Aluminum Electrolytic Capacitors

General technical information

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1 Basic construction of aluminum electrolytic capacitors

Aluminum electrolytic capacitors assume a special position among the various types of capacitors since their principle of operation relies, in part, on electrochemical processes.

The advantages of aluminum 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 aluminum 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 aluminum 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 aluminum 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.

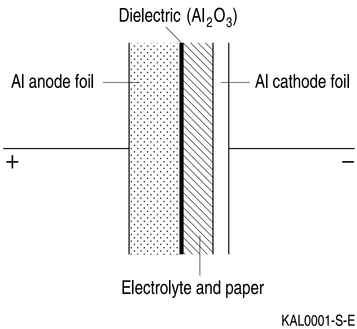


Figure 1
Basic construction of an aluminum electrolytic capacitor

$$C = \epsilon_0 \cdot \epsilon_r \cdot \frac{A}{d}$$

C	Capacitance	F
ε_0	Absolute permittivity	As/Vm
ε_r	Relative permittivity	(9.5 for Al_2O_3)
A	Capacitor electrode surface area	m^2
d	Electrode spacing	m

The anode of an aluminum 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 aluminum electrolytic capacitor dimensions to be achieved and are the form used almost exclusively nowadays. The electrical characteristics of aluminum 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.

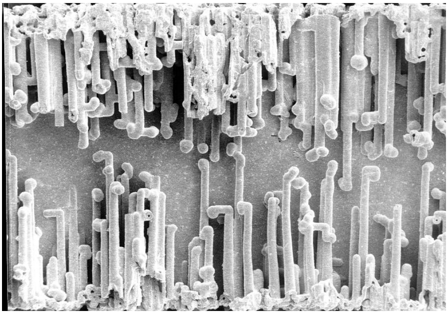


Figure 2
Anode foil for high-voltage capacitors (magnification 400x)

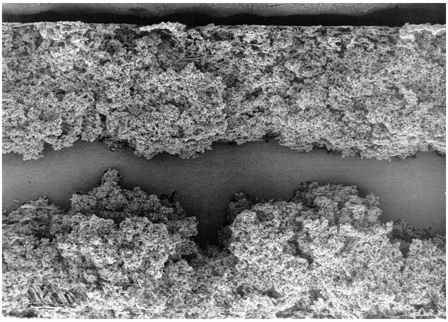
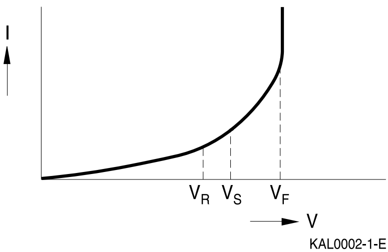


Figure 3
Anode foil for low-voltage capacitors (magnification 400x)

The dielectric layer of an aluminum 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.



V_R = Rated voltage
V_S = Surge voltage
V_F = Forming voltage

Figure 4
Current-voltage characteristic of an aluminum electrolytic capacitor

When the forming voltage V_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 V_R is defined as being on the quasi-linear part of the curve. As the capacitor is subjected to surge voltages V_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 to 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.

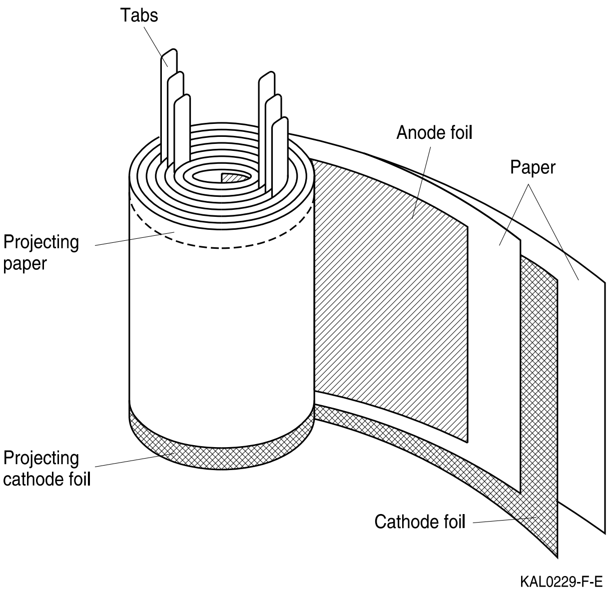


Figure 5
Winding construction of an aluminum electrolytic capacitor

An aluminum 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).

2 Standards and specifications

2.1 General-purpose grade and long-life grade capacitors

Aluminum 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 aluminum 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 aluminum 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.

Aluminum 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.

The sectional specification mentioned above is complemented by a set of detail specifications that applies 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 EN 60384-1, EN 60384-1): Generic specification: Fixed capacitors for use in electronic equipment
IEC 60384-4	(identical with EN 60384-4): Sectional specification: Aluminum electrolytic capacitors with solid and non-solid electrolyte
IEC 60384-4-1	(identical with EN 60384-4-1): Blank detail specification: Fixed aluminum electrolytic capacitors with non-solid electrolyte

Important notes on proper use of aluminum electrolytic capacitors can also be found in CLC/TR 50454 "Guide for the application of aluminum electrolytic capacitors".

