Technical Information

Construction

An aluminum electrolytic capacitor consists of two electrically conductive aluminum layers, separated by a dielectric layer. One of the electrodes (the aluminum foil called anode) undergoes a Process called ‘forming’, by which a dielectric layer of aluminum oxide (Al_2O_3) is electrochemically coated on it. The other electrode is a conductive liquid, called the electrolyte. The second aluminum foil, the cathode, acts as a large surfaced contact area for passing current to the electrolyte. The basic principle of the capacitor is to store electrical charge and is defined as:

Q = CV

Q = charge in Coulombs

C = capacitance, in Farads (between the plates)

V = potential difference between the plates

Based on the formula given above, it can be said that the unit of capacitance, the Farad, is the capacitance between the plates, across which appears a potential difference of 1 Volt when it is charged by 1 Coulomb of electricity. The value of capacitance in a capacitor is directly proportional to the area of the plates and is inversely proportional to the distance between them. Hence capacitance is expressed by the equation:

$$C = \frac{A}{d}\,\varepsilon_o\,\varepsilon_r$$

A = surface area of the plates in m^2

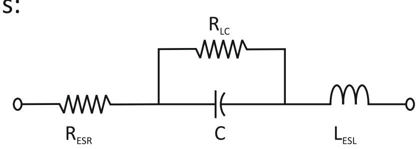
d = distance between the plates (or dielectric thickness) in metres

$E_{o.}$ = permittivity of free space = 8.885×10^{-12} F/m

$E_{r.}$ = relative permittivity of the dielectric (9.5 for Al_2O_3)

The surface area of the anode is enlarged (up to 200 times) by an electrochemical etching process. Similarly the cathode is also etched to increase the surface area. The thickness of the dielectric layer is very small (in microns) and increases in proportion to the forming voltage (approximately 1.2nm/v), making the distance between the two plates very small. This construction of aluminum electrolytic capacitors allows for very high capacitance per unit area in comparison with capacitors which use other dielectric materials.

An equivalent circuit of an aluminum electrolytic capacitor is:



R_{ESR} = equivalent series resistance (ESR)

C = capacitance

R_{LC} = resistance due to leakage current

L_{ESL} = equivalent series inductance (ESL)

The capacitance of the anode foil will depend on the etching pattern and the forming voltage. The cathode foil is etched and has a thin oxide layer on it, which is caused due to atmospheric oxidation.

Manufacturing Process

The main stages of the manufacturing process are:

Anode foil : Etching → Forming → Slitting → Winding

Cathode foil : Etching → Slitting → Winding

Capacitor paper : Slitting → Winding

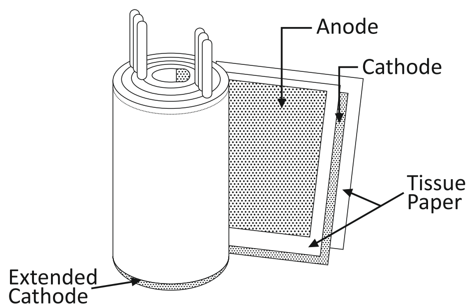
Winding ↓

Assembly 1 → Impregnation → Assembly2 → Ageing

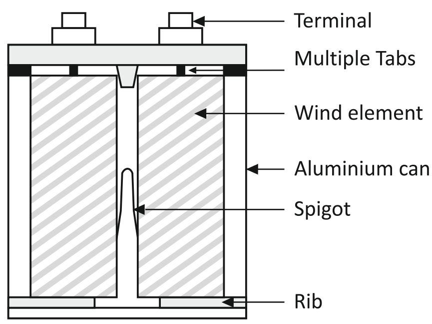
Ageing ↓

Sleeving → Testing → Packing

Super pure aluminium foil is etched to increase the surface area. The anode foil undergoes an electrochemical process called forming by which a dielectric layer is ‘formed’ on it. The anode and cathode are interleaved with different densities and thickness papers and wound into a cylinder as shown in the fig. below. During winding, aluminum tabs are attached to the foil for electrical contacts by a cold welding process.



