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1.General Description of Aluminum Electrolytic Capacitors

1-1 The Principle of Capacitor

The principle of capacitance can be presented by the principle drawing as Fig.1-1.

When a voltage is applied between the metal electrodes placed opposite on the surfaces of a dielectric. electric charge can be stored proportional to the voltage.

Q=CV
Q: Quantity of electricity(C)
V: Voltage (V)
C: Capacitance (F)

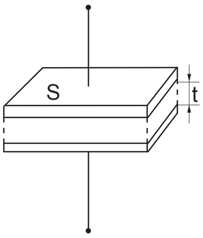

Fig. 1-1

C. called the capacitance of capacitor, is expressed by the following expression with the electrode area S [m^2], the electrode spacing t [m] and the dielectric constant of dielectric" ε " :

$$C[F]= \varepsilon_0 \cdot \varepsilon \cdot S/t$$

ε_0: Dielectric constant in vacuum (=8.85×10^{-12} F/M)
The dielectric constant of an aluminum oxide film is 7 to 8. Larger capacitances can be obtained by enlarging the electrode area S or reducing t.

Table 1-1 shows the dielectric constants of typical dielectrics used in the capacitor. In many cases, capacitor names are determined by the dielectric material used, for example, aluminum electrolytic capacitor, tantalum capacitor, etc.

Table 1

Dielectric	Dielectric Constant	Dielectric	Dielectric Constant
Aluminum oxide film	7 to 8	Porcelain(ceramic)	10 to 120
Mylar	3.2	Polystyrene	2.5
Mica	6 to 8	Tantalum oxide film	10 to 20

Although the aluminum electrolytic capacitor is small, it has a large capacitance. It is because the electrode area is roughened by electrochemical etching, enlarging the electrode area and also because the dielectric is very thin.

The schematic cross section of the aluminum electrolytic capacitor is as in Fig. 1-2

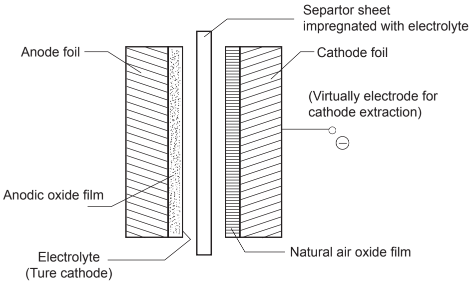

Fig. 1-2

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Structure of aluminum electrolytic capacitors
The aluminum electrolytic capacitor is mainly composed of a inside element, which is made up of an anode foil, a cathode foil and separator paper wound together and impregnated with an electrolyte, external terminals, which are connected to tabs drawn from anode and cathode foils, a can and sealing materials.

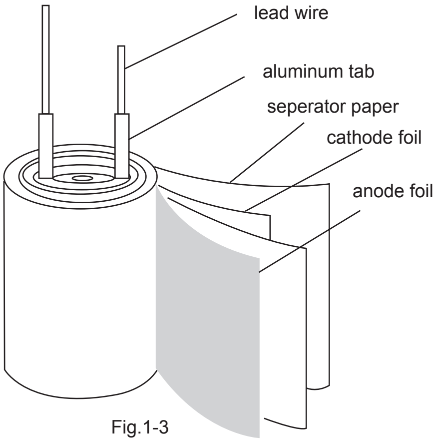

Fig.1-3

1-2 Equivalent Circuit of the Capacitor
The electrical equivalent circuit of the aluminum electrolytic capacitor is as presented in Fig.1-4

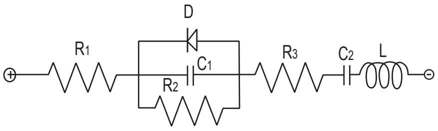

Fig. 1-4

R_1: Resistance of terminal and electrode
R_2: Resistance of anode oxide film and electrolyte
R_3: Insulation resistance because of defective anodic oxide film
D_1: Oxide semiconductor of anode foil
C_1: Capacity of anode foil
C_2: Capacity of cathode foil
L: Inductance caused by terminals, electrodes, etc.

1-3 Basic Electrical Characteristics
1-3-1 Capacitance:
The capacitance of capacitor is determined as AC capacitance by measuring its impedance. As the AC capacitance depends on frequency, voltage and other measuring methods. The capacitance of an aluminum electrolytic capacitor shows smaller values as a measuring frequency increases.
Measuring temperature as well as frequency effects the capacitance. As the measuring temperature decreases, the capacitance shows smaller values.
On the other hand, DC capacitance, which can be determined by measuring the charge when a DC voltage is applied, shows a slightly larger value than AC capacitance at a normal temperature and has the flatter characteristic over the temperature range.