The technical specifications given for aluminum 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 B43698 B43699
CECC 30301-802	B41690, B41790 B41691, B41791 B41692, B41792 B41693, B41793 B41694, B41794 B41695, B41795 B41696, B41796 B43693, B43793
CECC 30301-803 CECC 30301-807	B43455, B43457 B43456, B43458 B43564, B43584 B43740, B43760
CECC 30301-804	B41554 B41550, B41570
CECC 30301-805	B43510, B43520 B43511, B43521
CECC 30301-806	B43305
CECC 30301-808	B43515, B43525
CECC 30301-809	B41605 B41607 B43504 B43505 B43508 B43543
CECC 30301-810	B41456, B41458 B41560, B41580 B43464, B43484
CECC 30301-811	B43501 B43601 B43540

3 Definitions of electrical parameters

3.1 Voltages

3.1.1 Rated voltage V_R

The rated voltage V_R is the direct voltage value for which the capacitor has been designed and which is indicated upon it. For aluminum electrolytic capacitors, rated voltages of ≤100 V are usually designated as "low voltage" and rated voltages >100 V as "high voltage" (refer to chapter "General technical information, 15 Structure of the ordering code (part number)").

3.1.2 Operating voltage V_{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 (refer to chapter "General technical information, 3.1.6 Reverse voltage").

3.1.3 Surge voltage V_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 $V_R \leq 315$ V: $V_S = 1.15 \cdot V_R$

for $V_R > 315$ V: $V_S = 1.10 \cdot V_R$

3.1.4 Transient voltage

Some capacitor types produced by EPCOS can withstand voltage pulses exceeding the surge voltage V_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 aluminum 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 (refer to chapter "General technical information, 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 ≤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.

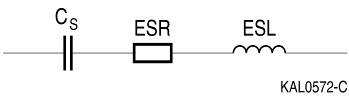


Figure 6
Simplified equivalent circuit diagram of an electrolytic capacitor

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 IEC 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 41328-4, 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 IEC 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 Hz or 120 Hz and 20 °C, to 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 to IEC 60062; this code letter is also part of the ordering code (refer to chapter "General technical information, 13 Marking of the capacitors").

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.

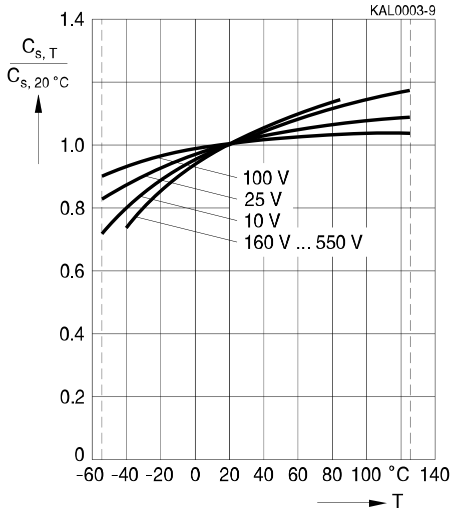


Figure 7
Temperature dependence of series capacitance C_S (typical behavior)
Reference value: AC capacitance at 20 °C and 100 Hz

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

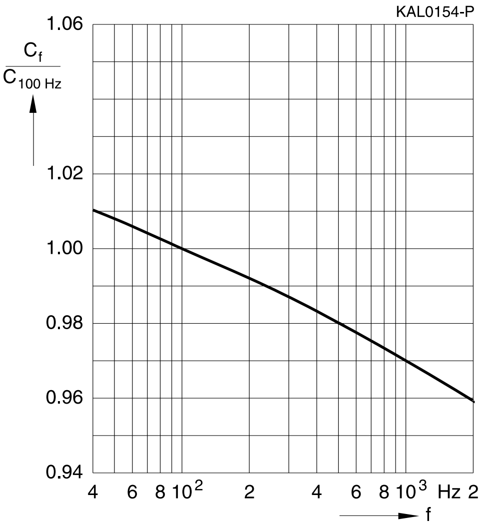


Figure 8
Capacitance C versus frequency f
Typical behavior

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 to 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 (see figure 6).
IEC 60384-4 specifies the following maximum values:

Rated voltage	$4\ V < V_R \leq 10\ V$	$10\ V < V_R \leq 25\ V$	$25\ V < V_R \leq 63\ V$	$63\ V < V_R$
Maximum value for the 100-Hz dissipation factor (to IEC 60384-4)	0.5	0.35	0.25	0.20

These values apply to capacitors with a maximum charge of 100000 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.

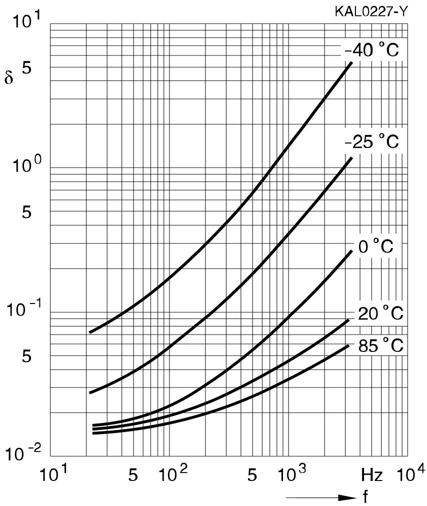


Figure 9
Low-voltage aluminum electrolytic capacitor
(Example: 100 µF/63 V DC)

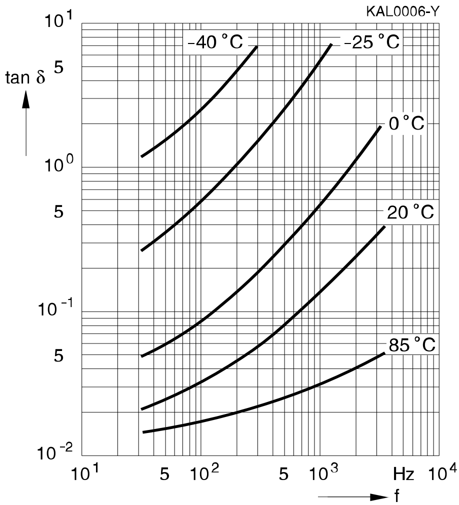


Figure 10
High-voltage aluminum electrolytic capacitor
(Example: 47 µF/350 V DC)