The capacitor element is impregnated with an electrolyte, under vacuum. In the assembly process, terminals are riveted and/or welded to the tabs and housed in an aluminium can without anchoring material, as shown:



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Capacitors are then sealed and aged. The aging process repairs any damage to the oxide layer that may have been caused during the process of assembling the capacitor into the aluminium can. A thorough test is carried out for seepage by placing the capacitors in an oven. A visual check is carried out on each capacitor for any sign of electrolyte leakage.

Next, capacitors are tested for the following electrical parameters.

I) Capacitance	ii) ESR
iii) Leakage current	iv) Tan δ

The capacitors are then sleeved and packed. After completion of the production process, the company's Q.A. Personnel carry out a sample test.

Electrical Characteristics

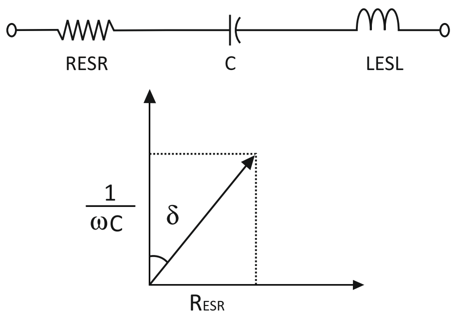
- **Rated voltage:** The rated voltage is the DC voltage for which the capacitor has been designed. The capacitors can be operated continuously at the full rated voltage within the operating temperature range.
- **Surge voltage:** The surge voltage is the maximum DC voltage that a capacitor can be subjected to, for a very short duration, not exceeding 30 seconds. This includes transients and peak ripple at highest line voltage.
  Capacitors are designed to withstand 6 such surge in an hour, at a minimum interval of 10 minutes. The capacitor will withstand the following surge test: The capacitor is connected in series with a current limiting resistor.
  The rated surge voltage is applied at room temperature for a period not exceeding 30 seconds. The capacitor is then discharged through a suitable resistor. This cycle (charge discharged) may be repeated for a maximum of 6 cycles in one hour, each being at an interval of 10 minutes.
- **Ripple voltage:** The ripple voltage is the superimposed AC voltage that may be applied to the capacitor provided that:
  i) the sum of DC voltage and superimposed AC Voltage dose not exceed the rated voltage.
  ii) rated ripple current is not exceeded.
- **Reverse voltage:** Aluminium electrolytic capacitors are polar capacitors. Reverse voltage $\leq$ 1.5V can be applied for a duration of less than 1 second, but not continuously or repeatedly. The reverse voltage of 1.5 V is the voltage at which the breakdown of the oxide layers on the cathode takes place. Where necessary a diode may be connected to prevent any reverse voltage from appearing on the capacitor.
- **Selection of current limiting resistor:**
  A current limiting resistor, which is to be connected in series with the capacitor, may be chosen as follows:
  a) for capacitors of rating up to 2500µF, the limiting resistor will be of 1000 ohms.
  b) for capacitors of rating higher than 2500µF, the value of current limiting resistor will be determined on the formula:

$$R = \frac{2.5 \times 10^6}{C}$$

  C = capacitance in µF
  R = resistor value in Ohms
- **Capacitance:** Capacitance can be measured by:
  i) measuring its AC impedance after taking into account amplitude and phase
  ii) measuring the charge it will hold when DC voltage is applied DC capacitance is approximately equal to 1.1 to 1.5 times AC capacitance

Notes: Measurement of capacitance is made at frequency of 100 Hz and ambient temperature of 25°C. The value is in microfarads (µF or MFD) and is indicated on the capacitor. Capacitance increases with temperature and decreases with increases in frequency.

