## 1 Basic construction of aluminum electrolytic capacitors

Aluminum electrolytic capacitors, which will be abbreviated to “Al electrolytic capacitors” in the following, assume a special position among the various types of capacitors since their principle of operation relies, in part, on electrochemical processes.

The advantages of Al electrolytic capacitors that have led to their wide application range are their high volumetric efficiency (i.e. capacitance per unit volume), which enables the production of capacitors with up to one Farad capacitance, and the fact that an Al electrolytic capacitor provides a high ripple current capability together with a high reliability and an excellent price/performance ratio.

As is the case with all capacitors, an Al electrolytic capacitor comprises two electrically conductive material layers that are separated by a dielectric layer. One electrode (the anode) is formed by an aluminum foil with an enlarged surface area. The oxide layer ($Al_2O_3$) that is built up on this is used as the dielectric. In contrast to other capacitors, the counter electrode (the cathode) of Al electrolytic capacitors is a conductive liquid, the operating electrolyte. A second aluminum foil, the so-called cathode foil, serves as a large-surfaced contact area for passing current to the operating electrolyte.

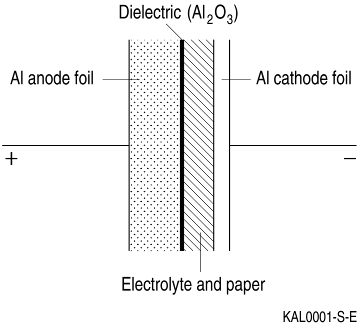


Figure 1 Basic construction of an aluminum electrolytic capacitor

$$C = \varepsilon_0 \cdot \varepsilon_r \cdot \frac{A}{d}$$

| | | |
|---|---|---|
| $C$ | Capacitance | F |
| $\varepsilon_0$ | Absolute permittivity | As/Vm |
| $\varepsilon_r$ | Relative dielectric constant | (9,5 for $Al_2O_3$) |
| A | Capacitor electrode surface area | $m^2$ |
| d | Electrode spacing | m |

The anode of an Al electrolytic capacitor is an aluminum foil of extreme purity. The effective surface area of this foil is greatly enlarged (by a factor of up to 200) by electrochemical etching in order to achieve the maximum possible capacitance values. The type of etch pattern and the degree of etching is matched to the respective requirements by applying specific etching processes.

Etched foils enable very compact Al electrolytic capacitor dimensions to be achieved and are the form used almost exclusively nowadays. The electrical characteristics of Al electrolytic capacitors with plain (not etched) foils are, in part, better, but these capacitors are considerably larger and are only used for special applications nowadays.

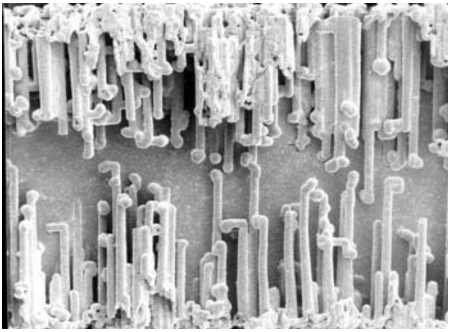


Figure 2 Anode foil for high-voltage capacitors (magnification 400x)

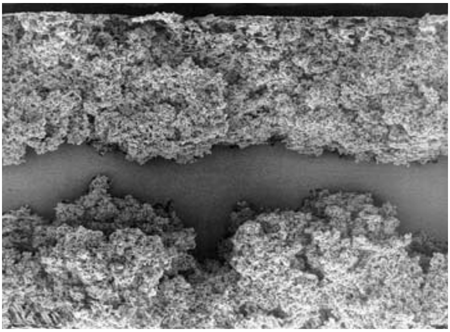
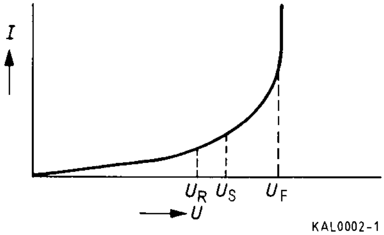


Figure 3 Anode foil for low-voltage capacitors (magnification 400x)

The dielectric layer of an Al electrolytic capacitor is created by anodic oxidation (forming) to generate an aluminum oxide layer on the foil. The layer thickness increases in proportion to the forming voltage at a rate of approximately 1,2 nm/V. Even for capacitors for very high voltages, layer thicknesses of less than 1 µm are attained, thus enabling very small electrode spacings. This is one reason for the high volumetric efficiency achieved (e.g. in comparison to the minimum thickness of a paper dielectric, 6 to 8 µm).

During the forming process the very fine pits of the etched foils will encrust partially in proportion to the forming voltage and thus also to the achieved layer thickness. Due to this effect, the final operating voltage range must already be taken into account when the foils are etched.

The oxide layer constitutes a voltage-dependent resistance that causes the current to increase more steeply as the voltage increases. A characteristic curve as shown in figure 4 is obtained.



$U_R$ = Rated voltage
$U_S$ = Surge voltage
$U_F$ = Forming voltage

Figure 4 Current-voltage characteristic of an Al electrolytic capacitor

When the forming voltage $U_F$ is exceeded, the forming process starts a new and large amounts of gas and heat are generated. The same effect, yet on a smaller scale, can already be observed in the knee of the curve. In order to achieve a high degree of operating safety of the capacitor, the rated voltage $U_R$ is defined as being on the quasi-linear part of the curve. As the capacitor is subjected to surge voltages $U_S$ for short periods only, this range lies between the rated voltage and the forming voltage. The difference between forming voltage and operating voltage, the so-called over-anodization, thus has a substantial effect on the operating reliability of the capacitor. High over-anodization offers the possibility of producing especially reliable capacitors designated as long-life grade “LL” capacitors in accordance with IEC 60384–1.

Since the electrolytic capacitors have a liquid as a cathode, they are also designated as “wet” or “non-solid” capacitors. The liquid has the advantage that it fills the fine etching pits, therefore optimally fitting into the anode structure.

The two aluminum foils are separated by paper spacers. The paper serves various purposes, it serves as a container for the electrolyte – the electrolyte is stored in the pores of the absorbent paper – and also as a spacer to prevent electric short-circuits, as well as ensuring the required dielectric strength between the anode and cathode foils.

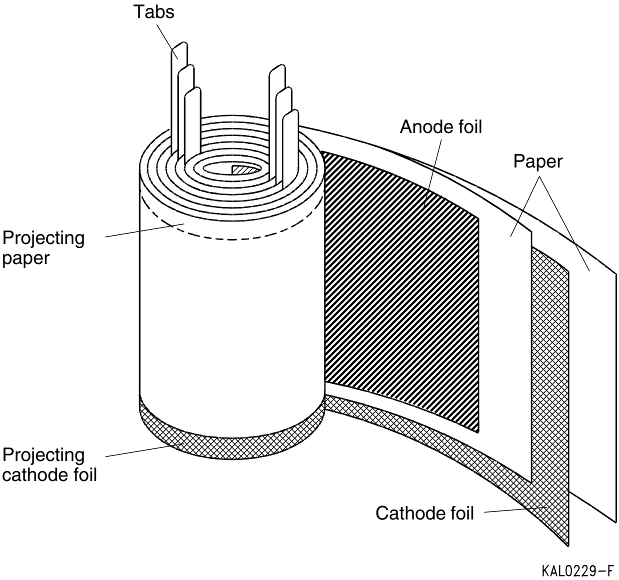


Figure 5 Winding construction of an Al electrolytic capacitor

An Al electrolytic capacitor constructed in the way described above will only operate correctly if the positive pole is connected to the formed Al foil (or anode), and the negative pole to the cathode foil. If the opposite polarity were to be applied, this would cause an electrolytic process resulting in the formation of a dielectric layer on the cathode foil. In this case strong internal heat generation and gas emission may occur and destroy the capacitor. Secondly, the cathode capacitance, which will progressively decrease as the oxide layer thickness increases, and which is connected in series with the anode capacitance, would reduce the overall capacitance considerably.

An electrolytic capacitor of the basic design described here is therefore only suitable for dc operation. The dc voltage may also be a ripple voltage, i.e. a dc voltage with a superimposed alternating voltage; the positive pole must be connected to the anode. Capacitors with this configuration are polar versions that can be used for most applications.

As already pointed out, polar capacitors do not tolerate a voltage reversal. Incorrect polarities of up to 1,5 V are, however, permissible for short periods of time as the formation of a damaging oxide layer on the cathode only starts at voltages of this magnitude. (This is because the cathode foil is covered by an air-oxide layer that corresponds to an anodized dielectric layer with a breakdown voltage of approximately 1,5 V.)

### Bipolar Al electrolytic capacitors

Bipolar Al electrolytic capacitors are also available. In bipolar designs, not only the anode foil but also the cathode foil is anodized in the production process. The cathode foil has the same capacitance rating as the anode foil. This construction allows for operation at direct voltage of either polarity, as well as operation at purely alternating voltages. Since it causes internal heating, the applied alternating voltage must be kept considerably below the direct voltage rating.

Due to series connection of the two capacitor elements the total capacitance amounts to only half the individual capacitance values. In comparison to a polar capacitor, a bipolar electrolytic capacitor of similar construction thus requires up to twice the volume for the same total capacitance. More over, twice the leakage current must be expected.

## 2 Standards and specifications

### 2.1 General-purpose grade and long-life grade capacitors

Al electrolytic capacitors are generally divided into two basic reliability categories: capacitors for high-reliability applications and capacitors for general-purpose applications. This differentiation has also been adopted in the relevant IEC standards.

