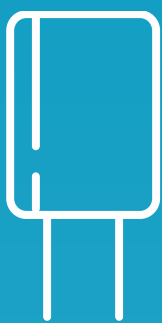
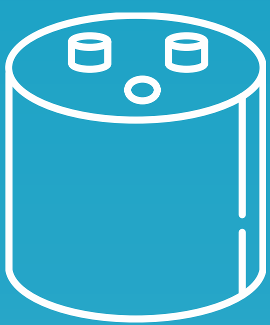
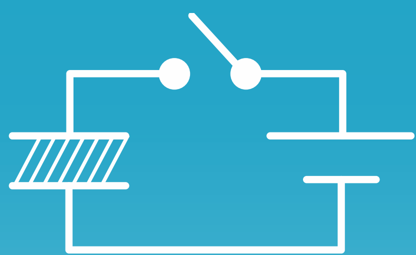
『For correct understanding and safe use』

The Three Essential Characteristics of Capacitors



- Capacitance
- Impedance
- DC Leakage current





AIC tech Inc.

The Three Essential Characteristics of Capacitors

Capacitors are one of the most fundamental and important components in electrical and electronic circuits. Therefore, it is very important for engineers responsible for circuit design, equipment maintenance, and quality to acquire knowledge of the characteristics and properties of capacitors. Capacitors have a wide range of characteristics. However, since these characteristics vary depending on the electrical conditions and environment in which the capacitor is used, it is difficult to accurately understand the characteristics from limited media such as specification sheets and data sheets. A correct understanding of the characteristics of capacitors will lead to safe use of capacitors. This paper explains the basic knowledge of capacitor characteristics with specific examples and data.

CONTENTS

Helpful TIPS

1 CAPACITANCE

1.1 Definition : The ability to store an electric charge

When conductive plates such as metals are placed parallel to each other in a vacuum and a voltage is applied, different and equal amounts of electric charge Q accumulate on the plates. At this time, an electric field is created in the space between the plates (Figure 1-01)[*1-01,1-02].The magnitude of this electric field, E, is expressed by (1-01) as the quotient of the voltage V applied between the plates and the distance d between the plates.

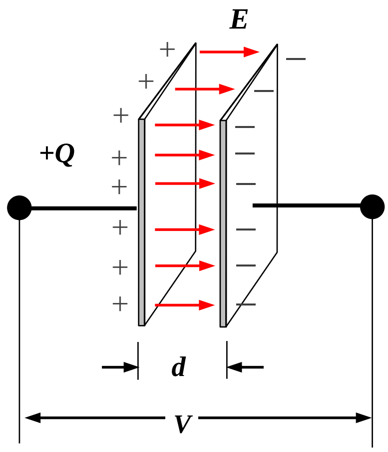


Fig. 1-01. Electric charge Q and electric field strength E

$$E = \frac{V}{d} \quad \cdots \quad (1\text{-}01)$$

E : magnitude of this electric field
V : applied voltage
d : distance between the plates

The electric field can be thought of as a vector of lines of electric force, which emanate from a positive charge and go toward a negative charge, and the flat plate emits lines of electric force of Q / ε_0 [lines] [*1-03] . Since the area density of the lines of electric force is equal to the magnitude of the electric field, if the area of the flat plate is S [m^2], the relationship is as in Equation (1-02), and the charge Q on the flat plate accumulated by the power supply is expressed in Equation (1-03), indicating that the parallel plate has the function of storing electric charge.

$$\frac{V}{d} = \frac{\left(\frac{Q}{\varepsilon_0}\right)}{S} \quad \cdots \quad (1\text{-}02)$$

$$Q = \frac{\varepsilon_0 \times S \times V}{d} \quad \cdots \quad (1\text{-}03)$$

V : applied voltage
C : capacitance
Q : electric charge
ε_0 : permittivity of vacuum
S : area of the flat plate
d : distance between the plates

*1-01
Electric charge is the amount of electricity a charged object has. More electrons compared to protons equals - and less electrons equals +. The symbol is Q and the unit is expressed in C (coulomb).