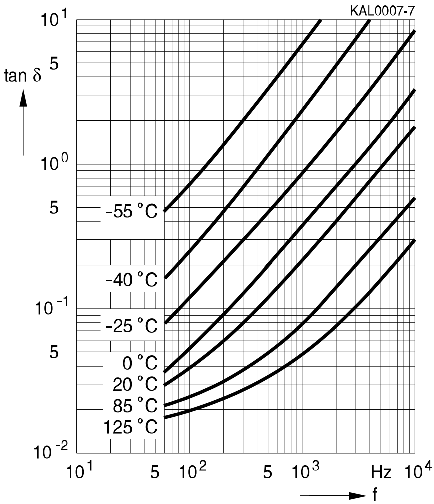


Figure 11
Low-voltage electrolytic capacitor "SIKOREL 125" (Example: 220 µF/40 V DC)

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 6.

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):

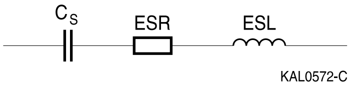


Figure 12
Simplified equivalent circuit diagram of an electrolytic capacitor

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 ωESL of the capacitor winding and the terminals.

The inductive reactance ωESL 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.

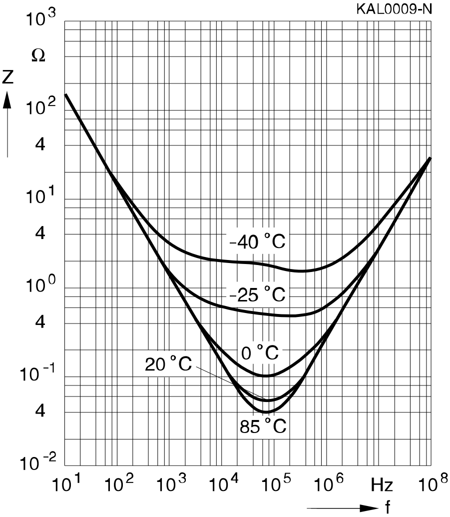


Figure 13
Impedance versus frequency and temperature
Example: 100 µF/63 V DC (simplified graph)

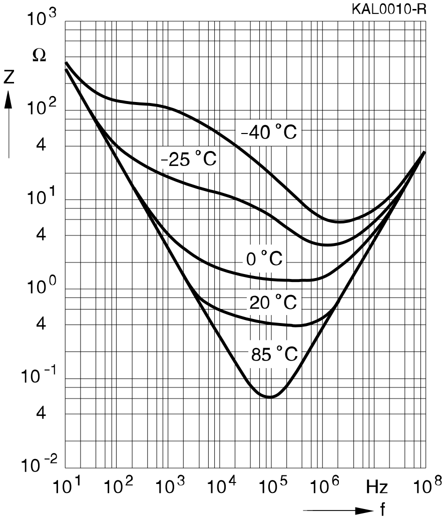


Figure 14
Impedance versus frequency and temperature
Example: 47 µF/350 V DC (simplified graph)

3.7 Leakage current I_{leak}

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.

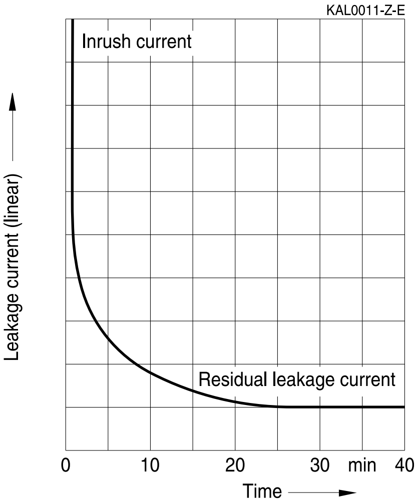


Figure 15
Leakage current versus time for which a voltage is applied

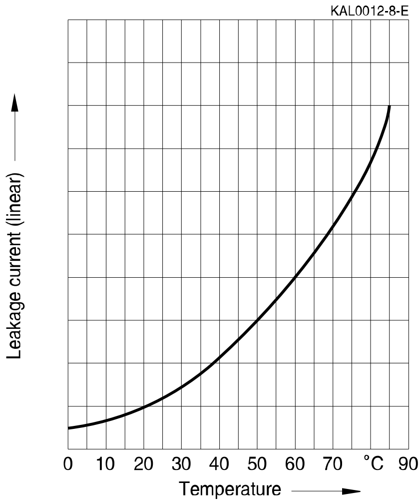


Figure 16
Leakage current versus temperature

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.

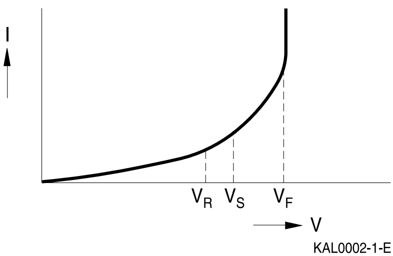


Figure 17

Voltage dependence of the leakage current

3.7.3 Operating leakage current $I_{leak,op}$

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

LL grade:

$$I_{leak,op} = \frac{0.00025\ \mu A}{\mu F \cdot V} \cdot C_R \cdot V_R + 1\ \mu A$$

GP grade:

$$I_{leak,op} = \frac{0.0005\ \mu A}{\mu F \cdot V} \cdot C_R \cdot V_R + 3\ \mu A$$

$I_{leak,op}$ Operating leakage current
C_R Rated capacitance
V_R Rated voltage

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

In accordance with DIN 41240 and DIN 41332, 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 V_R	20	30	40	50	60	70	80	90	100
Typical values, in % of the operating leakage current $I_{leak,op}$ (General-purpose grade)	3	6	9	14	18	25	40	50	100
Typical values, in % of the operating leakage current $I_{leak,op}$ (Long-life grade)	8	14	17	23	30	40	50	70	100

3.7.4 Leakage current for acceptance test I_{leak}

As the leakage current varies with time and temperature, it is necessary to define reference values for measuring time and temperature. To IEC 60384-4 and IEC 60384-1 the leakage current is to be measured at 20 °C, after the rated voltage has been applied for 5 minutes.