In IEC publications Al electrolytic capacitors for high-reliability applications are identified as “Long-Life Grade” capacitors. The abbreviation LL is stamped on the capacitors. In addition to the over-anodization as described in chapter 1, further measures are taken to enhance the reliability. Generally, the materials used for Al electrolytic capacitors must meet strict purity requirements, and those used for producing LL grade capacitors must be specially selected. The design effort required for such capacitors affects both the case size and the price.

Al electrolytic capacitors for general applications are called “General-Purpose Grade” in IEC publications.

## 2.2 Applicable standards

The international standard for aluminum electrolytic capacitors is IEC 60384-4, which is also available in German as DIN IEC 60384, part 4. In future, German specifications will be adapted to these IEC specifications or will be brought into line with EN 130300, which has the same technical contents as the IEC standard.

The sectional specifications mentioned above are complemented by a set of detail specifications that apply to specific design types (e.g. electrolytic capacitors with axial wire leads). Frequently these detail specifications state better electrical ratings than the sectional specifications. The detail specifications also include maximum permissible dimensions in relation to capacitance and rated voltage.

The capacitance ratings given in recent specifications are in accordance with the E3 or E6 series. The rated voltage values are standardized according to the R5 series, in exceptional cases the voltage ratings have been chosen to meet specific requirements.

The following standards are applicable to aluminum electrolytic capacitors with a non-solid electrolyte:

| | |
|---|---|
| IEC 60384-1 | (identical with DIN IEC 60384, part 1, EN 130000):<br>Generic specification:<br>Fixed capacitors for use in electronic equipment |
| IEC 60384-4 | (identical with DIN IEC 60384, part 4, EN 130300):<br>Sectional specification:<br>Aluminum electrolytic capacitors with solid or non-solid electrolyte |
| IEC 60384-4-1 | (identical with DIN IEC 60384, part 4-1, EN 130300):<br>Blank detail specification<br>Aluminum electrolytic capacitors with non-solid electrolyte |

Important notes on proper use of aluminum electrolytic capacitors can also be found in CENELEC report R040-001 “Guide to use of aluminum electrolytic capacitors”. This guide has also been published as DIN 45811.

The technical specifications given for Al electrolytic capacitors produced by EPCOS are in line with the CECC detail specifications (if available). The individual type series can be roughly assigned as follows.

| CECC detail specifications | Comparable EPCOS type series and design types derived from these |
|---|---|
| CECC 30301-801 | B43697<br>B43698<br>B43699 |
| CECC 30301-802 | B41693, B41793<br>B41694, B41794<br>B41695, B41795<br>B41696, B41796<br>B43693, B43793 |
| CECC 30301-803<br>CECC 30301-807 | B41754<br>B43455, B43457<br>B43564, B43584<br>B43456, B43458<br>B43566, B43586<br>B43560, B43580 |
| CECC 30301-804 | B41554<br>B41550, B41570 |
| CECC 30301-805 | B43510, B43520<br>B43511, B43521 |
| CECC 30301-806 | B41303<br>B43303<br>B43304 |
| CECC 30301-808 | B43514, B43524 |
| CECC 30301-809 | B41605<br>B41607<br>B43504<br>B43505 |
| CECC 30301-810 | B41456, B41458<br>B41560, B41580 |
| CECC 30301-811 | B43501 |

# 3 Definitions of electrical parameters

## 3.1 Voltages

### 3.1.1 Rated voltage $U_R$

The rated voltage $U_R$ is the direct voltage value for which the capacitor has been designed and which is indicated upon it. For Al electrolytic capacitors, rated voltages of $\leq 100$ V are usually designated as “low voltage” and rated voltages $> 100$ V as “high voltage” (cf. chapter 13).

### 3.1.2 Operating voltage $U_{op}$

The capacitors can be operated continuously at full rated voltage (including superimposed ac voltage) within the entire operating temperature range.

The permissible voltage range for continuous operation lies between the rated voltage and 0 V. For short periods of time, the capacitors can also handle voltages up to –1,5 V (see paragraph 3.1.6 “Reverse voltage”).

### 3.1.3 Surge voltage $U_S$

The surge voltage is the maximum voltage which may be applied to the capacitor for short periods of time, i.e. up to 5 times for 1 minute per hour. IEC 60384-4 specifies the surge voltage as follows:

for $U_R \leq 315$ V: $U_S = 1{,}15 \cdot U_R$
for $U_R > 315$ V: $U_S = 1{,}10 \cdot U_R$

### 3.1.4 Transient voltage

Some capacitor types produced by EPCOS can withstand voltage pulses exceeding the surge voltage $U_S$. As the requirements differ largely depending on the individual applications, we do not state general ratings but match the overvoltage capability to customer requirements.

### 3.1.5 Superimposed AC, ripple voltage

A superimposed alternating voltage, or ripple voltage, may be applied to Al electrolytic capacitors, provided that:

- the sum of the direct voltage and superimposed alternating voltage does not exceed the rated voltage, and
- the rated ripple current is not exceeded (cf. chapter 4, “ripple current considerations”) and that no polarity reversal will occur.

### 3.1.6 Reverse voltage

Aluminum electrolytic capacitors are polar capacitors. Where necessary, voltages of opposite polarity should be prevented by connecting a diode. The diode’s conducting-state voltage of approximately 0,8 V is permissible. Reverse voltages $\leq 1{,}5$ V are tolerable for a duration of less than 1 second, but not in continuous or repetitive operation.

## 3.2 Capacitance

### 3.2.1 AC and DC capacitance

The capacitance of a capacitor can be determined by measuring its ac impedance (taking into account amplitude and phase) or by measuring the charge it will hold when a direct voltage is applied. The two methods produce slightly different results. As a general rule, it can be said that dc-voltage based measurements (DC capacitance) yield higher values (DC capacitance) than the alternating current method (AC capacitance). The factors are approximately 1,1 to 1,5 and maximum deviations occur with capacitors of low voltage ratings.

Corresponding to the most common applications (e.g. smoothing and coupling), it is most usual to determine the AC capacitance of aluminum electrolytic capacitors.

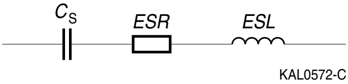


Figure 6 Simplified equivalent circuit diagram of an electrolytic capacitor

For this purpose, the capacitive component of the equivalent series circuit (the series capacitance $C_S$) is determined by applying an alternating voltage of ≤ 0,5 V. As the AC capacitance depends on frequency and temperature, IEC 60384-1 and 60384-4 prescribe a measuring frequency of 100 Hz or 120 Hz and a temperature of 20 °C (other reference values by special request).

There are also applications (e.g. discharge circuits and timing elements) in which the DC capacitance is decisive. In spite of this fact, capacitors for which the capacitance has been determined by the ac method are also used in such applications, whereby allowances are made to compensate for the difference between the two measuring methods.

However, in exceptional cases it may be necessary to determine the DC capacitance. The IEC publications do not provide any corresponding specifications. Because of this, a separate DIN standard has been defined. This standard, DIN 41 328, part 4, describes a measuring method involving one-time, non-recurrent charging and discharging of the capacitor.

### 3.2.2 Rated capacitance $C_R$

The rated capacitance is the AC capacitance value for which the capacitor has been designed and which is indicated upon it. $C_R$ is determined by specific measurement methods described in the relevant standards (IEC 60384-1 and 60384-4). Preferred capacitance values are taken from the E3 or E6 series.

EPCOS specifies $C_R$ in µF as the AC capacitance measured at 100 or 120 Hz and 20 °C, in accordance with IEC 60384-4.

### 3.2.3 Capacitance tolerance

The capacitance tolerance is the range within which the actual capacitance may deviate from the specific rated capacitance. Where the capacitance tolerances are to be indicated on the components themselves, EPCOS uses code letters in accordance with IEC 60062; this code letter is also part of the ordering code (cf. chapters 10 and 13).

### 3.2.4 Temperature dependence of the capacitance

The capacitance of an electrolytic capacitor is not a constant quantity that retains its value under all operating conditions. The temperature has a considerable effect on the capacitance. With decreasing temperature, the viscosity of the electrolyte increases, thus reducing its conductivity. The resulting typical behavior is shown in figure 7.

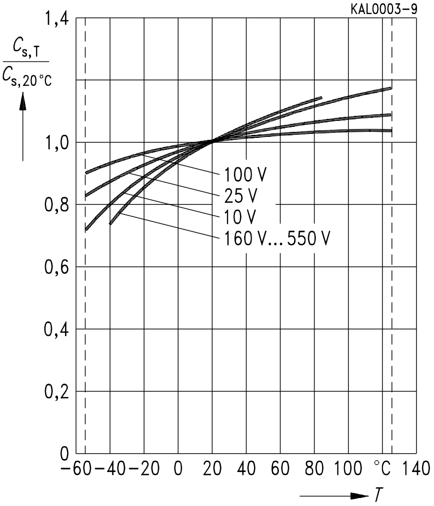


Figure 7 Temperature dependence of series capacitance $C_s$ (typical behavior)
Reference value: AC capacitance at 20 °C and 100 Hz

As a general rule, the characteristic curves are steeper for lower rated voltages and increasing anode surface roughness (deeper etching).

The most favorable flat shape of the curves shown in figure 7 is obtained by using special electrolytes which ensure that the capacitors can be operated at temperatures far below zero.

The shape of the curves varies widely, depending on whether the temperature relationship of the AC or of the DC capacitance is determined. The DC capacitance has a flatter temperature characteristic.