*1-02
An Electric field can be considered an electric property associated with each point in the space where a charge is present in any form.
It is represented by a vector because of its magnitude and direction.
An electric field is also described as the electric force per unit charge. Electric fields are usually caused by varying magnetic fields or electric charges. Electric field strength is measured in the SI unit volt per meter (V/m).

*1-03
This is an equation based on Gauss's law. Gauss's law is one of Maxwell's equations. In a medium with dielectric constant ε, the number of lines of electric force perpendicular to a closed surface is proportional to the total amount of electric charge Q in the closed surface and is equal to Q/ε
https://physnotes.jp/em/gauss-law/

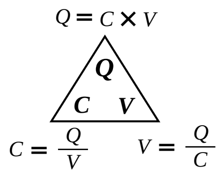
The value obtained by dividing the charge Q by the applied voltage V indicates the amount of charge per unit voltage (Equation (1-04)) [*1-04], and this value is called **capacitance** as a physical quantity that indicates the ability to store an electric charge. The capacitance C_0 of a parallel plate capacitor in a vacuum is expressed by Equation (1-05).

$$\frac{Q}{V} = C_0 \qquad \cdots \quad (1\text{-}04)$$

$$C_0 = \frac{Q}{V} = \frac{\varepsilon_0 \times S}{d} \qquad \cdots \quad (1\text{-}05)$$

*1-04

The relationship between charge Q, voltage V, and capacitance C can be shown by the following triangle



The relationship between the charge Q, voltage V, and capacitance C can be explained by imagining the capacitor as a water tank (tank). This is called "Water Tank Analogy." In Figure 1-02, the water storage capacity W of a tank is the product of the tank's bottom area S and the water level h. Considering the water storage volume as an electric charge and the water level as a voltage, the capacitance can be interpreted as the bottom area of the tank, Equations (1-06, 1-07). That is, the stored charge Q is proportional to the voltage V, and its proportionality constant is the capacitance C.

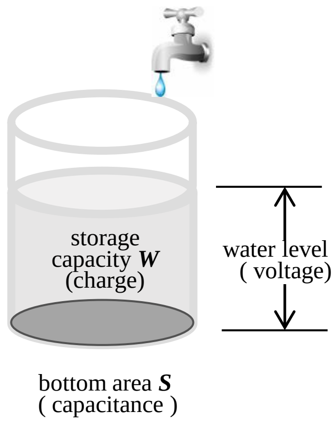


Fig. 1-02 Water Tank Analogy

Storage Capacity		Bottom Area		Water Level		
W	$=$	S	$\times$	h	$\cdots$	(1-06)
Electric Charge		**Capacitance**		**Voltage**		
Q	$=$	C	$\times$	V	$\cdots$	(1-07)

Key Takeaway

- **Capacitance is a physical quantity that the ability to store an electric charge.**
- **The stored charge Q is proportional to the voltage V, and its proportionality constant is the capacitance C.**

Helpful TIPS 1

<<<<< The Energy Stored in a capacitor >>>>>

When an external charge dQ applied to a capacitor, its terminal voltage rises (dV) and energy dU is stored in the capacitor. If the voltage is V when the capacitor is charged until the charge reaches Q, the energy U stored in the capacitor can be expressed as the product of voltage and charge using equation (1-08). This is illustrated in Figure 1-03.

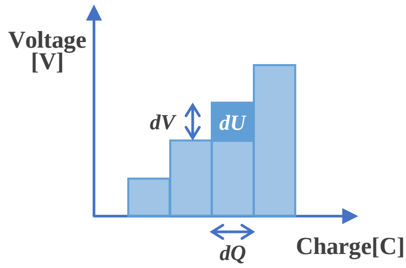


Fig. 1-03
Charge versus voltage

$$U = \int_0^Q VdQ \qquad \cdots \quad (1\text{-}08)$$

Using equation(1-07), dQ can be expressed as equation(1-09). So, the energy stored in a capacitor is proportional to its capacitance and the square of voltage（equation(1-10)）。

