the parallel resistance due to alumina layers, \( R_1 \) is series resistance of connections, frames and separator, and \( L \) is equivalent inductance series of connections and windings.

In practice, usually, is used simplified electrical model for electrolytic capacitor – Figure 6.

\[
Z_C = \sqrt{ESR^2 + \left(ESL \cdot \omega - \frac{1}{C \cdot \omega} \right)^2}
\]

\[
C = C_{AK} \left(1 + \frac{1}{R_p \cdot C_{AK} \cdot \omega^2} \right)
\]

\[
ESR = R_1 + \frac{R_p}{1 + R_p^2 \cdot C_{AK}^2 \cdot \omega^2}
\]

\[
ESL = L
\]

3. ESR-meters
Troubleshooting power electronic circuits requires an investment in quality equipment. Today, to fix the problems in power electronic circuits must be used: an oscilloscope, a good analogue multimeter, a high quality digital multimeter, and an ESR-meter to verify electrolytic capacitors.

Figure 6. Simplified electrical model for electrolytic capacitor

![Figure 6. Simplified electrical model for electrolytic capacitor](image)

Figure 7. Fishbone diagram of failure mechanisms in aluminium electrolytic capacitor [18]
During a short time or a long time operation of aluminum electrolytic capacitors there are a lot of failure mechanisms which switch off the operation of electronic circuits (Figure 7).

An ESR meter is an instrument that measures equivalent resistances for electrolytic capacitors (ESR). It is an alternating current meter using pulse or high frequency signals (tens of kHz). It can be used with AC measurement bridges.

The capacitor is measured either directly or in a circuit free of voltage, with the capacitor discharged, because the measured resistance will be less than any component from the circuit.

An ideal capacitor has a value close to 0 Ω (ESR). A second verification can be done with an ohmmeter.

If the ESR value is high, over 10 Ω, the capacitor is defective, regardless of capacity of capacitor.

Table 1. Maximum value for ESR (Ω) depending on nominal capacity of electrolytic capacitor and nominal voltage [9], [16]

| Capacity (µF) | 10 (V) | 16 (V) | 25 (V) | 35 (V) | 50 (V) | 100 (V) | 160 (V) | 250 (V) |
|--------------|--------|--------|--------|--------|--------|---------|---------|---------|
| 1            | 5.0    | 7.0    | 10.0   | 14.0   |
| 2.2          |        |        |        |        |        |         |         |         |
| 4.7          | 2.0    | 2.0    | 2.0    | 1.2    | 1.5    | 2.8     |         |         |
| 10           | 1.3    | 1.3    | 1.3    | 1.3    | 0.66   | 1.1     | 1.2     |         |
| 22           | 1.3    | 1.3    | 1.3    | 0.6    | 0.32   | 0.46    | 0.60    |         |
| 47           | 1.3    | 0.6    | 0.6    | 0.33   | 0.33   | 0.16    | 0.24    | 0.30    |
| 100          | 0.6    | 0.33   | 0.33   | 0.25   | 0.19   | 0.09    | 0.14    | 0.27    |
| 470          | 0.33   | 0.25   | 0.19   | 0.14   | 0.09   | 0.06    |         |         |
| 1000         | 0.19   | 0.14   | 0.09   | 0.07   | 0.06   |         |         |         |
| 2200         | 0.09   | 0.07   | 0.06   | 0.05   | 0.04   |         |         |         |
| 3300         | 0.07   | 0.06   | 0.05   | 0.04   |         |         |         |         |
| 4700         | 0.06   | 0.05   | 0.04   | 0.03   |         |         |         |         |
| 10000        | 0.04   |         |         |         |         |         |         |         |

4. Making an analogue ESR-meter

The analogue ESR meter is made with a JFET integrated circuit, which can be used to identify defective electrolytic capacitors (Figure 8).

It is powered by continuous voltage and consists of a differential voltage source, a 100 kHz oscillator, a Wheatstone bridge with resistors supplied with alternating voltage, in a connecting arm of bridge being connected the electrolytic capacitors to be checked, a voltage amplifier-comparator with optical warning, a high-pass filter and a voltage-current converter [16].