### 3.2.5 Frequency dependence of the capacitance

The AC capacitance depends not only on the temperature but also on the measuring frequency. figure 8 shows the typical behavior. Typical values of the effective capacitance can be derived from the impedance curve, as long as the impedance is still in the range where the capacitive component is dominant.

$$C = \frac{1}{2 \cdot \pi \cdot f \cdot Z}$$

| | | |
|---|---|---|
| $C$ | Capacitance | F |
| $f$ | Frequency | Hz |
| $Z$ | Impedance | Ω |

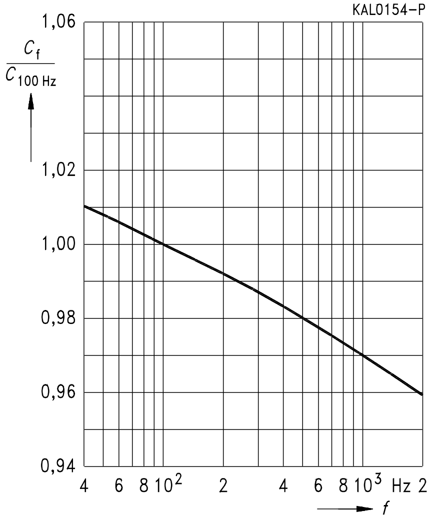


Figure 8 Capacitance $C$ versus frequency $f$
Typical behavior

### 3.2.6 Charge-discharge proof

Frequent charging/discharging cycles may lead to a decrease in capacitance. Due to their special design aluminum electrolytic capacitors produced by EPCOS are charge-discharge proof. This means that $10^6$ switching cycles will cause a capacitance reduction of less than 10 %.

(Charge-discharge test in accordance with IEC 60384-4).

### 3.3 Dissipation factor tan δ

The dissipation factor tan δ is the ratio of the equivalent series resistance to the capacitive reactance component in the equivalent series circuit, or the ratio of effective power (dissipated power) to reactive power for sinusoidal voltages.

It is measured using the same set-up as for the series capacitance $C_S$ (refer to figure 6).

IEC 60384-4 specifies the following maximum values:

| Rated voltage | $4\ V < U_R \leq 10\ V$ | $10\ V < U_R \leq 25\ V$ | $25\ V < U_R \leq 63\ V$ | $63\ V < U_R$ |
|---|---|---|---|---|
| Maximum value for the 100 Hz dissipation factor, as specified by IEC | 0,5 | 0,35 | 0,25 | 0,20 |

These values apply to capacitors with a maximum charge of 100 000 µC. Proportionally higher dissipation factors are permissible for capacitors with higher maximum charges.

### 3.3.1 Frequency and temperature dependence of the dissipation factor

The dissipation factor, like the capacitance, varies with frequency and temperature. figure 9, figure 10 and figure 11 show some examples of commonly used low-voltage and high-voltage electrolytic capacitors.

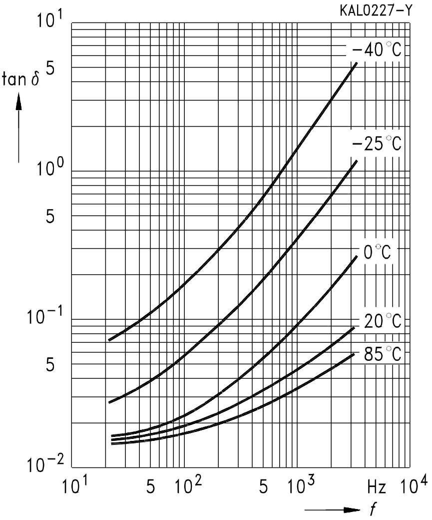


Figure 9 Low-voltage Al electrolytic capacitor (Example: 100 µF/63 VDC)

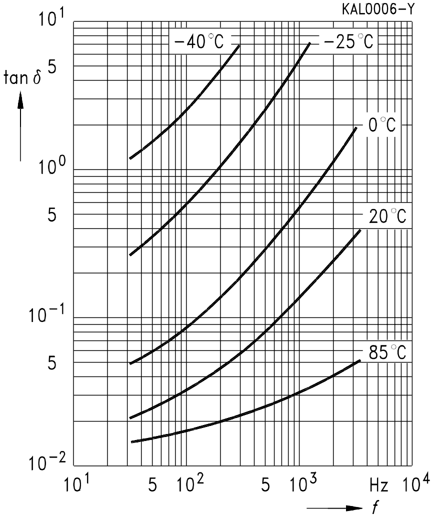


Figure 10 High-voltage Al electrolytic capacitor (Example 47 µF/350 VDC)

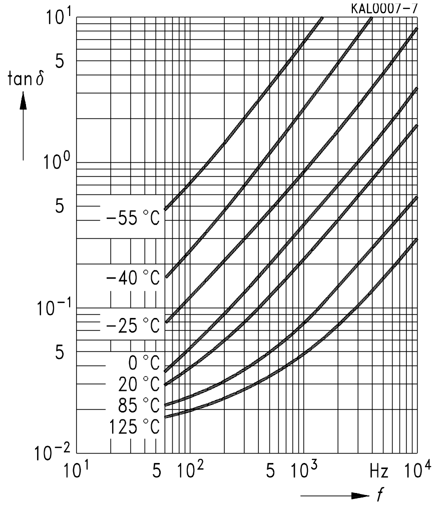


Figure 11 Low-voltage electrolytic capacitor
"SIKOREL 125" (Example: 220 µF/40 VDC)

### 3.4 Self-inductance *ESL*

The self-inductance or equivalent series inductance results from the terminal configuration and the internal design of the capacitor. It is defined by the equivalent series circuit shown in figure 12.

### 3.5 Equivalent series resistance *ESR*

The equivalent series resistance is the resistive component of the equivalent series circuit. The *ESR* value depends on frequency and temperature and is related to the dissipation factor by the following equation:

$$ESR = \frac{\tan\delta}{\omega \cdot C_s}$$

| | | |
|---|---|---|
| *ESR* | Equivalent series resistance | Ω |
| tan δ | Dissipation factor | |
| $C_S$ | Series capacitance | F |

The tolerance limits of the rated capacitance must be taken into account when calculating this value.

### 3.6 Impedance *Z*

The impedance of an electrolytic capacitor results primarily from the series circuit formed by the following índividual equivalent series components (figure 12):

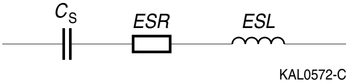


Figure 12 Simplified equivalent circuit diagram of an electrolytic capacitor

1) Capacitive reactance $1/\omega C_S$ of the capacitance $C_S$
2) Dielectric losses and ohmic resistance of the electrolyte and the terminals (*ESR*)
3) Inductive reactance $\omega ESL$ of the capacitor winding and the terminals.

The inductive reactance $\omega ESL$ only depends on the frequency, whereas $1/\omega C_S$ and *ESR* depend on frequency and on temperature.

The characteristics of the individual resistive and reactive components determine the total impedance of the capacitor. Figures 13 and 14 show typical frequency and temperature characteristics of aluminum electrolytic capacitors.

- Capacitive reactance predominates at low frequencies.
- With increasing frequency, the capacitive reactance ($X_C = 1/\omega C_S$) decreases until it reaches the order of magnitude of the electrolyte resistance.
- At even higher frequencies and unchanged temperatures (see 20 °C curve), the resistance of the electrolyte predominates.
- When the capacitor's resonance frequency is reached, capacitive and inductive reactance mutually cancel each other.
- Above this frequency, the inductive resistance of the winding and its terminals ($X_L = \omega L$) becomes effective and leads to an increase in impedance.

The resistance of the electrolyte increases strongly with decreasing temperature. Figures 13 and 14 show that this component already has an effect at low frequencies for low temperature ranges.

Specific impedance values are given in the individual data sheets.

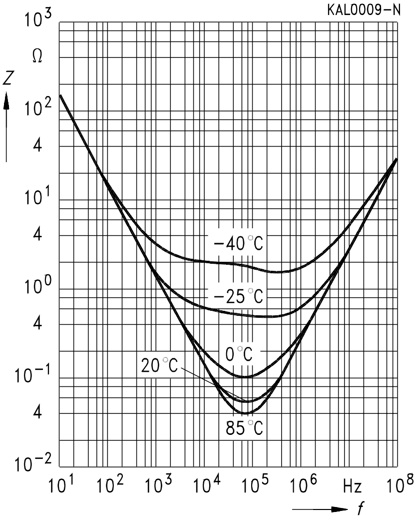


Figure 13 Impedance versus frequency and temperature
Example: 100 µF/63 VDC
(simplified graph)

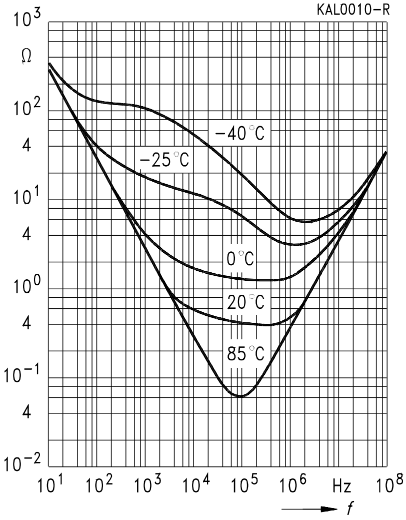


Figure 14 Impedance versus frequency and temperature
Example: 47 µF/350 VDC
(simplified graph)

### 3.7 Leakage current $I_L$

Due to the special properties of the aluminum oxide layer that serves as a dielectric, a small current will continue to flow even after a dc voltage has been applied for longer periods. This current is called the leakage current. A low leakage current is an indication that the dielectric is well designed.

### 3.7.1 Time and temperature dependence of the leakage current

As figure 15 shows, a high leakage current flows (inrush current) in the first minutes after applying a voltage to the capacitor, in particular after prolonged storage without any applied voltage. In the course of continuous operation, the leakage current will decrease and reach an almost constant "steady-state" value.

The temperature dependence of the leakage current is shown in figure 16, taking a capacitor of the 85 °C temperature category as an example.