Acceptance testing for leakage current as specified in the particular series 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

To IEC 60384-4, aluminum 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 $V_R \leq 100$ V DC, or 1000 Ω for $V_R > 100$ V DC, 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 aluminum 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.

Aluminum 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 chapter "General technical information, 3.7.5 Reforming" 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 aluminum electrolytic capacitors made by EPCOS are enveloped by an insulating sleeve. The minimum breakdown strength of the sleeve is 2500 V AC or 3500 V DC. 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.

As a standard feature, capacitors with an upper category temperature of +85 °C and +105 °C are fitted with external PVC insulation. 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 δ (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 "General technical information, 5.3 Calculation of useful life" for an calculation of useful life 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 aluminum 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 the upper category temperature for each capacitor type. For most of the 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 (refer also to chapter "Quality and environment, 1.8 Service life/reliability").

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

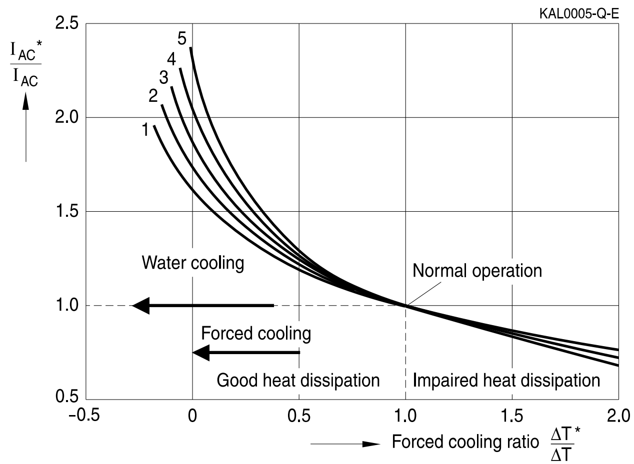
The useful life values stated in these data sheets apply to aluminum electrolytic capacitors with natural cooling, i.e. the heat generated in the winding is dissipated through the casing and by natural convection. It is possible to increase the permissible ripple current and/or prolong the useful life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

5.2.1 Forced air cooling

In case of forced air cooling it should be kept in mind that the mounting position can influence only the thermal resistance between the case and the surrounding air. Under natural convection this thermal resistance is greater than the inner thermal resistance between the capacitor winding and the case.

For a given ripple current load the thermal resistance is proportional to the difference between the capacitor case temperature and the ambient temperature. The user can measure this temperature difference ($T_{case} - T_A$) under normal conditions (ΔT) and under forced-air conditions (ΔT^*) by applying constant ripple current load conditions. Hence the relative reduction or increase of the thermal resistance can be calculated 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_{AC}^*/I_{AC}. 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 18) shows the effect of the forced cooling ratio, as determined by measurement, on the ripple current factor I_{AC}^*/I_{AC} for various case sizes. In this diagram the useful life of the capacitor with forced cooling (ripple current load: I_{AC}^*) has been equated to the useful life rating of the aluminum electrolytic capacitor under normal operating conditions (ripple current load: I_{AC}).



Dimensions d × l (mm)
1: 75 × 220, diam. = 90
2: 75 × 145
3: 50 × 105
4: 35 × 80
5: 18 × 31.5

Figure 18
Effect of forced cooling on the ripple current capability

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

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_{AC}* of aluminum electrolytic capacitors with impaired heat dissipation is lower than the rated value I_{AC}.

5.2.2 Base cooling with heat sink

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. For heat sink mounting EPCOS offers special designed versions of high-voltage capacitors with screw or snap-in terminals in order to ensure an optimal heat transfer from the heat generation area via base of the case to the heat sink.

If a cooling plate with cooling fluid (e.g. water or oil) is used that is colder than the ambient temperature, the forced cooling ratio shown in figure 18 may be reduced to zero or may even have a negative value. Due to the limited thermal capacity of such 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 cooling elements or/and forced convection are used.

Screw terminal capacitors

The special design comprises:

- Winding elements and cans are designed for a low inner thermal resistance in order to generate an excellent thermal connection between winding element and base. This assures good heat transfer from the heat generation spot to outside.
- Two thermal pads at the base. The first (thickness 0.5 mm) closes the air gap at the base in the area which is not covered by the insulating sleeve. The second (thickness 0.2 mm) ensures the electrical insulation of the case.
- Minimized tolerance (±0.35 mm) of the overall length l_1 of the capacitor (figure 19) to avoid unwanted mechanical forces on the terminals, especially when several capacitors are mounted between heat sink and bus bar.
- Case with extra groove near the base for ring clamp mounting (recommended accessory B44030A0165B...A0190B). The clamp ensures an optimal pressing of the case to the heat sink.