At the output of voltage-current converter is a milliammeter pointing out the ESR value (up to 20 Ω). Measurements were made on a batch of electrolytic capacitors (new and used) and a comparative analysis was performed between the measured values with an analogue ESR-meter and a digital one.

Components list (in Figure 8):

| R1=1K5 | C1,C2,C5,C6=1µF | R19=680 Ω |
| R2,R3,R4,R5=10K | C3=1nF, POLY | R20=100 Ω |
| R6=68K | C4=100nF, POLY | R21=500 Ω |
| R7=4K7 | DS1,DS2=1N4007 | R10,R12=5,6 Ω, 1% R14,R15 =1K |
| R8=12K | DS3=1N4148 | T1,T3=BC547 T2=BC557 |
| R9,R11=1K, 1% | DL1=LED | R13,R16,R17=47K IC1=TL084 |

In Table 2: C(µF) – nominal capacity; U (V) – nominal voltage; Cm (µF) – measured capacity; εV (%) – percentage voltage loss; ESR_{max} (Ω) – the maximum ESR; ESR_{d} (Ω) – measured ESR with
digital ESR-meter, LCR-T5 Multifunction Tester; $\text{ESR}_a$ (Ω) - measured ESR with analogue ESR-meter; $\varepsilon_{\text{ESR}}$ (%) – relative error for measuring ESR between analogue and digital ESR-meters.