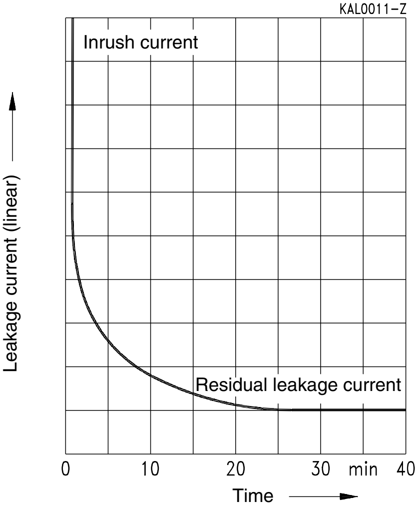


Figure 15 Leakage current versus time for which a voltage is applied

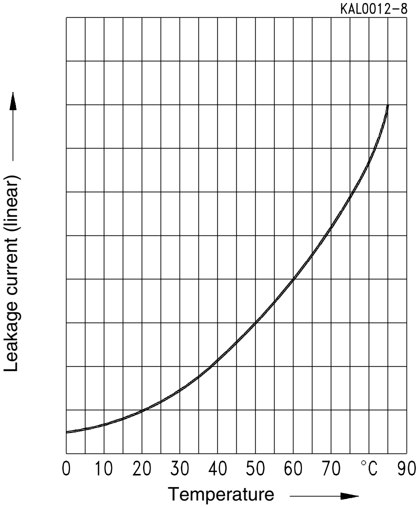


Figure 16 Leakage current versus temperature

### 3.7.2 Voltage dependence of the leakage current

The relationship between the leakage current and the voltage applied under constant temperature conditions is shown schematically in figure 17.

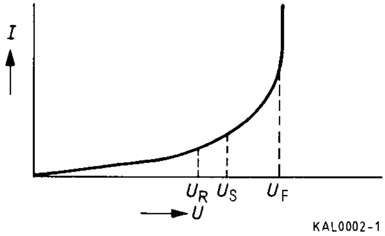


Figure 17 Voltage dependence of the leakage current

### 3.7.3 Operating leakage current $I_{Lop}$

The operational leakage current is the steady-state current that is attained during continuous operation. The $I_{Lop}$ of Al electrolytic capacitors made by EPCOS can be calculated using the following equation:

LL grade:

$$I_{Lop} = \frac{0{,}0005\ \mu A}{\mu F \cdot V} \cdot C_R \cdot U_R + 1\ \mu A$$

GP grade:

$$I_{Lop} = \frac{0{,}001\ \mu A}{\mu F \cdot V} \cdot C_R \cdot U_R + 3\ \mu A$$

For bipolar capacitors, the values are doubled

| | |
|---|---|
| $I_{Lop}$ | Operating leakage current |
| $C_R$ | Rated capacitance |
| $U_R$ | Rated voltage |

The results refer to the rated voltage $U_R$ and a temperature of 20 °C.

In accordance with DIN 41 240 and DIN 41 332, the results obtained for 20 °C must be multiplied by the following factors, to allow for the temperature dependence of the operating leakage current of both General-purpose and Long-life grade capacitors:

| Temperature (°C) | 0 | 20 | 50 | 60 | 70 | 85 | 125 |
|---|---|---|---|---|---|---|---|
| Factor (typical value) | 0,5 | 1 | 4 | 5 | 6 | 10 | 12,5 |

“SIKOREL” types are an exception to this rule. The following values apply to these:

| Temperature (°C) | 0 | 20 | 55 | 70 | 85 | 105 | 125 |
|---|---|---|---|---|---|---|---|
| Factor (typical value) | 0,7 | 1 | 2 | 3 | 4 | 5 | 8 |

When the actual operating voltage is below the rated voltage, the operating leakage current is substantially lower:

| Operating voltage, in % of the rated voltage $U_R$ | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 | 100 |
|---|---|---|---|---|---|---|---|---|---|
| Typical values, in % of the operating leakage current $I_{L, op}$ (General-purpose grade) | 3 | 6 | 9 | 14 | 18 | 25 | 40 | 50 | 100 |
| Typical values, in % of the operating leakage current $I_{L, op}$ (Long-life grade) | 8 | 14 | 17 | 23 | 30 | 40 | 50 | 70 | 100 |

### 3.7.4 Leakage current for acceptance test $I_L$

As the leakage current varies with time and temperature, it is necessary to define reference values for measuring time and temperature. According to EN 130 300 the leakage current is to be measured at 20 °C, after the rated voltage has been applied for 5 minutes. The following equation apply:

$$I_L \leq 0{,}3\ \mu\text{A} \cdot \left(\frac{C_R}{\mu\text{F}} \cdot \frac{U_R}{\text{V}}\right)^{0{,}7} + 4\ \mu\text{A}$$

For bipolar capacitors, double the values apply.

Acceptance testing for leakage current can be carried out at any temperature between 15 °C and 35 °C. The permissible limit values are then multiplied by the following conversion factors, with reference to the 20 °C value:

| Temperature (°C) | 15 | 20 | 25 | 30 | 35 |
|---|---|---|---|---|---|
| Factor (guideline value) | 0,8 | 1 | 1,5 | 2 | 2,5 |

Referee tests are to be carried out at 20 °C.

### 3.7.5 Reforming

In accordance with IEC 60384-4, Al electrolytic capacitors are to be subjected to a reforming process before acceptance testing. The purpose of this preconditioning is to ensure that the same initial conditions are maintained when comparing and assessing different products.

For this purpose, the rated voltage is applied to the capacitors via a series resistance of approximately 100 Ω for $U_R$ ≤100 VDC, or 1000 Ω for $U_R$ >100 VDC, for a period of one hour.

Subsequently, the capacitors are stored under no-voltage conditions for 12 to 48 hours at a temperature between 15 and 35 °C. The leakage current must then be measured, at the latest after 48 hours.

If the capacitors meet the leakage current requirements without preconditioning, this procedure can be omitted.

### 3.7.6 Leakage current behavior with no voltage applied ( voltage-free storage)

The oxide layer may deteriorate when Al electrolytic capacitors are stored without an externally applied voltage, especially at higher temperatures. Since there is no leakage current to transport oxygen ions to the anode in this case, the oxide layer is not regenerated. The result is that a higher than normal leakage current will flow when a voltage is applied after prolonged storage. As the oxide layer is regenerated in use, however, the leakage current will gradually decrease to its normal level.

Al electrolytic capacitors can be stored voltage-free for at least 2 years, and capacitors of the SIKOREL series for as long as 15 years without any loss of reliability. Provided that these storage periods have not been exceeded, the capacitors can be operated at rated voltage directly after being taken out of storage. In this case, reforming as described under 3.7.5 is not required.

When designing application circuits, attention must be paid to the fact that the leakage current may be up to 100 times higher than normal during the first minutes following the application of power.

When the capacitors have been stored for more than two years, it is decisive whether the circuit will tolerate high initial leakage currents. A circuit that has been stored for more than two years with the capacitors incorporated, should be operated trouble-free for one hour. This will usually regenerate the capacitors so far that storage can be continued.

### 3.8 Breakdown strength and insulation resistance of insulating sleeves

Most Al electrolytic capacitors made by EPCOS are enveloped by an insulating sleeve. The minimum breakdown strength of the sleeve is 2 500 VAC or 3 500 VDC. A test method for verifying the breakdown strength of the sleeves is described in IEC 60384-4.

In order to ensure full breakdown strength, care must be taken not to damage the insulating sleeve, especially when ring clips are used for mounting.

The insulation resistance of the sleeve is at least 100 MΩ. IEC 60384-4 specifies corresponding test methods.

Capacitors with an upper category temperature of + 85 °C and + 105 °C are fitted with a shrunk sleeve of PVC. They can also be supplied with polyester encapsulation. Capacitors with an upper category temperature of + 125 °C have polyester encapsulation to standard.

## 4 Ripple current considerations

### 4.1 General

The term ripple current is used for the rms value of the alternating current that flows through the device as a result of any pulsating or ripple voltage. The maximum permissible ripple current value depends on the ambient temperature, the surface area of the capacitor (i.e. heat dissipation area), the dissipation factor tan $\delta$ (or *ESR)* and on the ac frequency.

As thermal stress has a decisive effect on the capacitor's life expectancy, the dissipation heat generated by the ripple current is an important factor affecting the useful life. Diagrams showing the useful life as a function of the ambient temperature $T_A$ are given in the individual data sheets (refer to section 5.3 for an explanation on how to use these diagrams).

These thermal considerations imply that, under certain circumstances, it may be necessary to select a capacitor with a higher voltage or capacitance rating than would normally be required by the respective application.

### 4.2 Frequency dependence of the ripple current

The dissipation factor (which is related to the equivalent series resistance) of Al electrolytic capacitors varies with the frequency of the applied voltage. As a result, the ripple current is also a function of the frequency. In the individual data sheets, the ripple current capability of the capacitors is generally referred to a frequency of 100 or 120 Hz, or in some cases to 10 or 20 kHz. Conversion factors for other operating frequencies are given for each type in the form of a graph.

### 4.3 Temperature dependence of the ripple current

The data sheets specify the maximum permissible ripple current for ambient temperatures of 40 °C as well as for the upper category temperature for each capacitor type. For all types with category temperature above 85 °C, the ripple current ratings for 85 °C have also been included for the purpose of comparison.

The data sheets for each capacitor type also include a diagram showing the limit values for continuous operation at other ambient temperatures and ripple currents. This diagram also permits the expected useful life to be estimated for given operating conditions.

## 5 Useful life

Useful life (also termed service life or operational life) is defined as the life achieved by the capacitor without exceeding a specified failure rate. Total failure or failure due parametric variation is considered to constitute the end of the useful life (see also paragraph 4 of chapter "Quality Assurance", page 62).