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1-3-2 Tan δ (tangent of loss angle or dissipation factor):

The Tan δ is the ratio of the resistive component (R_{ESR}) to the capacitive reactance (1/ωC) in the equivalent series circuit, and its measuring conditions are the same as the capacitance.

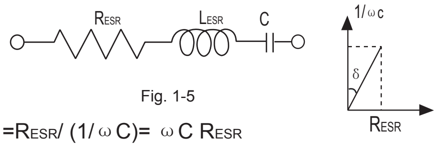

Fig. 1-5

$\tan\delta = R_{ESR}/(1/\omega C) = \omega C R_{ESR}$

where : R_{ESR}=ESR at 120Hz

$\omega = 2\pi f$

f=120Hz

The Tan δ shows higher values as a measuring frequency increases and a measuring temperature decrease.

1-3-3 Equivalent series resistance (ESR)

The ESR is comprised of the resistance due to aluminum oxide layer and electrolyte/separator combination and other resistance effected with foil length, foil surface area, etc.

The ESR value depends on the temperature. Dectreasing the temperature makes the resistivity of the electrolyte increase with the result of the ESR increasing.

As the measuring frequency increases, the ESR decreases and reaches an almost constant value that is mainly the frequency-independent resistance due to electrolyte/separator combination.

1-3-4 Impedance (Z):

The impedance is the resistance which opposes the flow of alternating current at a specific frequency. It is related to capacitance (C) and inductance (L) in terms of capacitive and inductive reactance, and also related to the ESR. It is expressed as follows:

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

Where: $X_C = 1/\omega C = 1/2\pi fC$

$X_L = \omega L = 2\pi fL$

1-3-5 Leakage current:

The dielectric of a capacitor has a very high resistance which prevents the flow of DC current. However, due to the characteristics of the aluminum oxide layer that functions as a dielectric in contact with electrolyte, a small amount of current, called leakage current, will flow to reform and repair the oxide layer while a voltage is being applied. A high leakage current flows in the first minutes as a voltage is applied to the capacitor, and then the leakage current will decrease and reach an almost steady-state value with time.

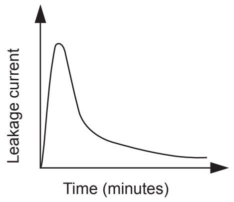

Fig. 1-6 Leakage current vs. Time

Measuring temperature and voltage affect the leakage current. The leakage current shows higher values as the temperature and voltage increase.

2 About the Life of an Aluminum electrolytic Capacitor

2-1 Estimation of life with minimal ripple current (negligible).

Generally, the life of an aluminum electrolytic capacitor is closely related with its ambient temperature and the life will be approximately the same as the one obtained by Arrhenius' equation.

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$$L=L_o\times 2^{\left(\frac{T_o-T}{10}\right)} \text{---------}(1)$$

Where L: Life at temperature T

L_o: Life at temperature T_o

The effects to the life by derating of applied voltage etc. are neglected because they are small compared to that by the temperature.

2-2 Estimation of life considering the ripple current.

The ripple current affects the life of a capacitor because the internal loss (ESR) generates heat. The generated heat will be:

$P=I^2R \cdots\cdots\cdots\cdots\cdots\cdots (2)$

Where I: Ripple current (Arms)

R: ESR (Ω)

With increase in the temperature of the capacitor:

$$\triangle T=\frac{I^2R}{A\cdot H} \text{---------}(3)$$

Where △T: Temperature increase in the capacitor core (deg.)

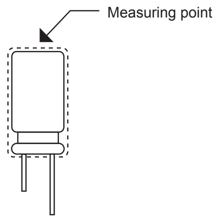
I: Ripple current (Arms)

R: ESR (Ω)

A: Surface area of the capacitor (cm^2)

H: Radiation coefficient (Approx. $1.5\sim2.0\times10^{-3}W/cm^2\times$℃)

The above equation (3) shows that the temperature of a capacitor increase in proportion to the square of the applied ripple current and ESR, and in inverse proportion to the surface area. Therefore, the amount of the ripple current determines the heat generation, which affects the life. The value of △T varies depending on the capacitor types and operating conditions. The usage is generally desirable if △T remains less than 5℃. The measuring point for temperature increase due to ripple current is shown below;



Test results:

(1) The life equation considering the ambient temperature and the ripple current will be:

$$L=L_0\times 2^{\left(\frac{T_0-T}{10}\right)}\times K^{\left(\frac{-\triangle T}{10}\right)} \text{---------}(4)$$

Where L_0: Life at DC operation (h)

K: Ripple acceleration factor

(K=2, if with in allowable ripple current)

(K=4, if exceeding allowable ripple current)

T_0: Maximum guaranteed temperature (℃)

T: Operating temperature (℃)

△T: Temperature increase at capacitor core (deg.)