**Figure 8.** The electronic diagram for analogue ESR-meter [16]

**Table 2.** Measurements made on electrolytic capacitors (new and used) with digital and analogue ESR-meters

| No. | C(μF) | U (V) | $C_m$ (μF) | $\varepsilon_v$ (%) | $\text{ESR}_{\text{max}}$ (Ω) | $\text{ESR}_d$ (Ω) | $\text{ESR}_a$ (Ω) | $\varepsilon_{\text{ESR}}$ (%) | Cap. |
|-----|-------|-------|-----------|-------------------|----------------|-------------|-------------|----------------|-------|
| 1   | 4.7   | 50    | 5.272     | 12.17             | 3              | 3.64        | 2.64        | -27.47         | √     |
| 2   | 10    | 25    | 11.81     | 18.10             | 2              | 3.94        | 3.44        | -12.69         | X     |
| 3   | 10    | 63    | 10.43     | 4.30              | 1.3            | 0.86        | 2.39        | 177.91         | ?     |
| 4   | 22    | 10    | 25.49     | 15.86             | 1.3            | 14          | 19          | 35.71          | X     |
| 5   | 22    | 100   | 24.64     | 12.00             | 0.66           | 0.43        | 0.39        | -9.30          | √     |
| 6   | 47    | 10    | 48.73     | 3.68              | 1.3            | 13          | > 20        | 13.16          | X     |
| 7   | 47    | 10    | 57.03     | 21.34             | 1.3            | 17          | > 20        | 63.64          | X     |
| 8   | 47    | 10    | 61.57     | 31.00             | 1.3            | 1.14        | 1.29        | 13.16          | √     |
| 9   | 47    | 16    | 46.1      | -1.91             | 1.3            | 2.8         | 2.65        | -5.36          | X     |
| 10  | 100   | 10    | 102.8     | 2.80              | 1.3            | 1.24        | 0.99        | -20.16         | √     |
| 11  | 100   | 10    | 76        | -24.00            | 1.3            | 11          | 18          | 63.64          | X     |
| 12  | 100   | 10    | 109.3     | 9.30              | 1.3            | 2.6         | 3.2         | 23.08          | X     |
| 13  | 100   | 10    | 97.91     | -2.09             | 1.3            | 3.5         | 3.6         | 2.86           | X     |
| 14  | 100   | 10    | 112.3     | 12.30             | 1.3            | 0.96        | 0.96        | 0.00           | √     |
| 15  | 100   | 10    | 104.6     | 4.60              | 1.3            | 0.84        | 0.99        | 17.86          | √     |
| 16  | 100   | 10    | 102.2     | 2.20              | 1.3            | 0.69        | 0.89        | 28.99          | √     |
| 17  | 100   | 10    | 120.7     | 20.70             | 1.3            | 0.84        | 0.94        | 11.90          | √     |
| 18 | 100 | 50 | - | - | 0.33 | > 20 | X |
|---|---|---|---|---|---|---|---|
| 19 | 220 | 6.3 | 217.2 | -1.27 | 1.3 | 0.46 | 0.49 | 6.52 | √ |
| 20 | 220 | 10 | 164.6 | -25.18 | 0.6 | 0.49 | 0.59 | 20.41 | √ |
| 21 | 220 | 10 | 214.3 | -2.59 | 0.6 | 0.15 | 0.49 | 226.67 | √ |
| 22 | 220 | 10 | 214.5 | -2.50 | 0.6 | 1.74 | 1.91 | 9.77 | X |
| 23 | 220 | 10 | 244.6 | 11.18 | 0.6 | 0.43 | 0.69 | 60.47 | √ |
| 24 | 220 | 10 | 202.1 | -8.14 | 0.6 | 0.32 | 0.59 | 84.38 | √ |
| 25 | 470 | 10 | 506.4 | 7.74 | 0.33 | 0.23 | 0.24 | 4.35 | √ |
| 26 | 470 | 25 | 128 | -72.77 | 0.19 | 13 | 21 | 61.54 | X |
| 27 | 470 | 25 | - | 0.19 | > 1000 | > 20 | X |
| 28 | 470 | 25 | - | 0.19 | > 1000 | > 20 | X |
| 29 | 470 | 25 | 26x10-6 | 0.19 | > 1000 | > 20 | X |
| 30 | 1000 | 16 | 639.8 | -36.02 | 0.14 | 0.21 | 0.54 | 157.14 | ? |
| 31 | 1000 | 35 | 973.5 | -2.65 | 0.07 | 0.12 | 0.04 | -66.67 | √ |
| 32 | 1000 | 50 | 705.1 | -29.49 | 0.14 | 0.19 | 1.04 | 447.37 | X |
| 33 | 1000 | 50 | 932.3 | -6.77 | 0.06 | 0.09 | 0.01 | -88.89 | ? |
| 34 | 1000 | 50 | 844.5 | -15.55 | 0.06 | 0.1 | 0.09 | -10.00 | ? |
| 35 | 1000 | 50 | 932.3 | -6.77 | 0.06 | 0.09 | 0.04 | -55.56 | ? |
| 36 | 2200 | 25 | 2219 | 0.86 | 0.06 | 0.08 | 0.04 | -50.00 | ? |
| 37 | 2200 | 25 | 2233 | 1.50 | 0.06 | 0.08 | 0.04 | -50.00 | ? |
| 38 | 2200 | 25 | 2219 | 0.86 | 0.06 | 0.08 | 0.04 | -50.00 | ? |
| 39 | 2200 | 25 | 2240 | 1.82 | 0.06 | 0.09 | 0.01 | -88.89 | ? |
| 40 | 3300 | 16 | 3447 | 4.45 | 0.06 | 0.08 | 0.01 | -87.50 | ? |
| 41 | 3300 | 16 | 3435 | 4.09 | 0.06 | 0.07 | 0.09 | 28.57 | ? |
| 42 | 3300 | 16 | 3332 | 0.97 | 0.06 | 0.09 | 0.04 | -55.56 | ? |
| 43 | 3300 | 16 | 3493 | 5.85 | 0.06 | 0.09 | 0.04 | -55.56 | ? |
| 44 | 4700 | 25 | 5458 | 16.13 | 0.04 | 0.07 | 0.04 | -42.86 | ? |

Increasing the ESR over the maximum value is not related to a decrease in capacitor capacitance.

Some faulty capacitors have been identified with the analogue ESR-meter (the digital ESR-meter considers them good).

5. Conclusion

ESR-meter is an electronic device, relatively new introduced in power electronic troubleshooting. Using the ESR-meter to troubleshoot electronic circuits becomes an indispensable device because most of the power electronics failures are due to electrolytic capacitor failure. Sometimes measurements can be made without removing the capacitors in the circuit, so the repair time is greatly diminished.

ESR (Equivalent Series Resistance) is the sum of all internal resistors of a capacitor measured in ohms (reactance is not included). ESR is a dynamic size and must be measured at alternating voltage of tens of kHz.