Depending on the circuit design, device failure due to parametric variation does not necessarily imply equipment failure. This means that the actual life of a capacitor may be longer than the specified useful life. Data on useful life have been obtained from experience gained in the field and from accelerated tests.

The useful life can be prolonged by operating the capacitor at loads below the rating values (e.g. lower operating voltage, current or ambient temperature) and by appropriate cooling measures. In addition to the standard type series, EPCOS is able to offer types with useful life ratings specially matched to customer specifications.

### 5.1 Load conditions

CECC defines the useful life of capacitors with liquid electrolytes on the basis of the following load conditions:

- rated voltage
- rated ripple current
  (the peak value of the ac voltage superimposed on the dc voltage must not exeed the rated voltage)
- rated temperature.

### 5.2 Cooling

The useful life values stated in these data sheets apply to Al electrolytic capacitors with natural cooling, i.e. the heat generated in the winding is dissipated through the casing and by natural convection. It is possible to increase the permissible ripple current and/or prolong the useful life by using additional cooling by heat sinks, water or forced ventilation. Conversely, impaired cooling (e.g. due to closely packed capacitor banks, thermally insulating sealing and vacuum) will reduce the useful life.

In order to lower the thermal resistance between winding and case, can-type capacitors produced by EPCOS have a thermal bridge between the capacitor winding and the base. As a large amount of heat is dissipated through the base of the case, the use of a heat sink connected to the capacitor base is the most efficient cooling method.

In order to ensure an optimal heat transfer between the base of the case and the heat sink EPCOS offers optionally for high-voltage screw-terminal series the so-called 2-pad-design, i.e. a thermopad design which minimizes the termal resistance between the base of the case and the heat sink (figure 18).

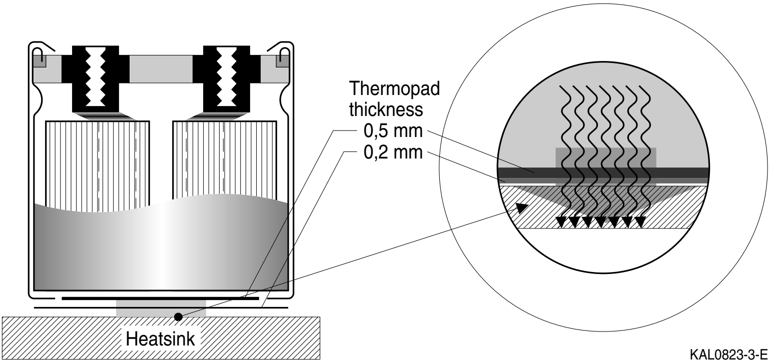
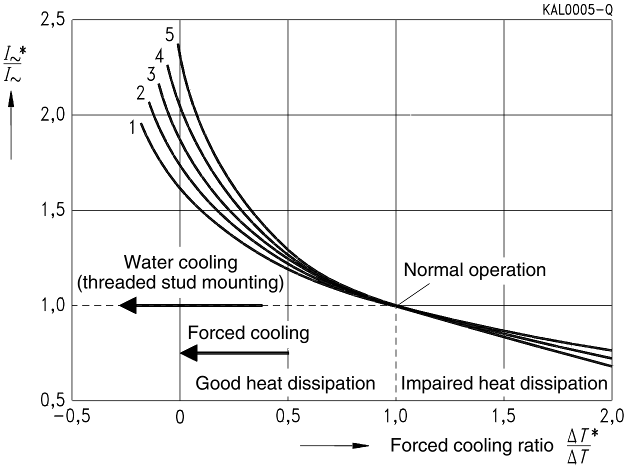


Figure 18 2-pad design for capacitors with screw terminals

If the base of a screw terminal high-voltage capacitor is cooled to keep it at constant temperature, the correspondingly higher rated current $I_{\sim R}$ (B) for base cooling has to be used instead of the rated current $I_{\sim R}$ for natural cooling. To determine useful life, enter capacitor base temperature $T_B$ in the diagrams of the data sheets instead of the ambient temperature $T_A$ (see also 5.3.).

Only the thermal resistance between the case and the surrounding air, which is greater than the thermal resistance between the capacitor winding and the case if forced cooling is not used, can be influenced by the mounting location. The thermal resistance is proportional to the temperature difference $\Delta T$. The user can measure this temperature difference ($T_{case} - T_A$) under normal conditions and under forced-air conditions ($\Delta T^*$) and constant ripple current load conditions, and then calculate the relative reduction or increase of the thermal resistance from the forced cooling ratio $\Delta T^*/\Delta T$. In turn, the forced cooling ratio can be used to determine the ripple current factor $I_\sim^*/I_–$. The latter is a measure of how much the ripple current load can be increased without reducing the useful life if forced cooling is used.

The diagram below (figure 19) shows the effect of the forced cooling ratio, as determined by measurement, on the ripple current factor $I_\sim^*/I_\sim$ for various case sizes. In this diagram, the useful life of the capacitor with forced cooling (ripple current load: $I_\sim^*$) has been equated to the useful life rating of the Al electrolytic capacitor under normal operating conditions (ripple current load: $I_\sim$).



Dimensions $d \times l$ (mm)

| | |
|---|---|
| 1 | 75 × 220, diameter = 90 |
| 2 | 75 × 145 |
| 3 | 50 × 105 |
| 4 | 35 × 80 |
| 5 | 18 × 31,5 |

$\Delta T$ Temperature difference $\Delta T = T_{case} - T_A$
$I_\sim$ Permissible ripple current under normal conditions (natural convection cooling)
* Values for forced cooling

Figure 19 Effect of forced cooling on the ripple current capability

The following table gives typical values for the forced cooling ratios that can be achieved by forced convection with the respective air velocities.

| Air velocity, approximate m/s | Forced cooling ratio $\Delta T^* / \Delta T$ |
|---|---|
| approx. 0,5 | 0,55 |
| approx. 1,0 | 0,45 |
| approx. 1,5 | 0,39 |
| approx. 2,0 | 0,35 |

Conversely, the ripple current capability $I^*_\sim$ of Al electrolytic capacitors with impaired heat dissipation is lower than the rated value $I_\sim$.

If a cooling fluid (e.g. water or oil) colder than the ambient temperature is used, the forced cooling ratio may be reduced to zero or may even attain negative values. Due to the limited thermal capacity of these media, the linear laws assumed for the use of pure thermal resistances no longer apply. In such cases the forced cooling ratio is also a function of the power dissipated in the capacitor itself. If such cooling measures are to be used, the maximum possible thermal load must be calculated. This is not necessary if only heat sinks and forced convection are used.

### 5.3 Calculation of useful life

The tables in the individual data sheets list the rated ripple current for the upper category temperature (UCT = + 85 °C, + 105 °C or +125 °C) and for a frequency of 100 Hz. The useful life for known ripple current loads and ambient temperatures is determined on the basis of the useful life graphs as follows:

Determine the quotient $\frac{I_\sim}{I_{\sim \mathrm{R,\,UC}}}$ of the required ripple current at the given ambient temperature and the rated ripple current at the upper category temperature. The corresponding useful life value is given by the curve passing through the respective ambient temperature and the current quotient coordinates, or it can be interpolated if none of the useful life curves passes directly through these coordinates.

The frequency dependence of the ripple current has not been taken into account in the procedure described above. This must be introduced into the calculation in the form of an additional factor.

For each series precise curves for conversion factor $I_\sim (f) / I_\sim$ (100 Hz) versus frequency $f$ are given in the individual data sheets.

The following examples illustrate the calculation procedure, using the data of a capacitor of the B43560 / B43580 series. For this type series, the upper category temperature is + 105 °C. As an example, a capacitor with the following ratings has been selected from the data sheets:

**Series B43560 / B43580 (screw terminals)**

| $U_R$<br>VDC | $C_R$<br>µF | Case dimensions $d \times l$ mm | $ESR_{max}$ 100 Hz 20 °C mΩ | $Z_{max}$ 10 kHz 20°C mΩ | $I_{\sim max}$ 100 Hz 40 °C A | $I_{\sim max}$ 100 Hz 85 °C A | $I_{\sim R}$ 100 Hz 105°C A | $I_{\sim R}$ (B) 100 Hz 105°C A | Ordering code |
|---|---|---|---|---|---|---|---|---|---|
| 400 | 4700 | 76,9 × 130,7 | 40 | 32 | 41 | 32 | 13 | 24 | B435*0A9478M000 |

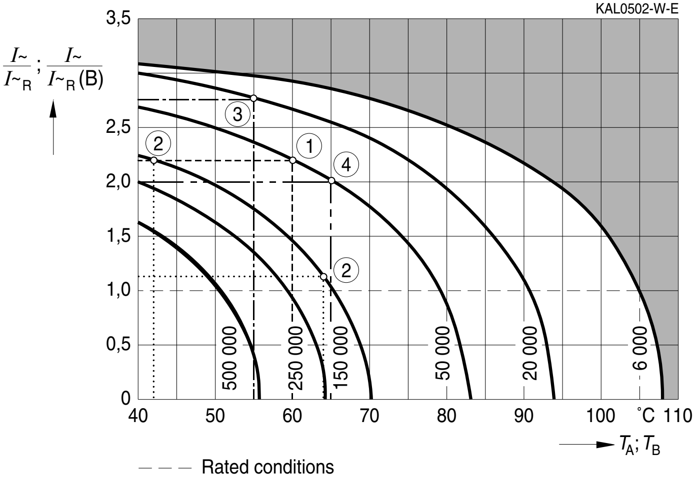


Figure 20 Useful life versus ambient temperature $T_A$ for natural cooling and base temperature $T_B$ for base cooling (series B43560/B43580).