$$dQ = C \times dV \qquad \cdots \quad (1\text{-}09)$$

$$U = C\int_0^V VdV \qquad \cdots \quad (1\text{-}10)$$

$$= \frac{1}{2}CV^2$$

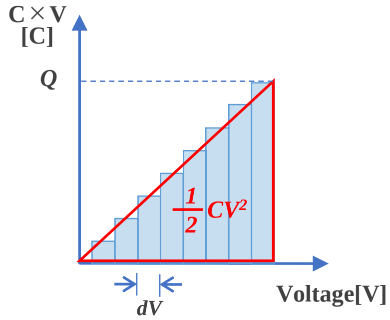


Fig. 1-04
Energy stored in a capacitor

1.2 Dielectric : An insulator with dielectric polarization

A real capacitor has an insulator called a "dielectric," and the properties of the dielectric affect many of the characteristics of the capacitor.

(1) Dielectric and dielectric polarization

When an insulator is placed between the electrodes of a parallel plate capacitor and a voltage V is applied, the insulator is exposed to the electric field between the electrodes.

Although no current flows when voltage is applied to the insulator, the electric field causes the atoms of the insulator to separate into positively charged and negatively charged parts[*1-05] (Figure 1-05).

In other words, an external electric field E $(=V/d)$ induces an electric field in the insulator that is opposite to the external electric field, and electrical energy is stored. This phenomenon is called **dielectric polarization**, and the induced electric field is called the induced electric field (E').

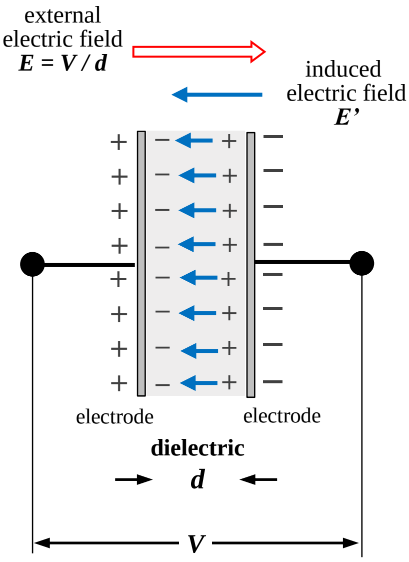


Fig. 1-05 Dielectric polarization [*1-05]

*1-05
An external electric field orients the electrons in the atoms and molecules of an insulator in the opposite direction of the external electric field.
As a result, the insulator's charge is biased negatively on the side opposite to the direction of the electric field and positively on the side in the direction of the electric field. The biased charge throughout the insulator creates an electric field within the insulator.

(2) The efficacy of dielectric

The voltage V between the electrodes becomes smaller because the external electric field is weakened by the induced electric field. When electric charge is supplied from the power supply to maintain the strength of the electric field at V/d until the voltage between the electrodes, which has become smaller, is restored to the original voltage, more electric charge accumulates on the electrodes. In other words, by inserting a dielectric between the electrodes, more charge can be stored at the same voltage.

The capacitance C_0 of a capacitor without dielectric is expressed as Equation (1-11), but if we consider that the charge stored by the dielectric is increased by a factor of ε_r, the capacitance C of a capacitor with dielectric is given by Equation (1-12).

$$C_0 = \frac{Q}{V} = \varepsilon_0 \times \frac{S}{d} \quad \cdots \quad (1\text{-}11)$$

$$C = \varepsilon_r \times C_0$$

$$= \varepsilon_r \times \varepsilon_0 \times \frac{S}{d} \quad \cdots \quad (1\text{-}12)$$

C_0 : capacitance without dielectric
C : capacitance with dielectric
Q : electric charge
V : voltage
ε_0 : permittivity in vacuum
S : electrode area
d : distance between electrodes
ε_r : capacitance factor (see next)

(3) Types of dielectrics[*1-06]

The "ε_r" discussed in the previous section is a dimensionless value called relative permittivity. The larger the dielectric with a larger ε_r, the larger the capacitance of the capacitor. Table 1-01 shows the types of dielectrics used in major capacitors.