- **Dissipation factor (Tan δ):** This is the ratio of ESR to capacitive reactance in the equivalent series circuit. Alternatively, it could be defined as the ratio of effective power (dissipated power) to the reactive power for a sinusoidal voltage:



$$\tan\delta = R_{ESR} \div \frac{1}{\omega C} = \omega C R_{ESR}$$

- **Equivalent series resistance (ESR):** The equivalent series resistance is the resistive component of equivalent series circuit. it is related to dissipation factor by the formula:

$$RESR = \frac{\tan\delta}{\omega C_s}$$

  RESR = equivalent series resistance in Ω
  Tanδ = dissipation factor
  Cs = series capacitance in Farads
  ω = 2πf (f=frequency)

  ESR values are measured by the bridge method (to eliminate the resistance of lead wires) at a frequency of 100Hz and ambient temperature of 25°C. ESR

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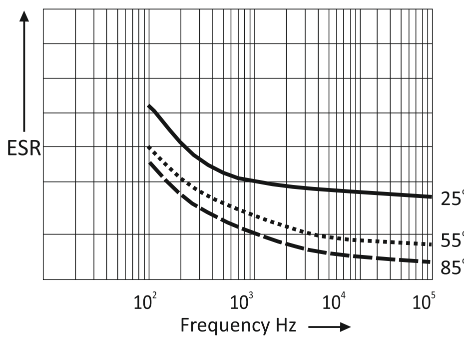
values decrease with increase in temperature and frequency:



- **Impedance:** Impedance is given by the formula:

Z = $\sqrt{ESR^2 + (X_L - X_c)^2}$

Z = impedance in Ohms

ESR = equivalent series resistance (Ω)

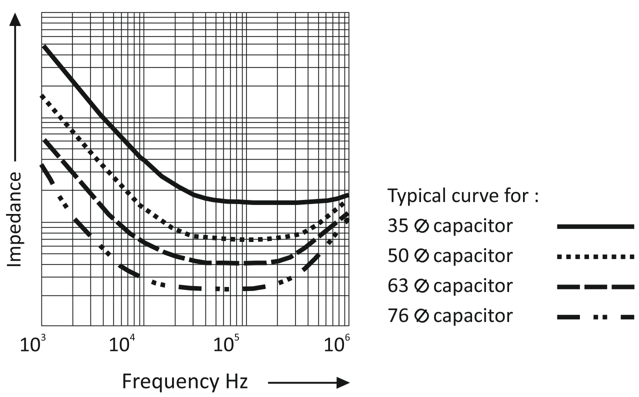
X_L = $2\pi f L$

X_c = $\frac{1}{2\pi f C}$

Impedance is dominated by capacitive reactance (Xc) at lower frequencies and by inductive reactance (XL) at higher frequencies. Resonance occurs when:

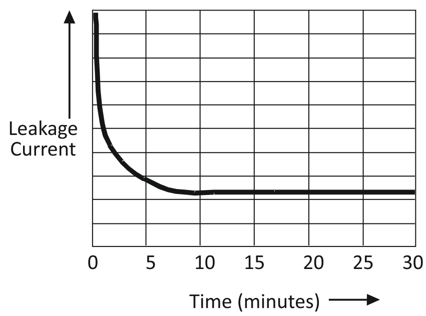
X_L = X_c at which Z = ESR

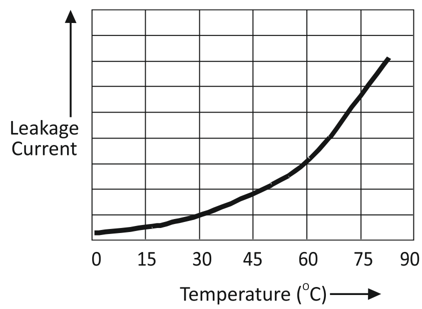
Impedance below resonance decreases with increase in temperature and frequency. However, impedance above resonance, decreases with temperature but increases asfrequency increases.



- **Leakage current:** Leakage current is the residual current which continues to flow through the capacitor even after the capacitor has been charged to the set voltage or rated voltage. After the capacitor has been fully charged to the set voltage, the leakage current will continue to fall with time until a steady state has been reached. Leakage current is a measure of the quality of the dielectric layer and is dependent on capacitance voltage and temperature. Measurement of leakage current is made at the rated DC voltage of the capacitor, which is applied from a steady source like a regulated power supply. A current limiting resistor must be connected in series with the capacitor under test.