### Example 1 – Calculating the useful life

The following values have been determined for capacitors to be used in a frequency converter. The corresponding useful life is to be calculated.

| | |
|---|---|
| Ripple current | 34 A |
| Frequency | 400 Hz |
| Ambient temperature | 60 °C |

The equivalent ripple current for 100 Hz is calculated using the frequency-dependence conversion factor (see page 156, series B43560 / B43580):

$$\frac{34\ \text{A}}{1{,}21} = 28\ \text{A}$$

The ripple current factor is then calculated using the resulting equivalent 100 Hz ripple current.

$$\frac{I_{\sim}}{I_{\sim \text{R, } 105\ °\text{C}}} = \frac{28\ \text{A}}{13\ \text{A}} = 2{,}2$$

The useful life curve passing through the coordinates for the ripple current factor (2,2) and the ambient temperature (60 °C) indicates the useful life that can be expected:

**50 000 h** (see ① page 41).

### Example 2 – Determining the maximum permissible ambient temperature

The operating conditions listed below have been defined for a traction application. The maximum permissible ambient temperature is to be calculated:

| | |
|---|---|
| Operating voltage | 400 VDC |
| Total ripple current | 48 A |
| Frequency | 50 Hz |
| Useful life | 150 000 h |

There are several methods of solving this problem:

First, the equivalent 100 Hz current value is determined (conversion factors given on page 156):

$$\frac{48\ \text{A}}{0{,}85} = 57\ \text{A}$$

The number of capacitors required is then determined for the respective ambient temperature by projecting the values along the 150 000 h curve:

| $\frac{I_{\sim}}{I_{\sim \text{R, } 105\ °\text{C}}}$ | Circuit | Ambient temperature |
|---|---|---|
| 2,2 | 2 parallel | 42 °C (see ② page 41) |
| 1,1 | 4 parallel | 64 °C (see ② page 41) |

Further value combinations can be determined in the same way.

## Example 3 – Checking the ripple current load on an aluminum electrolytic capacitor

In many applications, Al electrolytic capacitors are subjected to ripple currents of varying frequency.

The equivalent total ripple current load shall be calculated for the following given rms values:

| | |
|---|---|
| Current 1: $I_{\sim rms}$ at 400 Hz | 25 A |
| Current 2: $I_{\sim rms}$ at 1 kHz | 35 A |
| Ambient temperature | 55 °C |
| Required useful life | 20 000 h |

The first step is to calculate the equivalent 100 Hz values for the two current values (frequency-dependence conversion factors given on page 156) and the root-mean-square value of the two equivalent values:

Current $I_1$: $\frac{25\text{ A}}{1{,}21} \triangleq 21\text{ A at }100\text{ Hz}$

Current $I_2$: $\frac{35\text{ A}}{1{,}27} \triangleq 28\text{ A at }100\text{ Hz}$

$$I_{\text{totalrms}} = \sqrt{I_1^2 + I_2^2}$$

$$I_{\text{totalrms}} = \sqrt{(21\text{ A})^2 + (28\text{ A})^2} = 35\text{ A}$$

The ripple current factor can then be calculated:

$$\frac{I_\sim}{I_{\sim R,\,105\,°C}} = \frac{35\text{ A}}{13} = 2{,}7$$

The useful life curve that coincides with the respective coordinates, 2,7 on the Y-axis (ripple current factor) and 55 °C on the X-axis (ambient temperature) indicates a useful life of 20 000 h. The required useful life and a safety margin are thus achieved (see ③ page 41).

## Example 4 – Determining the maximum permissible ripple current for base cooling

The following figures are given for each capacitor in a frequency converter application with base cooling of the capacitors. The maximum ripple current capabilty is to be determined.

| | |
|---|---|
| Temperature of capacitor base | 65 °C |
| Useful life | 50 000 h |

The point of intersection of the useful life curve (50 000 h) and temperature of capacitor base (65 °C) produces the maximum permissible ripple current as

$I_{\sim rms} = 2{,}0 \cdot I_{\sim R,\,105\,°C}$ (B) = 2,0 · 24 A = **48 A** (see ④ page 41).

## 6 Climatic conditions

Limits must be set for the climatic conditions to which electrolytic capacitors are subjected (in part for reasons of reliability and in part due to the variation of the electrical parameters with temperature). It is therefore important to observe the permissible minimum and maximum temperatures and the humidity conditions stated in coded form as IEC climatic category (see paragraph 6.4). The IEC categories are given for each type in the corresponding data sheet.

### 6.1 Maximum permissible operating temperature (upper category temperature)

The upper category temperature (UCT) is the maximum permissible ambient temperature at which a capacitor may be continuously operated. It depends on the capacitor design and is stated in the respective IEC climatic category. If this limit is exceeded the capacitor may fail prematurely.

For some type series, however, operation at temperatures above the UCT is permissible for short periods of time. Details are given in the individual data sheets.

Useful life and reliability depend to a large extent on the capacitor's temperature. Operation at the lowest possible temperature will increase both useful life and reliability and is therefore recommended. For the same reason, it is advisable to select the coolest possible position within the equipment as a location for aluminum electrolytic capacitors.

### 6.2 Minimum permissible operating temperature (lower category temperature)

The conductivity of the electrolyte diminishes with decreasing temperature, causing an increase in electrolyte resistance. This, in turn, leads to increasing impedances and dissipation factors (or equivalent series resistances). For most applications, these increases are only permissible up to a certain maximum value. Therefore, minimum permissible operating temperatures are specified for Al electrolytic capacitors. These temperature limits are designated “lower category temperature” and are also part of the IEC climatic category.

It should be emphasized that operation below this temperature limit will not damage the capacitor. Especially when a ripple current flows through the device, the heat dissipated by the increased equivalent series resistance will raise the capacitor temperature so far above the ambient temperature that the capacitance will be ade quate to maintain equipment operation.

The typical response of impedance and capacitance of a capacitor with a lower category temperature of – 25 °C is illustrated in figures 21 and 22.

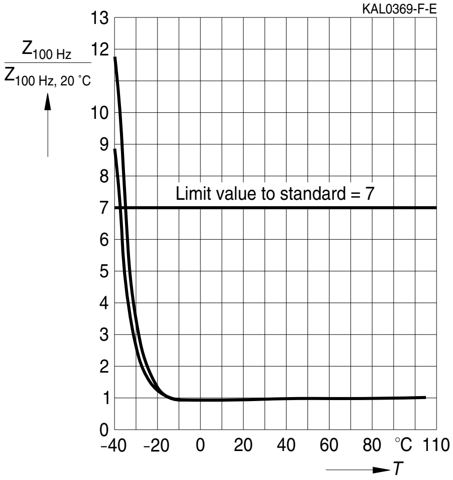


Figure 21

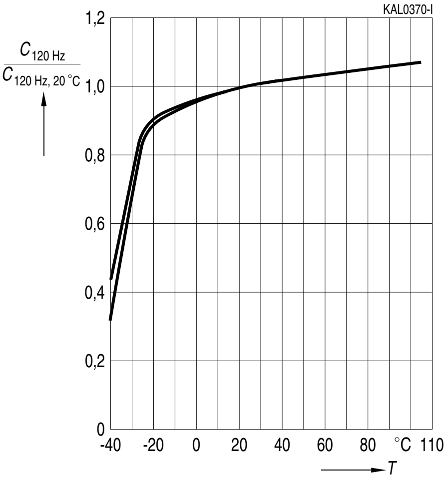


Figure 22

## 6.3 Storage temperature

Al electrolytic capacitors can be stored voltage-free at temperatures up to the upper category temperature. (see paragraph 3.7.6 “Leakage current behavior after voltage-free storage”.)

However, it must be taken into account that storage at elevated temperatures will reduce leakage current stability, useful life and reliability. In order not to impair these qualities unnecessarily, the storage temperature should not exceed + 40 °C and should preferably be below + 25 °C.

The standards for Al electrolytic capacitors specify a lower storage temperature that corresponds to the lower category temperature. Al electrolytic capacitors by EPCOS withstand the lowest specified storage temperature, i.e. – 65 °C, without being damaged.

### 6.4 IEC climatic category

The permissible climatic stress on an Al electrolytic capacitor is given by the respective IEC climatic category. In accordance with IEC 60068-1, the climatic category comprises 3 groups of numbers, separated by slashes.

Example: 40/085/56

| | |
|---|---|
| 1st group: | Lower category temperature (limit temperature) denoting the test temperature for test A (cold) in accordance with IEC 60068-2-1 |
| 2nd group: | Upper category temperature (limit temperature) denoting the test temperature for test B (dry heat) in accordance with IEC 60068-2-2 |
| 3rd group: | Number of days denoting the duration of test Ca (damp heat, steady state) at 93 +2/– 3 % relative humidity and 40 °C ambient temperature, in accordance with IEC 60068-2-3 |

## 7 Mechanical stress resistance

### 7.1 Vibration resistance

The vibration resistance values are specifed in the individual data sheets.

### 7.2 Operating altitude

Al electrolytic capacitors can be used in high-altitude locations (in accordance with EN 130300 subclause 4.11.4). Continuous operation at extreme altitudes may decrease the useful life of some capacitor types.

### 7.3 Robustness of terminals

The mechanical strength of terminals and leads is defined in the respective detail specifications. Terminals of the capacitors in this book also meet the test conditions specified by IEC 60068-2-21. For tightening torques for screw terminals, refer to 9.2 “Mounting torques”.

## 8 Maintanance

CENELEC R040-001 (chapter 1-19) provides general information on applications in which Al electrolytic capacitors are used. The most important subjects are: safety requirements and measures, installation in equipment with inherent heating, destruction by overpressure, fire hazards, parallel and series capacitor circuits.

