1. Overview of Aluminum Electrolytic Capacitors

1-1 Basic Model of Aluminum Electrolytic Capacitors

Capacitors are passive components. Among the various kinds of capacitors, aluminum electrolytic capacitors offer larger CV product per case size and lower cost than the others. In principles of capacitor, its fundamental model is shown in Fig. 1 and its capacitance \( C \) is expressed by Equation (1) below:

\[
C = \frac{\varepsilon S}{d} \left( \text{F} \right)
\]

where:
- \( \varepsilon \) : Dielectric constant
- \( S \) : Surface area of dielectric (m²)
- \( d \) : Thickness of dielectric (m)

Equation (1) shows that the capacitance \( C \) increases as the dielectric constant \( \varepsilon \) and/or its surface area \( S \) increases and/or the dielectric thickness \( d \) decreases.

An aluminum electrolytic capacitor comprises a dielectric layer of aluminum oxide \( (\text{Al}_2\text{O}_3) \), the dielectric constant \( \varepsilon \), which is 8 to 10. This value is not significantly larger than those of other types of capacitors.

However, by extending the surface area \( S \) of the aluminum foil electrode by means of etching, and by electrochemically forming a thinner but highly voltage-withstandable layer of oxide layer dielectric, the aluminum electrolytic capacitor can offer a larger CV product per case than other types of capacitors.

A basic model of aluminum electrolytic capacitor is shown in Fig. 2. An aluminum electrolytic capacitor comprises:
- Anode: Aluminum foil
- Dielectric: Electrochemically formed oxide layer \( (\text{Al}_2\text{O}_3) \) on the anode
- Cathode: A true cathode is electrolytic solution (electrolyte).

Other component materials include a paper separator that holds electrolyte in place and another aluminum foil that functions as a draw-out electrode coming into contact with the true cathode (electrolyte). In general, an aluminum electrolytic capacitor is asymmetrical in structure and polarized. The other capacitor type known as a bi-polar (non-polar) comprises the anodic aluminum foils for both electrodes.

Fig-1 Basic model of capacitor

Fig-2 Basic model and equivalent circuit of aluminum electrolytic capacitor

1-2 Structure of Aluminum Electrolytic Capacitor

1) The aluminum electrolytic capacitor has, as shown in Fig. 3, a roll of anode foil, paper separator, cathode foil and electrode terminals (internal and external terminals) with the electrolyte impregnated, which is sealed in an aluminum can case with a sealing material. The terminal draw-out structure, sealing material and structure differ depending on the type of the capacitor. Figure 4 shows typical examples.

Fig-3 Basic model of element

Fig-4 Construction of Aluminum Electrolytic Capacitors

1-3 Features of Capacitor Materials

Aluminum, which is main material in an aluminum electrolytic capacitor, forms an oxide layer \( (\text{Al}_2\text{O}_3) \) on its surface when the aluminum is set as anode and charged with electricity in electrolyte. The aluminum foil with an oxide layer formed thereon, as shown in Fig. 5, is capable of rectifying electric current in electrolyte. Such a metal is called a valve metal.
First, the foil material is electromechanically etched in a chloride solution to extend the surface area of the foil. Secondly, for the foil to form an aluminum oxide layer ($\text{Al}_2\text{O}_3$) as a dielectric, more than the rated voltage is applied to the foil in a solution such as ammonium borate. This dielectric layer is as dense and thin as $1.1 - 1.5 \text{ nm/volt}$ and showing a high insulation resistance ($10^8 - 10^9 \Omega \text{m}$). The thickness of the oxide layer determines withstand voltage according to their direct proportional relationship. For the etching pits to be shaped to the intended thickness of the oxide, the pit patterns have been designed to have efficient surface area extension depending on the intended withstand voltage (see Fig. 6).

An etching process is performed to the cathode aluminum foil as well as the anode foil. However, the formation process for oxide layer is generally not performed. Therefore, the surface of the cathode foil only has an oxide layer ($\text{Al}_2\text{O}_3$) that has spontaneously formed, which gives a withstand voltage of about 0.5 volt.

The electrolyte, an ion-conductive liquid functions as a true cathode coming into contact with the dielectric layer on the surface of the anode foil. The cathode foil serves as a collector electrode to connect the true cathode with the external circuit. Electrolyte is an essential material that controls the performance of the capacitor (temperature characteristics, frequency characteristics, service life, etc.).

The separator maintains uniform distribution of the electrolyte and keeps the anode-to-cathode foil distance unchanged.

An aluminum can case and seal materials mainly consisting of rubber are used for the purpose of keeping airtightness.

This etching process serves to extend the surface area of the aluminum foil. This is an AC or DC current-employed electrochemical process for etching the foil surface in a chloride solution (see Fig. 7).