Development of capacitors with long-life, high allowable ripple current and low impedance are effective to make high performance power supplies.

References

[1] Sankaran V A, Rees F L, A and C S 1997 Electrolytic Capacitor Life Testing and Prediction, IEEE Industry Applications Society Annual Meeting, October 5-9, New Orleans, Louisiana, USA, pp 1058-1065

[2] Zhao K, Ciufo P and Perera S 2010 Lifetime Analysis of Aluminum Electrolytic Capacitor
Subject to Voltage Fluctuations, Research Online, University of Wollongong, Australia, 7 pp

[3] Lahyani A, Venet P, Grellet G and Viverge P J 1998 Failure Prediction of Electrolytic Capacitors During Operation of a Switchmode Power Supply, *IEEE Transactions on Power Electronics* **13**(6) 1199-1207

[4] Pănoiu C, Rob R, Baciu I, Pănoiu M 2011 *IGBT Command in Active Filtering of the Harmonics Current*, WSEAS European Computing Conference Paris, France, April 28-30, pp 158-163

[5] Pănoiu C, Rob R, Baciu I and Pănoiu M 2011 Shunt Active Filter Command Designed in Labview, *International Journal of Circuits, Systems and Signal Processing* **5**(5) 513 – 520

[6] Harada K, Katsuki A and Fujiwara M 1993 Use of ESR for Deterioration Diagnosis of Electrolytic Capacitor, *IEEE Transactions on Power Electronics* **8**(4) October 355-361

[7] Hewitt D, Green J, Davidson J, et al. 2016 *Observation of Electrolytic Capacitor Ageing Behaviour For The Purpose Of Prognostics*, IECEN 2016, 42nd Annual Conference of the IEEE Industrial Electronics Society, October 24-27, Florence, Italy, 6 pp

[8] Kulkarni C S, Biswas G, Celaya J R and Goebel K 2013 Physics Based Degradation Models for Electrolytic Capacitor Prognostics under Thermal Overstress Conditions, *International Journal of Prognostics and Health Management* **4** 1-17

[9] Albertsen A 2008 *Electrolytic Capacitor Lifetime Estimation*, Jianghai Europe, January

[10] Kiuchi K and Yanagibashi M 1983 *Operating Life of Aluminum Electrolytic Capacitor*, IEEE, Telecommunications Energy Conference, INTELEC 03, Fifth International Conference, October 18-21, Tokyo, Japan, pp 535-540

[11] Wang H et al. 2014 Transitioning to Physics of Failure as a Reliability Driver in Power Electronics, *IEEE Journal of Emerging and Selected Topics in Power Electronics* **2**(1) March 97-114

[12] Laadjal K, Sahraoui M, Marques Cardoso A J and Amaral A M R 2017 *On-Line Estimation of Aluminum Electrolytic-Capacitor Parameters Using a Modified Prony’s Method*, Diagnostics for Electrical Machines, Power Electronics and Drives (SDEMPED), 2017 IEEE 11th International Symposium on, 29 August - 01 September, Tinos, Greece, pp 387-393

[13] Sood B 2013 *Root-Cause Failure Analysis of Electronics*, Philadelphia, University of Maryland, USA, March 14, 2013, pp 1-19

[14] Parler S G 1999 *Thermal Modeling of Aluminum Electrolytic Capacitors*, IEEE Industry Applications Society Conference, Thirty-Fourth IAS Annual Meeting, October, pp 2418-2429

[15] ***https://enphase.com/sites/default/files/Electrolytic_Capacitor_Expert_Report.pdf

[16] ***www.epsicom.com/kits.php

[17] Kulkarni C, Biswas G, Celaya J and Goebel K 2011 *Prognostic Techniques for Capacitor Degradation and Health Monitoring*, The Maintenance and Reliability Conference, Knoxville, TN, USA, September 13-15, 2011, pp 1-14

[18] Kulkarni C, Biswas G, Celaya J and Goebel K 2013 *Physics Based Degradation Models for Capacitor Prognostics under Thermal Overstress Conditions*, International Journal of Prognostics and Health Management **4**(005) 1-17