Make periodic inspections for the capacitors that have been used in the devices for industrial applications. Before the inspection, make sure to turn off the power supply and carefully discharge the electricity of the capacitors. To check the capacitors, make sure of the polarity when measuring the capacitors by using a volt-ohm meter, for instance. Also, do not apply any mechanical stress to the capacitor terminals. The following items should be checked by the periodic inspections.

- Significant damage to appearances: venting, electrolyte leakage, etc.
- Electrical characteristics: leakage current, capacitance, tan δ and other characteristics prescribed in the catalogs or product specifications.

If any of the above is found, replace it or take any other proper measure.

## 9 Mounting

### 9.1 Mounting positions (overpressure vent)

During operation Al electrolytic capacitors will always conduct a leakage current which causes electrolysis. On the one hand, the oxygen produced by electrolysis will regenerate the dielectric layer but, on the other hand, the hydrogen released may cause the internal pressure of the capacitor to increase.

An overpressure vent ensures that the gas can escape when the pressure reaches a certain level.

To prevent electrolyte from leaking out when the gas is “vented”, the capacitor should be mounted in the positions recommended by figure 23. All of these mounting positions are intended to avoid a vent-down installation of the capacitor.

Example:

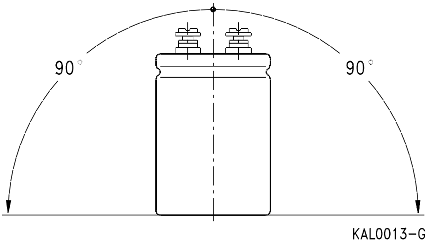


Figure 23 Recommended range of mounting positions

- Upright mounting is ideal, particularly when the capacitors are fixed by their terminals, by a threaded stud or mounted by their base.
- If the capacitor is horizontally mounted, the overpressure vent should be in a “12 o’clock” position.

Please note that other mounting positions will not cause any damage to the capacitor. However, minor contamination of the equipment may occur due to electrolyte leaking out of the overpressure vent.

### 9.2 Mounting torques

The maximum torques listed below may not be exceeded when tightening screw terminals or mounting stud nuts.

| Thread | Maximum torque |
|---|---|
| M5 | 2 Nm |
| M6 | 2,5 Nm |
| M8 | 4 Nm |
| M12 | 10 Nm |

### 9.3 Mounting considerations for single-ended capacitors

The internal structure of single-ended capacitors might be damaged if excessive force is applied to the lead wires. Stresses like push, pull, bend etc. might cause increased leakage current, intermittent capacitance, electrolyte leakage or open/short circuit, due to rupture of terminals or internal elements.

Following actions should be prevented:

- Move the capacitor after soldering to PC board.
- Pick up PC board by holding the soldered capacitor.
- Insert capacitor to PC board with hole space unequal to specified lead space.

Example:

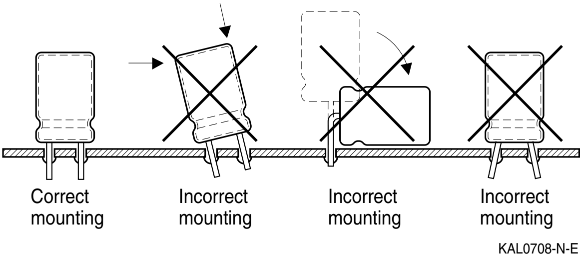


Figure 24 Mounting considerations for single-ended capacitors

### 9.4 Soldering

Excessive time or temperature during soldering will affect capacitor’s characteristics and cause damage to the insulation sleeve. Capacitors should be dipped in solder less than 10 seconds. Contact of the sleeve with soldering iron must be avoided.

## 9.5 Cleaning agents

Halogenated hydrocarbons may cause serious damage if allowed to come into contact with aluminum electrolytic capacitors. These solvents may dissolve or decompose the insulating film and reduce the insulating properties to below the permissible level. The capacitor seals may be affected and swell, and the solvents may even penetrate them. This will lead to premature component failure.

Because of this, measures must be taken to prevent electrolytic capacitors from coming into contact with the solvents when using halogenated hydrocarbon solvents to clean printed circuit boards after soldering the components, or to remove flux residues. If it is not possible to prevent the electrolytic capacitors from being wetted by the solvent, halogen-free solvents must be used in order to eliminate the possibility of damage.

### Halogen-free solvents:

Ethanol (methylated spirits)
Propanol
Isopropanol
Isobutanol
Propylenglycolether
Diethyleneglycoldibutylether

### Critical solvents:

The following list contains a selection of critical halogenated hydrocarbons and other solvents frequently used, partially in pure form, partially in mixtures with other solvents, as cleaning agents in the electrical industry.

Trichlorotrifluoroethane (trade names e.g. Freon, Kaltron, Frigene)
Trichloroethylene
Trichloroethane (trade names e.g. Chlorothene, Wacker 3 × 1)
Tetrachloroethylene (trade name: Per)
Methylenechloride
Chloroform
Carbontetrachloride
Acetone
Methylethylketone
Ethylacetate
Butylacetate

However, printed-circuit board cleaning equipment is available which uses halogenated solvents but is designed to enable thorough cleaning in a very short time (four-chamber ultrasonic cleaning process). Furthermore, the processes used ensure that virtually no solvent remains on the cleaned parts.

This means that the general warning against the use of halogenated cleaning solvents on Al electrolytic capacitors can be qualified if the following conditions are met:

1. The cleaning period in each chamber must not exceed 1 minute.
2. The final cleaning stage must use a solvent vapor only. The temperature must be 50 °C or lower.
3. Adequate drying must be ensured immediately after the cleaning process in order to evaporate any condensed residual solvent.
4. Contaminated cleaning agents must be regularly replaced as specified by the manufacturer and by legal regulations.

## 10 Capacitor bank design

In some applications the required capacitance may not be achieved by using a single Al electrolytic capacitor. This may be the case if:

- the required electrical charge is too high to be stored in a single capacitor,
- the voltages that are to be applied are higher than can be attained by the permissible operating voltage ratings,
- charge-discharge and ripple current loads would generate more heat than could be safely dissipated by a single capacitor, and
- the requirements on the electrical characteristics (e.g. series resistance, dissipation factor or inductance) are so high that it would be too difficult or even impossible to implement them in a single capacitor.

In these cases, banks of capacitors connected in parallel or in series or in combined parallel and series circuits will be used. To prevent overloading of individual capacitors, the capacitance tolerance must be taken into account when determining the maximum ripple current. Furthermore, the individual capacitors must not be subjected to negative voltages when the bank is discharged. DIN 57 560, part 15, provides important information on the dimensioning and circuit configuration of capacitor banks. The following paragraphs explain and supplement this information.

### 10.1 Parallel connection of Al electrolytic capacitors

If one of the capacitors in a parallel circuit fails as a result of an internal short circuit, the entire bank is discharged through the defective capacitor. In the case of large banks with high energy content this may lead to extremely abrupt and severe discharge phenomena. It is therefore advisable to take measures to prevent or limit the short-circuit discharge current. In smoothing capacitor banks, for example, this is achieved by installing individual fuses; the principle is shown in figure 25.

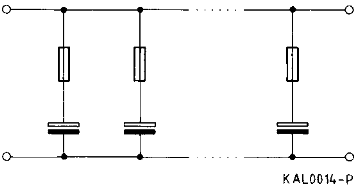


Figure 25 Individual fuses in smoothing capacitor banks

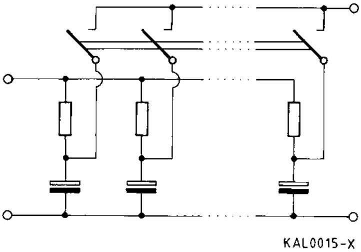


Figure 26 Protection by charging resistors

This principle is not suitable for capacitor banks designed for impulse discharges. Here, the capacitors should be protected during the charging process by means of appropriate resistors. The capacitors are then connected in parallel immediately before they are to be discharged. The principle is shown in figure 26.

### 10.2 Series connection of Al electrolytic capacitors

When designing series circuits with Al electrolytic capacitors, care must be taken to ensure that the load on each individual capacitor does not exceed its maximum permissible voltage. Here, the fact that the total dc voltage applied is divided up among the individual capacitors in proportion to their individual dielectric insulation resistances (figure 27) must be taken into consideration.

Since the dielectric insulation resistance of the individual capacitors may differ quite strongly, the voltage distribution may also be non-uniform, which may lead to the permissible voltage of individual capacitors being exceeded. For this reason, forced balancing of the voltage distribution is recommended. The safest method of achieving this is to use electrically isolated voltage sources for the individual capacitors as shown in figure 28.

If this is not possible, external balancing resistors $R_{\mathrm{Symm}}$ (see figure 29) can be connected to the individual capacitors. The balancing resistances must be equal to one another, and must be substantially lower than the dielectric insulation resistance of the capacitor.