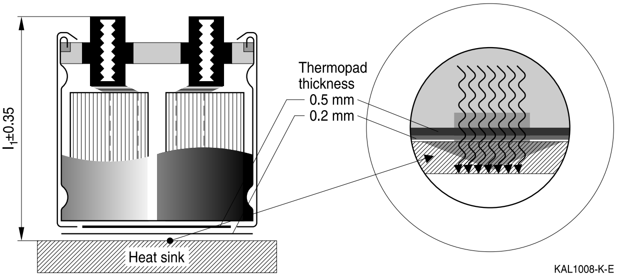


Figure 19
Heat sink mounting for capacitors with screw terminals

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

Snap-in capacitors

In comparison to standard snap-in capacitors the special design comprises:

- Winding elements and cans are designed for a low inner thermal resistance in order to generate an excellent thermal connection between winding element and base. This assures good heat transfer from the heat generation spot to outside.
- Minimized overall length tolerance (±0.2 mm) of the capacitor is provided by a special can design with length adjustment process. This allows thinner thermal pads to be used for connecting a capacitor bank to the heat sink which leads to reduced thermal resistance as well as to reduced costs.
- Reinforced capacitor can to provide long term stable can dimensions during operation in order to ensure a constant low thermal resistance.
- The alternative versions with and without insulation allow a simple and effective connection of the capacitor base to the heat sink providing a cost optimized solution with reduced thermal resistance.

5.3 Calculation of useful life

The tables in the individual data sheets list the rated ripple current $I_{AC,R}$ for the upper category temperature (+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 I_{AC} /$I_{AC,R}$ 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 co-ordinates, or it can be interpolated if none of the useful life curves passes directly through these co-ordinates.

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 $I_{AC,f}$ /$I_{AC,100\ Hz}$ 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 B43564/B43584 series. For this type series, the upper category temperature is +85 °C. As an example, a capacitor with the following ratings has been selected from the data sheets:

Series B43564 / B43584

V_R VDC	C_R 100Hz 20 °C µF	Case dimensions d × l mm	ESR_{typ} 100 Hz 20 °C mΩ	ESR_{max} 100 Hz 20 °C mΩ	Z_{max} 10 kHz 20 °C mΩ	$I_{AC,max}$ 100 Hz 40 °C A	$I_{AC,R}$ 100 Hz 85 °C A	$I_{AC,R}$ (B) 100 Hz 85 °C A	Ordering code
400	6800	76.9×143.2	18	27	20	46	17.1	29.7	B435*4A9688M00#

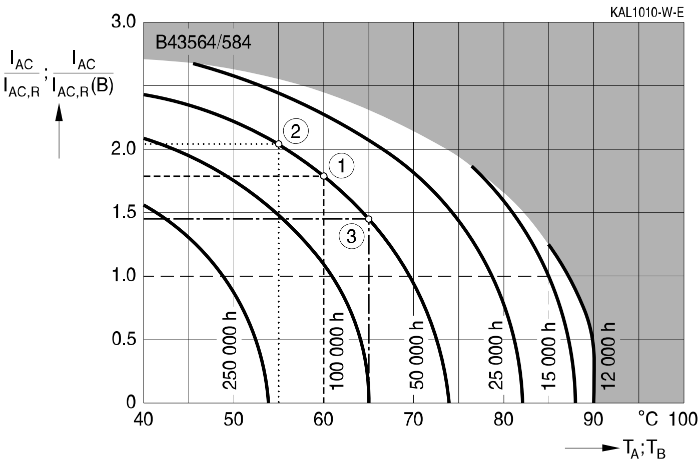


Figure 20
Useful life versus ambient temperature T_A for natural cooling
and capacitor base temperature T_B for base cooling (series B43564/B43584)

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	38 A
Frequency	300 Hz
Ambient temperature	60 °C

The equivalent ripple current for 100 Hz is calculated using the frequency-dependence conversion factor (see series B43564 / B43584 "Frequency factor of permissible ripple current I_{AC}"):

$$\frac{38\,\text{A}}{1.24} = 30.6\,\text{A}$$

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

$$\frac{I_{AC}}{I_{AC,R}} = \frac{30.6\,\text{A}}{17.1\,\text{A}} \cong 1.8$$

The useful life curve passing through the coordinates for the ripple current factor (1.8) and the ambient temperature (60 °C) indicates the useful life that can be expected:

50 000 h (see ① figure 20).

Example 2 – Checking the ripple current load on an aluminum electrolytic capacitor

In many applications, aluminum electrolytic capacitors are subjected to ripple currents of varying frequencies.

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

Current 1: $I_{AC,RMS}$ at 300 Hz	40 A
Current 2: $I_{AC,RMS}$ at 3 kHz	17 A
Ambient temperature	55 °C
Required useful life	50000 h

The first step is to calculate the equivalent 100 Hz values for the two current values (frequency factors given on series B43564 / B43584 "Frequency factor of permissible ripple current I_{AC}") and the root-mean-square value of the two equivalent values:

$$\text{Current } I_1 : \frac{40\ \text{A}}{1.24} = 32.3\ \text{A at } 100\ \text{Hz}$$

$$\text{Current } I_2 : \frac{17\ \text{A}}{1.4} = 12.1\ \text{A at } 100\ \text{Hz}$$

$$I_{total,RMS} = \sqrt{I_1^2 + I_2^2}$$

$$I_{total,RMS} = \sqrt{(32.3\ \text{A})^2 + (12.1\ \text{A})^2} = 34.5\ \text{A}$$

The ripple current factor can then be calculated:

$$\frac{I_{AC}}{I_{AC,R}} = \frac{34.5\ \text{A}}{17.1\ \text{A}} \cong 2.02$$

The useful life curve that coincides with the respective coordinates, 2.02 on the Y-axis (ripple current factor) and 55 °C on the X-axis (ambient temperature) indicates a useful life of 50000 h. The required useful life is thus achieved (see ② figure 20).

Example 3 – 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	50000 h

From the useful life curve (50000 h) we get a ripple current factor $I_{AC,R}/I_{AC,R}$ (B) = 1.45 at the capacitor base temperature of 65 °C. The maximum permissible ripple current is calculated to:

$I_{AC,RMS} = 1.45 \cdot I_{AC,R}$ (B) = $1.45 \cdot 29.7$ A ≅ **43 A** (see ③ figure 20).