Measurement is carried out at an ambient temperature of 25° C ± 3°C. The rated voltage is applied for 5 minutes before the leakage current measurement are taken:





- **Ripple current:** The ripple current rating of a capacitor is the rms value of AC current that flows through a capacitor due to the presence of ripple voltage. Ripple current generates heat inside the capacitor which is:

P = Ir^2xESR

p = power loss in watts

Ir = **rms** value or ripple current in Amperes

ESR = equivalent series resistance in Ohms

The maximum ripple current that a capacitor can handle depends on :

i) the winding design
ii) aluminium can design
iii) surface area of the can
iv) ESR

Since ripple current increases the temperature of the capacitor, it has a significant effect on the operational life of the capacitor. Ripple current handling capacity is dependent on frequency and temperature. Heat sinking and forced air cooling will aid heat transfer and allow higher ripple currents to be applied.

- **Shelf life:** Shelf life is defined as the times for which a capacitor can be stored without voltage being applied.

Normally the capacitance, ESR and impedance of a capacitor do not change significantly after extended storage period. However, the leakage current can slowly increase. The shelf life versus storage

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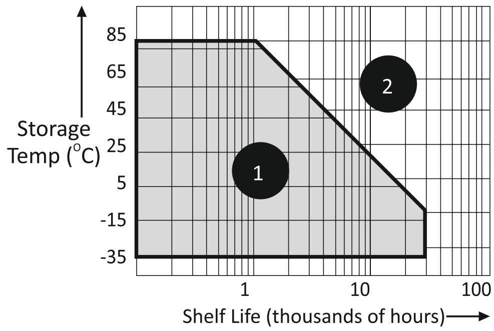
temperature graph is shown below:

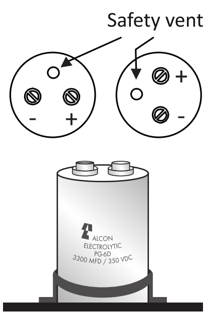


Region ❶ Leakage current remains unchanged
Region ❷ Leakage current increases
In both cases capacitance, ESR and impedance do not change significantly. If the capacitors are in region ❷, capacitors should be preconditioned prior to use. The procedure follows under, "preconditioning":

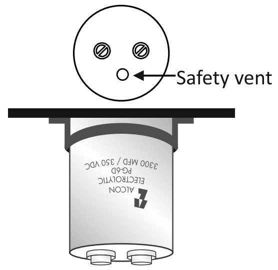
- **Preconditioning**: preconditioning is carried out by applying the rated working voltage across the capacitor. The power source should be a regulated power supply. A suitable current limiting resistor should be connected in series with the capacitor. The voltage should be maintained for one hour after its value has becomes equal to the rated working voltage applied $\pm$3%. After this, the capacitor should be discharge through a resistor of suitable value. The capacitor can now be stored idle for 12 to 24 hours. After this period, the capacitor can be tested for any of the specified parameters.

Application Notes

- **Mounting positions:** During operating, the leakage current of the capacitor will cause electrolysis of the electrolyte. The oxygen produced during electrolysis, helps in 'Self Healing' of the dielectric layer. The minute quantity of hydrogen released at this time, may increase the internal pressure in the capacitor over an extended period of time**.** All capacitors are provided with a safety vent, which punctures when the pressure inside the capacitor increase beyond the safe limit of 80 psi. Therefore, it is recommended that the capacitors be mounted upright or horizontal, with the vent on top, as shown:

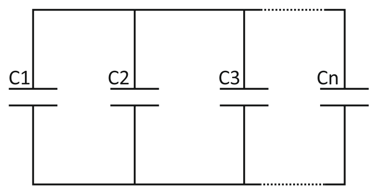


If capacitors are mounted with the safety vent at the lowest Position (shown below), a small pool of electrolyte may form near the safety vent. When the vent punctures, the electrolyte may spray out, on to other components, causing damage. Alternatively, the electrolyte may dry and crystallize inside the safety vent, over a period of time, making it non-functional.



- **Capacitor bank design**: capacitor may require parallel or series connections or both. This depends on the application.