(2) The life equation based on the life with the rated ripple current applied under the maximum guaranteed temperature will be a conversion of the above equation (4), as below:

$$L=L_0\times 2^{\left(\frac{T_0-T}{10}\right)}\times K^{\left(\frac{\triangle T_0-\triangle T}{10}\right)} \text{---------}(5)$$

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Where L_0: Life at the maximum guaranteed temperature with the rated ripple current (h)

$\triangle T_0$: Temperature increase at capacitor core, at the maximum guaranteed temperature (deg.)

(3) The life equation considering the ambient temperature and the ripple current will be a conversion of the above equation (5), as below:

$$L=L_0 \times 2^{\left(\frac{T_0-T}{10}\right)} \times K^{\left[1-\left(\frac{I}{I_0}\right)^2\right] \times \frac{\triangle T_0}{10}} \text{ - - - - - - - - - -(6)}$$

Where in I_0: Rated ripple current at the maximum guaranteed temperature (Arms)

I: Applied ripple current (Arms)

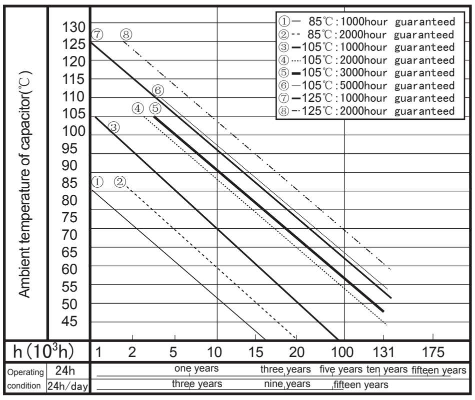
Since it is actually difficult to measure the temperature increase at the capacitor core, the following table is provided for conversion from the surface temperature increase to the core temperature increase.

Table 2-1

Case diameter	~10	12.5~16	18	22	25	30	35
Core/Surface	1.1	1.2	1.25	1.3	1.4	1.6	1.65

The life expectancy formula shall in principle be applied to the temperature range between the ambient temperature of +40℃ and maximum allowable working temperature. The expected life time shall be about fifteen years at maximum as a guide in terms of deterioration of the sealant.

(Fig 2-1Life Expectancy Chart)



3 To calculate Balance when connecting in series

3-1 Circuit layout

Circuit for connecting two capacitors (C_1, C_2) in series and equivalent circuit can be illustrated as below figure. Formula to calculate a balance resistance R_B of below figure is shown as follows.

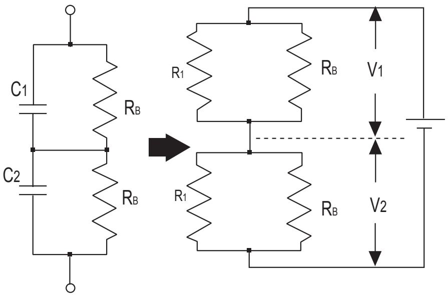


Fig. 3-1

Following are the preconditions of the circuit.

① V_2 shall be the rated voltage ($=V_0$).

② V shall be a times V_0x2, $V=2aV_0$ (a<1)

③ R_2 shall equal R_1xb (b>1) (1)

3-2 Formulas to calculate [RB]

3-2-1 Following formula can be established from balanced condition

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$$V_1 \left[\frac{1}{R_1}+\frac{1}{R_B}\right]=V_2 \left[\frac{1}{R_2}+\frac{1}{R_B}\right] \quad (2)$$

3-2-2 Following formula can be established from preconditions.

$V_2 \leqslant V_0$ (3)

$V_1=V-V_2$ (4)

$=2aV_0-V_2$ (4')

3-2-3 Put formulas (1,), (3) and (4') in formula (2).

$$(2aV_0-V_2)\left[\frac{R_1+R_B}{R_1 \cdot R_B}\right]=V_2\left[\frac{bR_1+R_B}{bR_1 \cdot R_B}\right]$$

$2abV_0(R_1+R_B)=V2\ \{b\ (R_1+R_B)+bR_1+R_B\}$

$2ab(R_1+R_B) \leqslant 2b\ R_1+(1+b)\ R_B$

Accordingly, balance resistance Rs shall be the following formula.

$$R_B \leqslant 2b\ R_1 \frac{(1-a)}{(2a-1)\cdot b-1}$$

3-3 Calculation Example

Calculation the value of the balance resistance in the case of connecting two 400V 470μF (LC standard value: 1.88mA) capacitors in series.

$$R_1=\frac{400(V)}{1.88(mA)}=2.13(K\Omega)$$

If a=0.8, 400(V) x2x0.8=640(V) as an impressed voltage.