6 Capacitor bank design

In some applications the required capacitance may not be achieved by using a single aluminum 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. CENELEC REPORT R040-001:1998, provides important information on the dimensioning and circuit configuration of capacitor banks. The following paragraphs explain and supplement this information.

6.1 Parallel connection of aluminum 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, e.g., this is achieved by installing individual fuses; the principle is shown in figure 21.

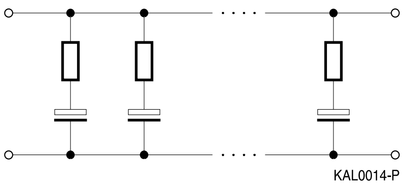


Figure 21
Individual fuses in smoothing capacitor banks

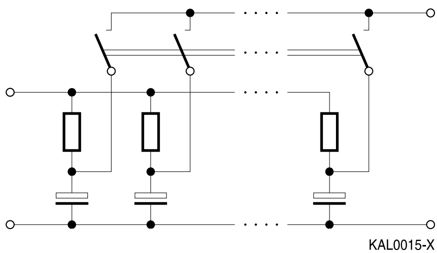


Figure 22
Protection by charging resistors

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 22.

6.2 Series connection of aluminum electrolytic capacitors

When designing series circuits with aluminum 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 23) 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 24.

If this is not possible, external balancing resistors R_{Symm} (see figure 25) 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.

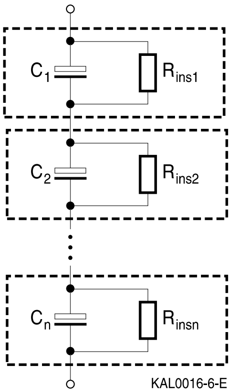


Figure 23
Series connection (with dielectric resistances)

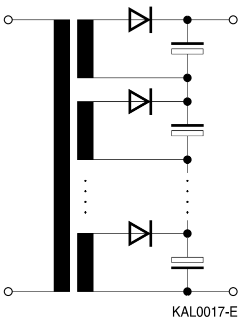


Figure 24
Series connection (forced voltage distribution balancing)

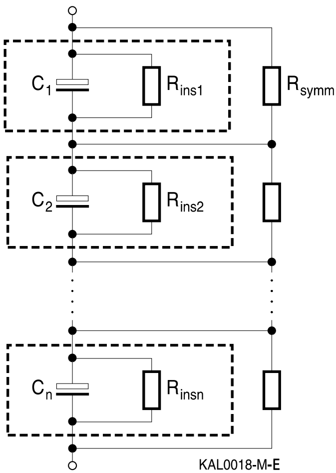


Figure 25
Series connection (external balancing resistors R_{Symm} connected to the individual capacitors)

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:

$$R_{Symm} = 100\,M\Omega \cdot \mu F \cdot \frac{1}{C_R}$$

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 $0.8 \cdot n \cdot V_R$. 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.

6.3 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 26).

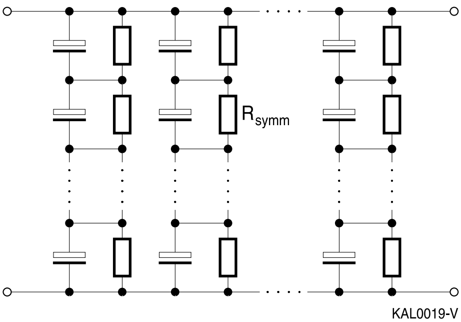


Figure 26
Combined parallel / series connection (voltage balancing by shunt resistors)

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 27.

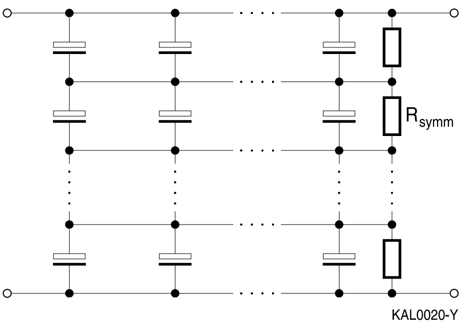


Figure 27
Combined parallel / series connection (group voltage balancing)

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 26, only the series branch with the defective capacitor is subject to this risk, whereas in the more simple configuration shown in figure 27, 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.

7 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 (refer to chapter "General technical information, 7.4 IEC climatic category"). The IEC categories are given for each type in the corresponding data sheet.

7.1 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 aluminum 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 28 and 29.

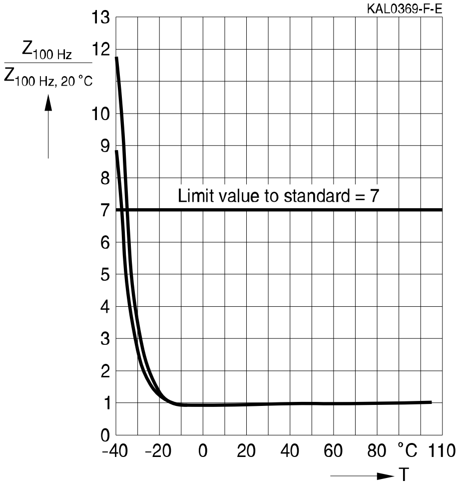


Figure 28

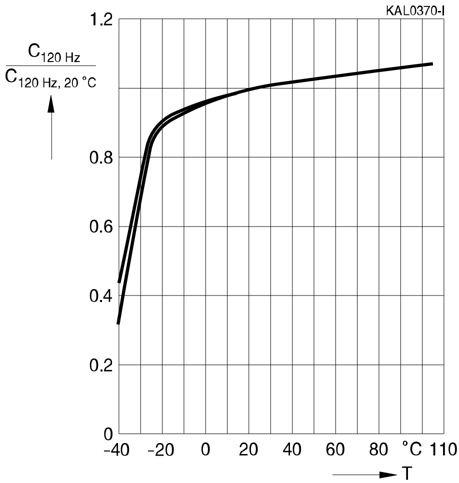


Figure 29

7.2 Maximum permissible operating temperature (upper category temperature)

The upper category temperature 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 upper category temperature 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.