Table 1-01. Types of dielectrics used in major capacitors

Dielectric	Relative permittivity ε_r	Capacitor
Aluminum oxide (Al2O3) Tantalum oxide (Ta2O5) Niobium oxide (Nb2O5)	8～10[*1-07] 23～27 41～42	Aluminum electrolytic capacitors Tantalum electrolytic capacitors Niobium electrolytic capacitors
Barium titanates (Class-1[*1-08]) Barium titanates (Class-2[*1-08]) Magnesium titanates	5～500 200～100,000 10～20	Ceramic capacitors
Polypropylene (PP) Polyethylene terephthalate (PET)	2.1～2.2 3～3.3	Film capacitors
Mica Paper	6～8 3.5～5.5	Mica capacitors Paper capacitors

Key Takeaway

- **A dielectric is an insulator in which an external electric field causes charge orientation and polarization.**
- **Dielectric has the function of increasing the capacitance of a capacitor.**
- **The coefficient by which a dielectric increases its capacitance is the relative permittivity.**

*1-06
Dielectrics are broadly classified into two types.(1) Non-polar typeWhen an electric field is applied to a dielectric, the electrons in the dielectric are displaced relative to the atomic nucleus, inducing a dipole and storing an electric charge.(2) Polarization typeWhen an electric field is applied to a dielectric with dipoles in random directions in advance, the dipoles align and store electric charge.Air, gases, polystyrene, etc. are non-polar dielectrics, while metal oxides, which are dielectrics for ceramics and electrolytic capacitors, are polar dielectrics.

*1-07
Simizu et.al., Journal of the Surface Finishing Society of Japan 72 (4) , 2021 https://www.jstage.jst.go.jp/article/sfj/72/4/72_216/_pdf

*1-08
The temperature characteristics of ceramic capacitors are attributed to the type of dielectric ceramic. Class-1 is a non-ferroelectric ceramic based on titanium dioxide and has excellent temperature stability due to its paraelectricity. Class-2 is ferroelectric, usually based on barium titanate. It has a very high dielectric constant compared to Class-1.

Helpful TIPS 2

<<<<< **Permittivity of vacuum** >>>>>

When there is a vacuum between the electrodes, charge is stored only at the electrodes. Its ability to store charge is expressed as the dielectric constant ε_0 of a vacuum as follows in Equation (1-13) [*1-09]. This constant indicates that if two electrodes with an area of 1 cm^2 are at a distance of 1 cm and there is a vacuum between the electrodes, their capacitance is 0.0854 pF.

$$\varepsilon_0 = \frac{1}{\mu_0 c^2} = \frac{1}{4\pi \times 10^{-7}[\mathrm{H/m}] \times (2.998 \times 10^{8}[\mathrm{m/s}])^2}$$

$$\fallingdotseq 8.854 \times 10^{-12}[\mathrm{F/m}]$$

$$= \mathbf{0.0854\ pF/cm} \quad \ldots \quad (1\text{-}13)$$

ε_0 ; permittivity of vacuum
μ_0 : permeability of vacuum ($4\pi \times 10^{-7}$[H/m])
c : speed of light (2.998×10^{8}[m/s])

*1-09

Dielectric constant is a physical quantity that describes the response of a dielectric material to an electric field. However, since a vacuum is not a dielectric, the dielectric constant of a vacuum is not a dielectric constant that represents a physical property.

1.3 Units and Symbols Rules

(1) Unit and Prefix

The unit of capacitance is the farad (abbreviated as F), named after the British physicist Michael Faraday[*1-10]. A capacitor with 1 farad stores 1 coulomb of charge at a voltage of 1 volt. That is, 1F = 1Q/V. However, since the capacitance of capacitors used in actual circuits is much smaller than 1 farad, the three prefixes **μ** (micro), **n** (nano), and **p** (pico) are usually used (Table 1-02).

*1-10

The "Faraday," a unit of electric charge, is also derived from Michael Faraday.