Parallel connection

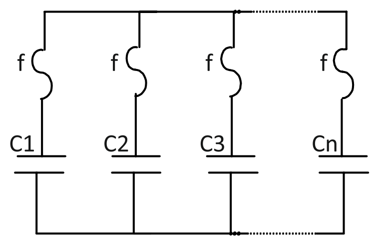


In a bank of 'n' capacitors connected in parallel, each with capacitance rating of C_1 C_2.........C_n and voltage rating V_1, V_2 ,....V_n, respectively, the effective capacitance and voltage of the bank will be:

C bank = $C_1 + C_2 + ... + C_n$
V bank = **minimum voltage rating of any capacitor in the bank**.

It is advisable to use capacitors of the same nominal capacitance value and voltage rating to avoid excessive stress on any one capacitor in the bank. In this circuit, if any capacitor in the bank fails due to an internal short circuit, then all the other capacitors in the bank will discharge through this particular capacitor, leading to an extremely abrupt and severe discharge phenomenon.

Hence it is advisable to connect these capacitors through a fuse:



f = fuse

For impulse discharge circuit, where it may not be feasible to use the fuses, the capacitors can be

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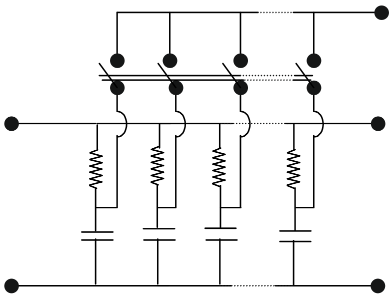
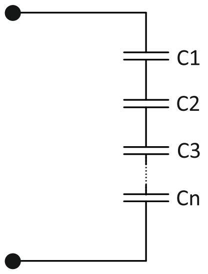
protected during charging by means of a suitable current limiting resistor and then connected in parallel at the time of discharge:



Series Connection

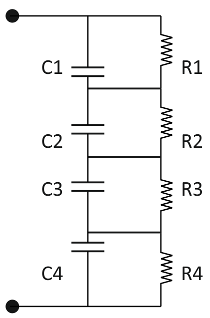


In the bank of 'n' capacitors connected in series, each with capacitance rating of C_1 C_2 ...... C_n and voltage rating V_1, V_2,.....V_n , respectively, the effective capacitance and voltage of the bank will be:

$$\frac{1}{C\ bank} = \frac{1}{C_1} + \frac{1}{C_2} + \ldots\ldots\ldots + \frac{1}{C_2}$$

$$V\ bank = V_1 + V_2 + \ldots\ldots\ldots\ldots + \ldots V_n$$

It is advisable to use capacitors of the same nominal capacitance value and voltage rating to avoid excessive stress on any one capacitor in the bank. When capacitors are connected in series, the voltage of any individual capacitor should not exceed the maximum permissible voltage. The total DC voltage applied is divided among individual capacitors in proportion to their insulation resistance value (leakage current). Hence to avoid any imbalance during charging of the bank, it is recommended that a shunt resistor be connected with each capacitor:



The value of the shunt resistance can be computed as follows:

A) $$R = \frac{nVr - Vb}{L.C.max \{(Vb / Vr) - ((n+9)/10)\}}$$

R : Shunt resistance value (minimum) in ohms
Vr : Rated voltage of each capacitor
n : Number of capacitors in($n \geq 2$)
Vb : Bank voltage
L. C. max : Maximum leakage current of one capacitor (in amp.)

B) Suggested wattage of resistor V^2r / R

Combined series-parallel connections Capacitors may be connected as follows:

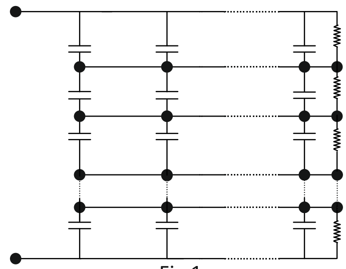


Fig 1

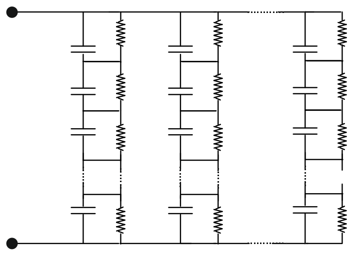


Fig 2

If one capacitor in the series bank (Fig.1) fails due to a short circuit, the other capacitors will be subjected to the total voltage. This may lead to an excess voltage on the other capacitors, causing all capacitors in the bank to fail. Hence it is recommended that capacitors are connected as shown in Fig 2, where only one "series bank" suffers the risk of failure, in the event of a short circuit of one capacitor.