This is a process for forming a dielectric layer ($\text{Al}_2\text{O}_3$), which is normally performed on the anode aluminum foil (see Fig. 8).

This is a process for slitting aluminum foils (both the anode and cathode) and paper separators to the specified product size (see Fig. 9).

This is a process for rolling a set of anode and cathode foils into a cylindrical form with a paper separator inserted between them. During this process, an inner terminal (called a tab) is attached to each of the aluminum foils. The roll made at this process is called a capacitor element.

This is a process for impregnating the element with electrolyte as a true cathode. The electrolyte also functions to repair the dielectric layer (see Fig. 11).

This process seals the element using the aluminum can case and sealing materials (rubber, rubber-lined cover, etc.) for keeping the case airtight (see Fig. 12).

After the aging, all products shall undergo testing for checking their electrical characteristics with chip termination, lead reforming, taping etc. finished, and then be packaged.

Outgoing inspections are performed as per standard inspection procedures.

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Proper Usage Methods of Liquid Aluminum Electrolytic Capacitor
2-1 Basic Electrical Characteristics
2-1-1 Capacitance

The larger the surface area of an electrode is, the higher the capacitance (capacity for storing electricity) is. For aluminum electrolytic capacitors, the capacitance is measured under the standard measuring conditions of 20°C and a 120Hz AC signal of about 0.5V. Generally, as the temperature rises, the capacitance increases; as the temperature decreases, the capacitance decreases (Fig. 13). With a higher frequency, the capacitance is smaller; with a lower frequency, the capacitance is larger (Fig. 14).

2-1-2 Tanδ (also called tangent of loss angle or dissipation factor)

(Fig. 15) is a simplified model of the equivalent circuit shown in (Fig. 2). For an ideal capacitor with an equivalent series resistance of $R = 0$, the tanδ shown in (Fig. 10) is zero. For an aluminum electrolytic capacitor, the equivalent series resistance ($R$) is not zero due to the presence of resistance of the electrolyte and paper separator and other contact resistances. $1/\omega C$ and $R$ are correlated as shown in (Fig. 16) and Equation (2).

2-1-3 Leakage Current (LC)

① As a feature of an aluminum electrolytic capacitor, when DC voltage is applied to it, the oxide layer that acts as a dielectric in the electrolyte allows a small amount of electric current to flow in it. The small amount of current is called a leakage current (LC). An ideal capacitor does not allow the leakage current to flow (this is not the case for charging current).

② The leakage current (LC) changes with time as shown in (Fig. 18). Therefore, the specifications of LC are defined as a value of the rated voltage at 20°C. As the temperature rises, the LC increases; as the temperature decreases, the LC decreases (Fig. 19). As the applied voltage decreases, the LC decreases.

2-2 Frequency Characteristics of Impedance (Z)

① When a capacitor is applied with a voltage with the frequency changed, the impedance ($Z$), a factor of preventing the AC current changes as shown in (Fig. 14). This is the impedance-frequency characteristics of the capacitor.

② (Fig. 15) is a simplified model of an equivalent circuit of an aluminum electrolyte capacitor. (Fig. 20) shows dotted lines representing a breakdown of the impedance-frequency characteristic curve into components (C, R and L). As can be seen in this figure, the impedance-frequency characteristics are a composition of C, R and L frequency characteristics.
### 3. Reliability

For designing the device with aluminum electrolytic capacitors, a failure rate and useful life are necessary to be considered for their reliability. The failure rate of aluminum electrolytic capacitors is approximated by the bathtub curve shown in (Fig.23).

#### a. Early failure period

At the comparatively early periods of use, devices/components fail by deficiencies in design or manufacturing process or incompatibility with operation conditions. For aluminum electrolytic capacitors, these defectives are removed by debugging at one of manufacturing processes before shipments.

#### b. Random failure period

Failure is stable low in occurrence and appears unrelated to their served term. Aluminum electrolytic capacitors are low in catastrophic failures in this period compared with semi-conductors and solid tantalum capacitors.

#### c. Wear-out failure period

In this period, the failure rate increases with the served time. For aluminum electrolytic capacitors, since they were completed in manufacturing, the electrolyte impregnated has gradually evaporated and diffused out of the capacitors through the rubber seal materials with time, which leads to decrease in the capacitance and/or increase in tanδ. When any of these values changes beyond the allowable range of specifications, the capacitors are defined as "fell into the wear-out failure". The served term until the capacitors fall into the wear-out failure period is called a useful life.

### 4. Failure Modes

Aluminum electrolytic capacitors have two categories of failures: catastrophic failure and wear-out failure.