Table 1-02 Prefixes in capacitance unit

Prefix	μ : micro	n : nano	p : pico
conversion	10^{-6} (millionth)	10^{-9} (billionth)	10^{-12} (trillionth)
	1,000,000μF = 1F	1,000nF = 1μF	1,000pF = 1nF

(2) Rules

The rated capacitance of capacitors is specified according to the E series of IEC. Generally, the E3 series or E6 series shown in Table 1-03 are often used.

The “E” in E series stands for exponent, and in the case of the E6 series, the value of 6√(10n) (the sixth power root of the nth power of 10) in the definition formula, where n is six numbers from 0 to 5, is used for the capacitance. In addition to E3, E6, and E12 shown in Table 1-03, there are E24, E48, E96, and E192.

Since each series is related to the capacitance tolerance, the E6 series is used for capacitors with ±20% tolerance, such as electrolytic capacitors, and the E12 series is used for capacitors with a required ±10% tolerance.

Table 1-03. Capacitance E series

	E3		E6		E12	
definition	$\sqrt[3]{10^n}$		$\sqrt[6]{10^n}$		$\sqrt[12]{10^n}$	
	n	capacitance	*n*	capacitance	*n*	capacitance
n value and capacitance	*0*	**1.0**	*0*	**1.0**	*0* *1*	**1.0** **1.2**
			1	**1.5**	*2* *3*	**1.5** **1.8**
	1	**2.2**	*2*	**2.2**	*4* *5*	**2.2** **2.7**
			3	**3.3**	*6* *7*	**3.3** **3.9**
	2	**4.7**	*4*	**4.7**	*8* *9*	**4.7** **5.6**
			5	**6.8**	*10* *11*	**6.8** **8.2**

In order to represent a variety of capacitance values, there is a rule that combines two digits of the capacitance value with a multiplier; this rule, based on pF (pico farad), is common to all capacitors. For example, the symbol for 100μF is determined as follows.

10μF can be rewritten as 100×10^{-6}F. Rewriting this using the prefix p(10^{-12}) yields 10 × 10^7pF. The multiplier "7" is combined with the first digit "1" and the second digit "0" to obtain "**107**". This is the capacitance symbol for 100μF[*1-11].

$$
\begin{aligned}
100\mu F &= 100 \times 10^{-6} \ [F] \\
&= 10 \times 10^{7} \ [pF]
\end{aligned}
$$

↓

Capacitance symbol
107

*1-11
Since 1000 μF is 1000 × 10^{-6} F, when expressed using the prefix p, the multiplier is “8,” so “108” is the capacitance symbol.
In the case of 47 μF, the symbol is "476", 4.7μF is "475", and 0.47μF is "474". The larger figure at the end means the larger the capacitance.

For capacitance of 100pF or less, read the displayed number as it is. Note, however, that there are two symbols for 100pF: "101" and "100. For a capacitance of less than 10pF, "R" is used as the decimal point. 2.2pF is written as "2R2".

Key Takeaway

- **Usually, μF or pF is used as the unit of capacitance.**
- **In order to represent various capacitance values, a common capacitance symbol is used for each capacitor.**

Helpful **TIPS 3**

<<<<< 1 coulomb, 1 farad, their sense of scale? >>>>>

What are the senses of scale of 1 coulomb [C] and 1 farad[F]?

According to Coulomb's law, the electrostatic force ***F*** acting on a positive point charge of 1 [C] and a negative point charge of 1 [C] at a distance of 1 [m] is about 10 billion newtons[N], equivalent to the force to lift a heavy object of about 1 million tons[*1-12] (Figure 1-06).

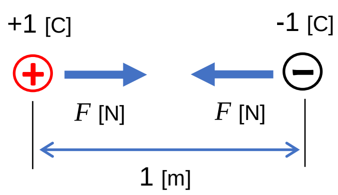


Fig. 1-06 Charge and electrostatic force

The amount of electricity generated by a lightning strike is said to be 0.2 to 20 [C] for summer lightning and 3.5 to 3,000 [C] for winter lightning[*1-13] .Thus, 1 coulomb is an impossible amount of electricity in a normal circuit, and capacitors with a capacitance of 1 [F] are rarely used in actual circuits, except in some power equipment[*1-14] .