- **Life Expectancy** : During the working life of capacitors, certain physical and parametric changes occur. These changes eventually make the capacitor unusable, either due to "thermal runaway" leading to catastrophic failure or an excessive parametric drift. At a higher temperature, degradation of the material, used to manufacture the capacitor, accelerates these effects. There are many reasons for these changes. Some performance aspects of the capacitors cannot be predicted. Hence evaluation of the capacitor's long term behavior must be determined by 'endurance' tests.

  Useful life (service life or operational life) is the life

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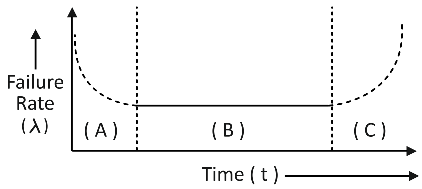
achieved by the capacitor without exceeding a specified failure rate. Useful life can be prolonged by operating the capacitors at load factors below the rated values specified, like lower operating voltage, ripple current and ambient temperature, Capacitor life can also be prolonged by appropriate cooling methods.

Failure percentage is the ratio of number of failures to total number of inspected capacitors. Failure rate(or long term failure)is the number of components failing per unit time. The characteristic curve is as follows:



Region A is the early failure period (or infant mortality), this can be decreased by improvement in the manufacturing process Region B is the useful life (operational life or service life) where failure rate is nearly constant Region C is the 'wear-out' period. This occurs due to the end of life of the capacitors and occurs when capacitor properties deteriorate. End of life of can be due to:

i) Catastrophic failure like short circuit, open circuit or operation of the safety vent
ii) Parametric failure like
   - ESR increases to more than thrice the initial specified limit
   - leakage current greater than specified maximum limit
   - capacitance changes of more than ±30%
   - a combination of these

Reliability is the probability that the capacitor will perform satisfactorily under given set of conditions for a given length of time. For calculation of useful life the components are taken from a normally manufactured batch. The components are tested under controlled conditions and the data for long term reliability is based on a confidence level of 55% . The figure can be taken only as a guide for reliability since actual working conditions are likely to deviate significantly from those used in routine testing. Meantime between failure (MTBF) is the inverse of failure rate

$$\textbf{MTBF} = \frac{1}{\lambda}$$

e.g. For given set of conditions

No. of components used in the field

N = 12,000

No. of operating hours to = 10.000 hrs

No. of failures n = 12

$$\text{Failures\%} = \frac{n}{N} = \frac{12}{12{,}000} = 0.1\% = F(\%)$$

$$\text{Failures rate } \lambda = \frac{F(\%)}{to} = \frac{0.1\%}{10{,}000} = 0.01\% / 1000\text{hours}$$

Forced Air Cooling

All capacitors are designed to ensure that heat from the core is transferred quickly and efficiently to the outer aluminium can. It is recommended that efficient air flow is created to enable the capacitor bank to remain at the lowest possible temperatures. This would increase the life expectancy of the capacitor. From the table given below it will be seen that the ripple current carrying capacity can be enhanced by increasing the air flow rate.