**<Catastrophic failure>**

This is a failure mode that completely destroys the function of the capacitor such as short circuit and open circuit failure

**<Wear-out failure>**

This is a failure mode where the electrical parameters of the capacitor gradually deteriorate and fail. The criteria for determining if this failure has occurred depend on the purpose of a device.

For each series of capacitors, the following electrical parameters have been defined as criteria in the specifications of Endurance in the catalogs or product specifications:

- Change in capacitance
- tanδ
- Leakage current

**①** Failure rates are often measured in units of % per 1000 hours (10^{-5}/hour). For higher reliability devices designed with a smaller failure rate, units of Failure In Time (FIT) (10^{-9}/hour) is used.

**②** Aluminum electrolytic capacitors are considered as components of wear-out failure mode, the electrical characteristics of which gradually deteriorate and their failure rate increases with time. In general, the failure rate in FIT is determined by total component-
5. Circuit Design

1) Operating Temperature, Equivalent Series Resistance(ESR), Ripple Current and Load Life

MTTF (Mean-Time-TO-Failure) means the useful life at room temperature 25°C.

1-1 Load life:
If the capacitor's max. operating temperature is at 105°C (85°C), then after applying capacitor's rated voltage (MV) for 1hr hours at 105°C (85°C), the capacitor shall meet the requirements in detail specification. where L0 is called "load life" or "useful life (lifetime) at 105°C (85°C)".

\[ L_x = L_0 \times x^{(T_0-Tx)/10} \times K \times (To-Tx)/15 \]

where \( T_0 =\) Temperature 25°C, \( T_x =\) Temperature of capacitor case for applying \( I_x \)

1-2 Ripple life:
If the capacitor's max. operating temperature is at 105°C (85°C), then after applying capacitor's rated voltage (MV) with the ripple current for 1hr hours at 105°C (85°C), the capacitor shall meet the requirements in detail specification. where Lr is called "ripple life" or "useful ripple life(ripple lifetime)" at 105°C (85°C)".

\[ L_x = L_r \times x^{(T_0-Tx)/10} \times K \times (To-Tx)/10 \]

where \( T_0 =\) Maximum temperature \( 85°C \), \( T_x =\) Temperature of capacitor case for applying \( I_x \)

The formula of ESR:

\[ ESR = \frac{DF}{2\pi f C} \quad \text{……(2)} \]

Where:
- \( DF: \) Dissipation Factor (tanδ)
- \( f: \) Operating frequency (Hz)
- \( C: \) Capacitance (F)
- \( ESR: \) Equivalent Series Resistance (Ω)

The operating frequency of ESR, DF, f & C must be the same, usually they test at 120 Hz.

ESR = DF / 2πf C  \quad \text{……(2)}

Where DF: Dissipation Factor (tanδ) f: Operating frequency (Hz)

1) Ripple Current calculation: no need Temperature Multiplying Factor.

\( L_x = \) Expected ripple life period (hrs) at actual operating temperature
\( T_r = \) Maximum operating temperature (°C) allowed
\( T_x = \) Actual operating ambient temperature (°C)
\( I_x = \) Actual applied ripple current (mArms) at operating frequency
\( f_0 = \) Frequency multiplier (Cf) at f0 (Hz)

\( L_0 = \) Rated maximum permissible ripple current IR (mArms) x frequency multiplier (Cf) at f0 (Hz)

For Ripple current, \( I_x \) Should be 80% equal or more of \( I_0 \), if less than 80%, calculate with 80%.

\( T_0 = 85°C \) Maximum temperature rise (°C) for applying \( I_0 \) (mArms)

\( T_x = \) Temperature rise (°C) of capacitor case for applying \( I_x \) (mArms)

\( K_x = \) Transfer coefficient between element and case of capacitor

\[ L_x = \text{Expected life period (hrs)} \quad \text{at actual operating temperature} \]

\[ T_r = \text{Maximum operating temperature (°C)} \quad \text{allowed} \]

\[ T_x = \text{Actual operating ambient temperature (°C)} \]

\[ I_x = \text{Actual applied ripple current (mArms) at operating frequency} \]

\[ f_0 = \text{Frequency multiplier (Cf) at f0 (Hz)} \]

The estimated life is limited to 15 years, if it exceeds 15 years, take 15 years as standard.

\( K_c = \) Capacitance (F)

\( \text{ESR} = \) Equivalent Series Resistance (ESR)

\( \text{DF} = \) Dissipation Factor (tanδ) f: Operating frequency (Hz)

The operating frequency of ESR, DF, f & C must be the same, usually they test at 120 Hz.

\( \text{ESR} = \text{DF} / 2\pi f C \quad \text{……(2)} \)

Where:
- DF: Dissipation Factor (tanδ)
- f: Operating frequency (Hz)
- C: Capacitance (F)

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