If b=2, R_2=b R_1=426(KΩ), LC=0.94(mA).

Balance resistance R_B will be:

$$R_B \leqslant 2x2x213(K\Omega)\frac{1-0.8}{(2x0.8-1)x2-1}=852(K\Omega)$$

4 Regarding Recovery Voltage

After charging and then discharging the aluminum electrolytic capacitor, and further causing short-circuit to the terminals and leave them alone, the voltage between the two terminals will rise again after some interval. Voltage caused in such case is called recovery voltage. Following is the process that causes this phenomenon:

. When the voltage is impressed on a dielectric, electrical transformation will be caused inside the dielectric due to dielectric action, and electrification will occur in positive-negative opposite to the voltage impressed on the surface of the dielectric. This phenomenon is called polarization action.

. After the voltage is impressed with this polarization action, and if the terminals are discharged till the terminal voltage reaches 0 and are left open for a while, an electric potential will arise between the two terminals and thus causes recovery voltage.

. Recovery voltage comes to a peak around 10 to 20 days after the two terminals are left open, and then gradually declines. Recovery voltage has a tendency to become bigger as the component (stand-alone base type) becomes bigger.

. If the two terminals are short-circuit after the recovery voltage as generated, a spark may scare the workers working in the assembly line, and may put low-voltage driven components (CPU, memory, etc) in danger of being destroyed. Measures to prevent this is to discharge the accumulated electric charge with resistor of about 100 to 1KΩ before using,or ship out by making the terminals in short-circuit condition by covering them with an aluminum foil at the production stage. Please consult us for adequate procedures.

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5 Reliability
5-1 The bathtub curve:
Aluminum electrolytic capacitors feature failure rates shown by the following bathtub curve.

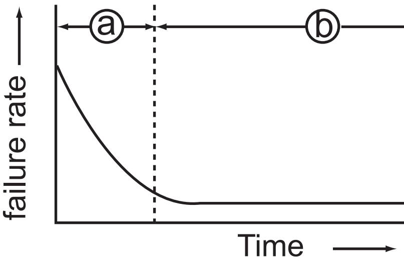

Fig. 5-1 bathrub curve

a) Infant failure period
This is a period during which failures are caused by deficiencies in design, structure, manufacturing process or severe misapplications. Such failures occur soon after the components are exposed to circuit conditions. In aluminum electrolytic capacitors, these failures are either corrected through aging process reforming or repairing a damaged oxide layer, or found by the aging process, removed by the sorting process, and thus do not reach the field.
Infant failures due to capacitor misapplication such as inappropriate ambient comditions, over-voltage, reverse voltage or excessive ripple current can be avoided with proper circuit design and installation.

b)Useful life period
This is a random failure period during which the failure rate is the lowest. These failures are not related to operating time but to application conditions. During this period, non-solid aluminum electrolytic capacitors show a slow decrease in capacitance and a slow increase in tan δ and ESR, which are caused by a small loss of electrolyte, and feature fewer catastrophic failures than semiconductors and solid tantalum capacitors.

c)Wear-out failure period
This is a period during which the properties of a component extremely deteriorate, and the failure rate increases with time. Non-solid aluminum electrolytic capacitors end their useful life during this period.

5-2 Failure types:
The two types of failures are classified as catastrophic failures and wear-out failures as follows,
① Catastrophic failure
Like a short circuit or open circuit failure, this is a failures mode which destroys the function of the capacitor.
② Wear-out failure
This is a failure mode resulted by the gradual deterioration of the capacitor electrical parameters. The criteria for judging the failures varies with application and design factors.
Capacitance decrease and tan δ increase are caused by the loss of electrolyte in the wear-out failure period. This is due primarily to loss of electrolyte by diffusion(as vapor)through the sealing material. Gas molecules can diffuse out through the material of the end seal. If the electrolyte vapor pressure within the capacitor is increased, by high temperatures for example, the diffusion rare is increased. Swelling of the seal material by electrolyte vapor pressure may also occur at elevated temperature.This swelling may further enhance diffusion and mechanically weaken the seal.

5-3 Failure modes:
Aluminum electrolytic capacitors show various failure modes in different applications.(see table below.)

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6 Electrical behaviour

Characteristics of electrical capacitors vary wity temperature, time, and applied voltage.