Ripple Current Multiplier
Air Flow Rate, metres per second (m/s)

Can Size (DxL) mm	< 1.0 m/s Free Convection	1.0 m/s Forced air cooling	2.5 m/s Forced air cooling	5.0 m/s Forced air cooling
35X62	1.00	1.15	1.37	1.54
35X80	1.00	1.15	1.18	1.51
35X105	1.00	1.14	1.33	1.46
50X80	1.00	1.15	1.37	1.55
50X105	1.00	1.14	1.34	1.49
50X120	1.00	1.14	1.33	1.47
63X105	1.00	1.15	1.35	1.51
63x120	1.00	1.14	1.33	1.47
63X145	1.00	1.13	1.32	1.45
76X105	1.00	1.15	1.36	1.52
76X120	1.00	1.15	1.36	1.52
76X145	1.00	1.14	1.32	1.46
76X177	1.00	1.08	1.32	1.37
76X220	1.00	1.12	1.27	1.38
90X105	1.00	1.15	1.37	1.54
90X120	1.00	1.15	1.35	1.51
90X145	1.00	1.14	1.33	1.47
90X220	1.00	1.12	1.27	1.38

Note : Above Ripple Current Multipliers are for Clamp Mounted Capacitors

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Precautions

- **Polarity:** Aluminium electrolytic capacitor are polar. Therefore, the capacitors should be connected accordingly. If the polarity of a capacitors is reversed, the capacitor will heat up and normally the safety vent will operate. In extreme cases there is possibility of an explosion and fire.
- **Mechanical stress:** During installation capacitors should not be mechanically damaged.
  - i) Capacitors have been designed with the can being negative. Hence damage to the insulation sleeve may causes a short circuit.
  - ii) The terminals of screw terminal type capacitors (AEST) are made of highly pure aluminium, the screw are made of brass or stainless steel which are a hard material. Hence mismatch of the threads during fitment can cause damage to the threads of the aluminium terminals. Also while connecting the screw terminals, the tightening torque

    For M5 threading : Maximum 2.5Nm (thread depth $\geq$ 8mm)

    For M6 threading : Maximum 4Nm (thread depth $\geq$ 9.5mm)
  - iii) Vibration resistance test : To IEC 60068-2-6, test Fc : Displacement amplitude 0-75 mm, frequency range 10... 55Hz, acceleration max. 10 g, duration 3 x 2 h. Capacitor mounted by its body which is rigidly clamped to the work surface.
- **Cleaning agents:** Halogenated hydrocarbons, if in contact with capacitor, may cause serious damage. These solvents may decompose the insulation sleeve and reduce insulating properties below permissible levels. Moreover, these may penetrate the capacitor through the capacitor seal leading to premature failure. Commonly used halogeneted hydrocarbons and other solvent which should not be used are freon, trichloroethylene, methylchloride, carbon tetrachloride, acetone, methyl ethyl ketone. Cleaning agents which normally do not have any detrimental effects are methanol, ethanol, propanol and isopropanol.
- **Operating conditions:** During operating, capacitors may fail due to the following:
  - i) Operating in very high ambient conditions.
  - ii) Surge voltage exceeds or surge voltage is applied for longer periods than specified.
  - iii) Voltage on the capacitor exceeds rated voltage
  - iv) Ripple current exceeds the specified values.
  - v) Reverse polarity.

  These can lead to catastrophic failure, with the possibility of an explosion and fire. Hence care should be taken during use. Also capacitors should be used in a well ventilated enclosure.
- **Exposure to electrolyte:** When an electrolyte comes in contact with skin, wash throughly with water. If electrolyte comes in contact with eyes, wash throughly with water and immediately seek medical advice.
- **Storage:** The following conditions for storage are recommended:
  - i) When not in use capacitors should be kept in their original packing.
  - ii) Capacitors should be stored indoors, away from direct sunlight, at a temperature of 5 to 35°C and a humidity level of less than 70%RH.
  - iii) Capacitors should be stored in an environment free from water, oil, salt water and gases like hydrogen sulphied. Keep away from other chemicals like sulfuric acid, hydrochloric acid, chlorine, ammonia or any corrosive environment.
  - iv) On storage, capacitors should not be subjected to severe mechanical shock or vibration, beyond specified limits.
- **Safety:** Due to the characteristics of electrolytic capacitor there can be a “rebound” voltage of up to of 40 to 50v even after the capacitor is discharged for a brief period. Therefore, it is necessary to ensure that the capacitor is totally discharge before using them, so that other sensitive components will not be affected.

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