*1-12
https://hegtel.com/coulomb.html

This force is equivalent to the thrust of a large rocket。

*1-13
https://www.jstage.jst.go.jp/article/jwea1977/31/4/31_4_98/_pdf

Takada et. al., JAPAN WIND ENERGY ASSOCIATION 38 (4) 98 2007

*1-14
Some electric double-layer capacitors (EDLCs) have capacities in excess of 1F. However, EDLCs have no dielectric and store electrical energy by physically adsorbing ions in the electrolyte on the surface layer of the electrodes.

1.4 What you should keep in mind about capacitance

Capacitors cover an extremely wide range of capacitance from pF (pF, 10^{-12} farads) to 1 farad (Figure 1-07). In general, aluminum electrolytic capacitors cover the large capacitance range, but in recent years, ceramic capacitors and film capacitors also have products with large capacitance in the 1mF (1000μF) class (Figure 1-07).

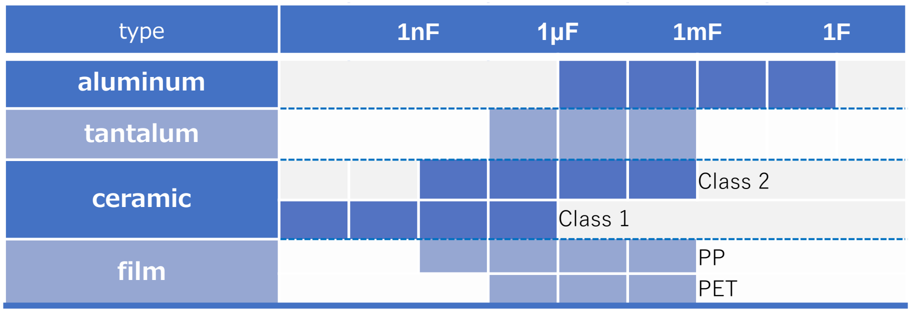


Fig. 1-07 Major capacitor types and capacitance range

(1) Nominal capacitance C_N and tolerance

The nominal capacitance $\boldsymbol{C_N}$ is a design value. The capacitance shown on the capacitor body is the nominal value, not the actual. There is a difference between the actual capacitance value[*1-15] and the nominal, which is called the tolerance. The tolerance is usually expressed as a percentage deviation from the nominal value and can be set in the range from -20% to +80% (Table 1-04).

*1-15
The measurement method is specified in JIS C 5101-1:2019 (IEC 60384-1:2016) Section 4.7, including frequency, measurement voltage (Vrms), and temperature.

If a capacitor with a nominal capacitance of 100 μF has a tolerance of ±20%, its actual capacitance is guaranteed to be between 80 μF and 120 μF.

Generally, capacitors with tolerances of "J (±5%)", "K (±10%)", and "M (±20%)" are used. Film capacitors, mica capacitors, and class 1 type ceramic capacitors are also available with smaller tolerances (higher capacitance accuracy). However, for capacitors with extremely small capacitance, the tolerance is sometimes expressed as a value, such as 10pF±1pF.

Table 1-04 Tolerances

	10pF <	≦10pF
B	±0.1 %	±0.1 pF
C	±0.25 %	±0.25 pF
D	±0.5 %	±0.5 pF
E	--------	±2 pF
F	±1 %	±1 pF
G	±2 %	----
H	±3 %	----
J	±5 %	----
K	±10 %	----
M	±20 %	----
N	±30 %	----
Q	−10～ +30%	----
T	−10～ +50%	----
S	−20～ +50%	----
Z	−20～ +80%	----

(2) Capacitance versus Temperature

Capacitance varies with temperature. This is due to the temperature characteristics of the dielectric and the structure of the electrodes, and the magnitude of capacitance change depends on the type of capacitor. Temperature compensated ceramic capacitors and film capacitors show a small change in temperature (Figures 1-08 and 1-09), but ceramic capacitors of high dielectric constant system and aluminum electrolytic capacitors using electrolytic solution show a very large change in temperature, so bypass circuits that are relatively insensitive to the magnitude of capacitance change, Therefore, they are used in bypass circuits and decoupling circuits, which are relatively insensitive to the magnitude of capacitance change.