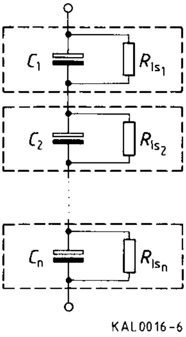


Fig. 27 Series connection (with dielectric resistances)

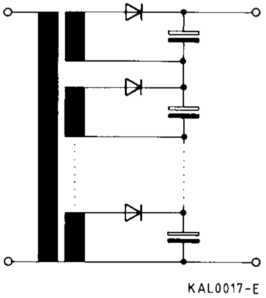


Fig. 28 Series connection (forced voltage distribution balancing)

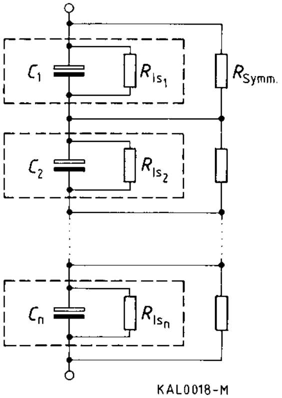


Fig. 29 Series connection (external balancing resistors $R_{\mathrm{Symm}}$ connected to the individual capacitors)

Experience has shown that it is preferable to choose balancing resistance values that will cause a current of approximately 20 times the leakage current of the capacitor to flow through the resistors. The equation for calculating the resistance value is:

$$R_{\mathrm{Symm}} = 50\ \mathrm{M\Omega} \cdot \mu\mathrm{F} \cdot \frac{1}{C_{\mathrm{R}}}$$

The balancing measures described above may be omitted in cases where the total dc voltage to be applied is substantially lower than the sum of the rated voltages of the capacitors to be used.

Experience has shown that this is possible for n = 2 to 3 single capacitors in series without any considerable risk if the total voltage does not exceed $0{,}8 \cdot n \cdot U_{\mathrm{R}}$. However, this solution can only be implemented if the series circuit consists of matching capacitors (same type, same capacitance), so that the dielectric insulation resistance of the capacitors, which is the only factor determining the voltage distribution in this case, will not vary too greatly from one capacitor to the next.

### 10.3 Combined parallel and series connection

The recommendations given above apply similarly to combinations of parallel and series circuits. If balancing resistors are to be used, it is advisable to allocate a separate resistor to each capacitor (figure 30).

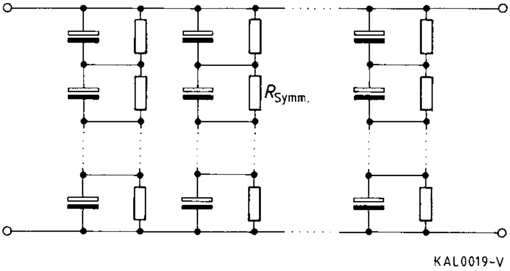


Figure 30 Combined parallel / series connection (voltage balancing by shunt resistors)

The alternative solution, parallel connection of the series capacitors in the individual branch and the use of one balancing resistor for each capacitor group, is shown in figure 31.

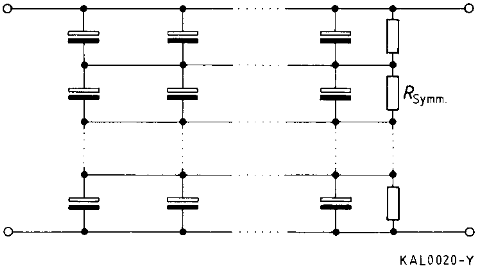


Figure 31 Combined parallel / series connection (group voltage balancing)

This solution is less complicated, but it has one serious disadvantage:

If a capacitor in one of the series branches fails and causes a short-circuit, the total voltage will be applied to the remaining capacitors. This will lead to a voltage overload and may destroy the remaining capacitors.

In the balancing arrangement shown in figure 30, only the series branch with the defective capacitor is subject to this risk, whereas in the more simple configuration shown in figure 31, the voltage overload affects all series branches due to the internal cross-connections, thus causing more severe damage. For the same reason, internal parallel connections should not be used in parallel groups connected in series without balancing resistors.

## 11 Marking of the capacitors

The example below shows how the snap-in capacitors are marked:

| | |
|---|---|
| EPCOS | Manufacturer (company logo) |
| LL | Grade (only on LL grade capacitors) |
| B43501-A2108-M | Part number (ordering code) |
| 1: 1000 µF (M) | Rated capacitance, tolerance (in coded form) |
| 200 VDC 40/085/56 | Rated voltage, climatic category (in accordance with IEC or coded as explained below) |
| 08.02 | Month and year of production, origin |

Terminal identification (if required)

Capacitance tolerances are coded in accordance with IEC 60062 using the codes shown below:

| Code letter | Capacitance tolerance | Code letter | Capacitance tolerance |
|---|---|---|---|
| A | Tolerances to which no other code applies | R | – 20 %/+ 30 % |
| | | S | – 20 %/+ 50 % |
| K | ± 10 % | T | – 10 %/+ 50 % |
| M | ± 20 % | V | – 10 %/+100 % |
| N | ± 30 % | Y | 0 %/+ 50 % |
| Q | – 10 %/+ 30 % | Z | – 20 %/+ 80 % |

The climatic category is specified in accordance with IEC 60068–1 (see paragraph 6.4). If there is not enough space on the case, the following codes may be used:

E.g.: 40/085/56, in coded form, would read GPF

1st letter (lower category temperature)

| Code letter | F | G | H |
|---|---|---|---|
| Temperature (°C) | – 55 | – 40 | – 25 |

2nd letter (upper category temperature)

| Code letter | K | M | P | S | U |
|---|---|---|---|---|---|
| Temperature (°C) | + 125 | + 105 (+ 100) | + 85 | + 70 | + 60 |

3rd letter (humidity)

Letter F: withstands test Ca (damp heat, steady state), test duration 56 days, in accordance with IEC 60068-2-3.

## 12 Packing

When packing our products, we naturally pay attention to environmental protection aspects. This means that only environmentally compatible materials are used for packing, and the amount of packing is kept to an absolute minimum.

In observing these rules, we are also complying with German packing regulations.

In order to further comply with the aims of the regulations concerning the reduction of waste, we have implemented the following measures:

- The use of standardized “Euro”-pallets.
- Goods are secured on the pallets using straps and edge protectors made of environmentally compatible plastics (PE or PP).
- The shipping cartons (transport packing) qualify for and carry the RESY logo.
- Separating layers between pallets and cartons are of a single material type, preferably paper or cardboard.
- Paper is used as filler and padding material.
- The shipping packaging are sealed with plastic tape to ensure technically efficient recycling.
- By agreement, we are prepared to take back the packing material (especially product-specific plastic packages). However, we ask our customers to send cardboard cartons, corrugated cardboard, paper etc. to recycling or disposal companies in order to avoid unnecessary transportation of empty packing materials.

## 13 Taking out of service and disposal (waste regulations)

All aluminum electrolytic capacitors from EPCOS are entirely free of PCB of course. Nor do they contain any harmful substances like DMF (dimethyl formamide) or DMAC (dimethyl acetamide).

Such aluminum electrolytics are not explicitly mentioned in national waste disposal regulations. This could be interpreted as meaning that they do not have to be disposed of in any special, supervised manner.

But because of our particular commitment to the environment, we request customers to consult their refuse disposal facilities and local or national authorities.

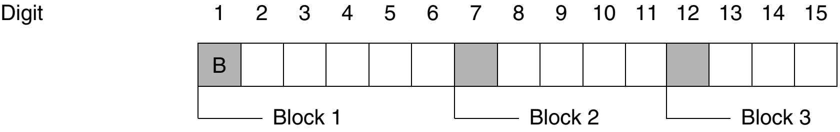
The code number of the European waste catalog that applies to their disposal is 120 103 “non-ferrous metal filings and turnings”.

Users outside of the European Union should refer to the waste disposal regulations of their own particular country.

## 14 Structure of the ordering code (part number)

All technical products made by EPCOS are identified by a part number (which is identical to the ordering code). This number is the unique identifier for any respective specific component that can be supplied by us. The customer can speed up and facilitate processing of his order by quoting the part numbers. All components are supplied in accordance with the part numbers ordered.

A part number consist of up to 15 digits and comprises three blocks of data. Each of these blocks starts with a letter, all other positions are allocated to numerals.



| Digit | Meaning |
|---|---|
| 1 | B = Passive components |
| 2 | 4 = Electrolytic capacitors |
| 3 | 1 = Low-voltage range ≤ 100 VDC<br>3 = High-voltage range ≥ 150 VDC |
| 4 bis 6 | Type |
| 7 | Revision status |
| 8 | Rated voltage<br>Low-voltage range (VDC) / High-voltage range (VDC)<br>1 3 / 1 150, 160<br>2 6,3 / 2 200$^{*)}$, 250<br>3 10, 12 / 3 300, 385$^{*)}$<br>4 15, 16 / 4 350<br>5 25 / 5 450<br>6 30, 50 / 6 500<br>7 35, 40 / 7 510, 520, 550 $^{*)}$<br>8 63, 70 / 8 330, 600$^{*)}$<br>9 100 / 9 360$^{*)}$, 400$^{*)}$<br>0 special / 0 special<br>*) Types already available with these voltages have the code number “0” (= special). Hence, there may be mixed designations. |

| Digit | Meaning |
|---|---|
| 9 to 11 | Capacitance<br>The capacitance is given in coded form. Examples:<br>Data digit 9 10 11<br>B 4 3 5 0 1 A 9 $\boxed{1}\boxed{5}\boxed{7}$ $= \underline{15} \cdot 10^{\underline{7}}$ pF = 150 µF |
| 12 | Capacitance tolerance (Code according to IEC 60062)<br>A Special tolerance<br>K ± 10 %<br>M ± 20 %<br>N ± 30 %<br>Q – 10/+ 30 %<br>R – 20/+ 30 %<br>S – 20/+ 50 %<br>T – 10/+ 50 %<br>V – 10/+ 100 %<br>Y 0/+ 50 %<br>Z – 20/+ 80 % |
| 13, 14, 15 | Code numbers for special versions, terminal styles and packing<br>*Capacitors with screw terminals:*<br>Code number for 2-pad solution and low-inductance versions<br>*Snap-in capacitors:*<br>Code number for versions with short or 3 terminals<br>*Axial-lead and soldering star capacitors:*<br>Code number for packing<br>*Single-ended capacitors:*<br>Code number for type of packing or tape packing, lead configuration (kinked, cut) and version with protection against polarity reversal |

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