7.3 Storage temperature

Aluminum electrolytic capacitors can be stored voltage-free at temperatures up to the upper category temperature. (Refer to chapter "General technical information, 3.7.6 Leakage current behavior with no voltage applied".)

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 aluminum electrolytic capacitors specify a lower storage temperature that corresponds to the lower category temperature. Aluminum electrolytic capacitors by EPCOS withstand the lowest specified storage temperature, i.e. −65 °C, without being damaged.

7.4 IEC climatic category

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

Example: 40 / 085 / 56

1st group: Lower category temperature (temperature limit) denoting the test temperature for test A (cold) to IEC 60068-2-1.

2nd group: Upper category temperature (temperature limit) denoting the test temperature for test B (dry heat) to IEC 60068-2-2.

3rd group: Number of days, the duration of test Cab (damp heat, steady state) at a relative humidity of 93 +2/−3% and an ambient temperature of 40 °C, to IEC 60068-2-78.

8 Flammability

8.1 Passive flammability

Under the influence of high external energy, such as fire or electricity, the flammable parts of capacitors may get inflamed. Clause 4.38 of the relevant specification IEC 60384-1 (Fixed capacitors for use in electronic equipment – Part 1: Generic specification) refers to the standard IEC 60695-11-5 (Test flames – Needle-flame test method – Apparatus, confirmatory test arrangement and guidance) for testing the passive flammability. IEC 60384-1 summarizes severities and requirements for different categories of flammability. In general category C is met by most of our aluminum electrolytic capacitors. Most of our snap-in and screw terminal capacitors with PVC insulation meet the requirement of category A.

8.2 Active flammability

In rare cases the component may ignite caused by heavy overload or some capacitor defect. One reason could be the following: During the operation of an aluminum electrolytic capacitor with nonsolid electrolyte, there is a small quantity of hydrogen developed in the component. Under normal conditions, this gas permeates easily out of the capacitor. But under exceptional circumstances, higher gas amounts may develop and may catch fire if a sparking would occur at the same time.

As explained above a fire risk can't be totally excluded. Therefore, it is recommended to use special measures in critical applications (e.g. additional encapsulation of the equipment for mining applications).

9 Mechanical stress resistance

9.1 Vibration resistance

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

9.2 Operating altitude

Aluminum electrolytic capacitors can be used in high-altitude locations (to EN 130300 subclause 4.11.4).

9.3 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 chapter "General technical information, 11.3 Mounting torques".

10 Maintenance

CENELEC R040-001 (chapter 1 to 19) provides general information on applications in which aluminum 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.

11 Mounting

11.1 Mounting positions of capacitors with screw terminals

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

A safety vent in the can disk allows the gas to escape when the pressure reaches a certain level and prevents the capacitor from exploding in case of pressure increase due to an overload condition.

To prevent electrolyte from leaking out when the gas has vented, the capacitor should not be mounted with the terminals (safety vent) upside down. The recommended mounting positions to avoid a vent-down installation of the capacitor are shown in figure 30.

Example:

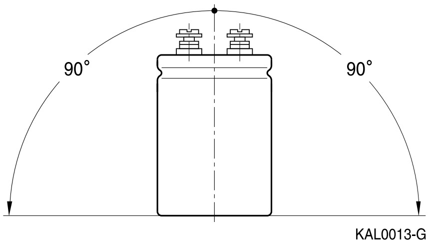


Figure 30
Recommended range of mounting positions

- Upright mounting is recommended, particularly when the capacitors are fixed by their terminals, by a threaded stud or near the base.
- In case of horizontal mounting, the safety vent should be at the "12 o'clock" position.

Mounting positions other than recommended will not cause any direct damage to the capacitor, but may result in serious consequential damage in the application during operation due to electrolyte leakage in the case of venting.

11.2 Potting and gluing of aluminum electrolytic capacitors

- Potting compound or glue must be free of halogens and other corrosive substances.
- The potting and gluing materials must not impair the function of the capacitor's safety vent.
- Potting compounds or glue may heat up capacitors while curing. If possible the upper category temperature should not be exceeded.
- Temperatures above 150 °C may damage the insulation.
- Depending on the duration a temperature rise during the curing process may lead to an increased leakage current of the capacitors when the application is switched on first time. The life span of the capacitors usually is not affected.
- Potting compounds usually have a low thermal conductivity, which may adversely affect the emission of heat from the capacitors during operation. Increased heating up may shorten the life span of the capacitors.
- When warmed up the potting compound may exert pressure on the capacitor. Such pressure shall not exceed 20 bars.
- The PVC of the heat shrink sleeve may contain substances that on a long-term basis can react aggressively with the potting compound or glue.
- If gluing is the only mechanical attachment, then the mechanical stability of the shrinking sleeves is the determining factor for the stability of the attachment of the capacitor.

11.3 Mounting torques

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

Thread	Maximum torque (Nm)
M5	2.0
M6	2.5
M8	4.0
M12	10.0

11.4 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.

Pay attention to the following cautions:

- Do not move the capacitor after soldering to PC board.
- Do not pick up the PC board by holding the soldered capacitor.
- Do not insert capacitor on the PC board with a hole space different to specified lead space.

Example:

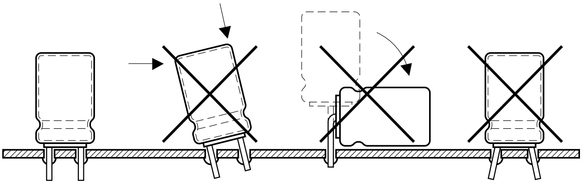


Figure 31
Mounting considerations for single-ended capacitors

11.5 Soldering

- Excessive time or temperature during soldering will affect capacitor's characteristics and cause damage to the insulation sleeve.
- Contact of the sleeve with soldering iron must be avoided.
- Soldering conditions (preheat, solder temperature and dipping time) should be within the limits prescribed in the product specifications.

11.6 Cleaning agents

Cleaning agents 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 cleaning agents and solvents to clean printed circuit boards after soldering the components, or to remove flux residues.

As a general rule, capacitors with Polyethylene terephthalate based insulation (PET) are not suggested to be washed with any cleaning agent either solvent based or aqueous. Aqueous residuals from the washing treatment can induce a slow hydrolytic degradation of the polymer at elevated temperature.

Polyvinyl chloride based insulation (PVC) can be treated with cleaning agents either aqueous or solvent based (but halogen-free).

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 aluminum 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.

12 Fumigation

International shipments of products are subjected in many countries to a fumigation treatment using halogenated chemicals (e.g. methyl bromide) in order to control insect infestation, particularly when wooden packaging is used. The halogenated gas can penetrate cardboard boxes, polymer bags or other packaging materials and come into direct contact with equipment or components contained within and may cause corrosion of aluminum electrolytic capacitors. The halogenated gas can also penetrate the seals of aluminum electrolytic capacitors and may cause internal corrosion, possibly resulting in an open-circuit after the equipment has been put into operation.

13 Marking of the capacitors

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

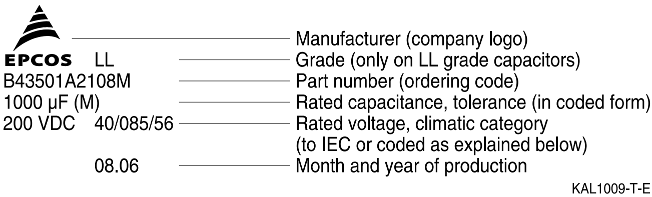


Figure 32
Marking example

Capacitance tolerances are coded to 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 to IEC 60068–1 (refer to chapter "General technical information, 7.4 IEC climatic category"). 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 Cab (damp heat, steady state), test duration 56 days, to IEC 60068-2-78.

14 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.

14.1 Bar code label

The packing of all EPCOS components bears a bar code label stating the type, ordering code, quantity, date of manufacture and batch number. This enables a component to be traced back through the production process, together with its batch and test report.

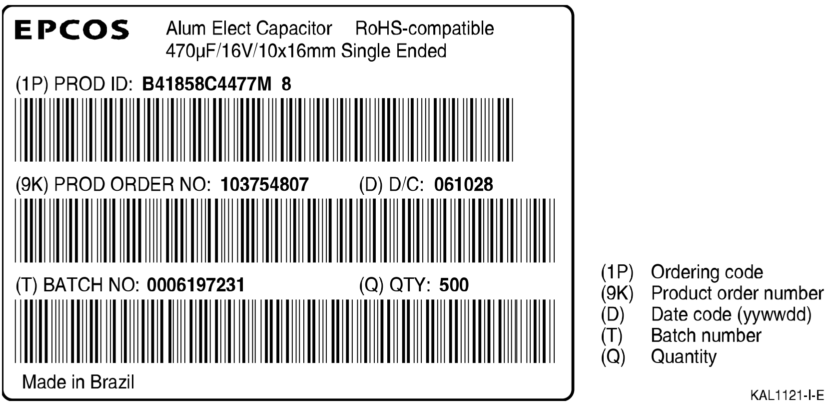


Figure 33
Example of bar code label

15 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	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	B														
	Block 1						Block 2					Block 3			

Digit	Meaning	
1	B = Passive components	
2	4 = Electrolytic capacitors	
3	1 = Low-voltage range ≤100 V DC 2 = Single-ended bipolar capacitors 3 = High-voltage range ≥150 V DC	
4 to 6	Type	
7	Design variant	
8	Rated voltage	
	Low-voltage range (V DC)	High-voltage range (V DC)
	1: 3	1: 150, 160
	2: 6.3	2: 200*), 250
	3: 10, 12	3: 300, 385*)
	4: 15, 16	4: 350
	5: 25	5: 450
	6: 30, 50	6: 500
	7: 35, 40	7: 510, 520, 550*)
	8: 63, 70	8: 330, 600*)
	9: 100	9: 360*), 400*)
	0: special	0: special
	*) Designation with code number "0" possible for older types.	
9 to 11	Capacitance The capacitance is given in coded form. Examples: Data digit 9 10 11 B 4 3 5 0 1 A 9 [1][5][7] = $15 \cdot 10^{7}$ pF = 150 µF	

12	Capacitance tolerance (code to IEC 60062) A: Special tolerance K: ±10 % M: ±20 % N: ±30 % Q: −10/+30 % R: −20/+30 % S: −20/+50 % T: −10/+50 % V: −10/+100 % Y: −0/+50 % Z: −20/+80 %
13, 14, 15	Code numbers for special versions, terminal styles and packing Capacitors with screw terminals: Code number for low inductance, heat sink mounting or PAPR style versions Snap-in and 4-pin snap-in capacitors: Code number for versions with short or 3 terminals, PET insulation sleeve or additional PET insulation cap Axial-lead and soldering star capacitors: Code number for packing Single-ended capacitors: Code number for type of packing or tape packing, lead configuration (kinked, cut) and version with protection against polarity reversal