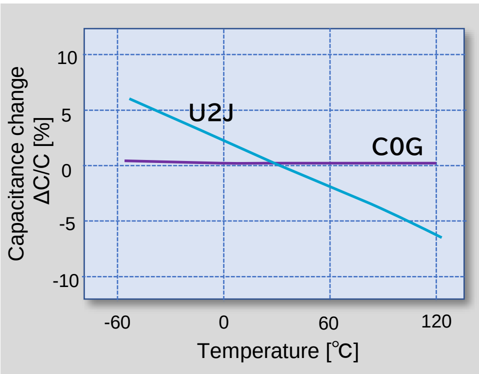


Fig. 1-08
Temperature compensated ceramic capacitors [*1-16, 1-17]

C0G : 0±30ppm/℃
U2J : -750±120ppm/℃

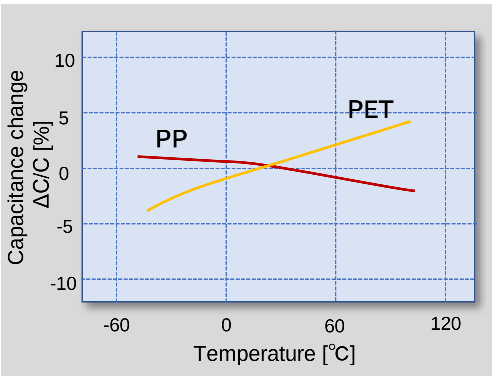


Fig.1-09
Metalized film capacitor [*1-18]

PP : polypropylene
PET : polyethylene terephthalate

*1-16 https://www.doeeet.com/content/eee-components/passives/class-1-ceramic-dielectrics/

*1-17 C0G and U2J are EIA code. Their JIS code are CG, U2J , UJ, repectively。

*1-18 https://www.garmanage.com/atelier/index.cgi?path=public&B&Energy_storage&B&Capacitors&B&Capacitance&B&Temperature&&id=psyitefg

[Temperature coefficient T_C for Class 1 ceramic and film capacitors]

When capacitance changes almost linearly with temperature as shown in Figure 1-08, the slope of the capacitance change with respect to temperature is called the temperature coefficient (T_C), which is defined by the equation 1-14. Specifically, the capacitance change when the temperature changes by 1°C from the reference temperature T_0 [*1-19] is expressed in units of parts per million (ppm/°C).

$$T_c = \frac{C_T - C_{T0}}{C_{T0}\,(T - T_0)} \times 10^6 \quad \text{[ppm/°C]} \quad \dots \quad (1\text{-}14)$$

C_T : capacitance at T°C
C_{T0} : capacitance at T_0°C

*1-19 The reference temperature differs between JIS and EIA standards: 20° C for JIS and 20° C for EIA.

Temperature coefficients are used in Class 1 temperature compensated ceramic and film capacitors (Tables 1-05 and 1-06). A positive temperature coefficient means that the capacitance increases as the temperature rises. A negative temperature coefficient is used when the capacitance decreases with increasing temperature.

Table 1-05
Temperature coefficient for ceramic capacitors

T_C , tolerance [ppm/℃]	JIS code (EIA)
0±30	CG (C0G)
-220±120	RH (R2H)
-750±250	UK (U2K)

Table 1-06
Temperature coefficient for film capacitors[*1-20]

dielectric	T_C , tolerance [ppm/℃]
PP	-250
PET	+600
PEN	+200

*1-20 G. Sitaramaraju et al., Electical Characteristics Of Metallized Polypropylene Film Capacitor With General Technical Data - Comparative Study, International Journal of Engineering Research & Technology (IJERT) Vol. 2 Issue 4, April - 2013

[Capacitance change of Class 2 ceramic and electrolytic capacitors]

In ceramic capacitors of high dielectric constant type and aluminum electrolytic capacitors, capacitance varies nonlinearly with temperature (Figure 1-10). In those cases, the characteristics are expressed using the capacitance change ratio defined by Equation (1-15).

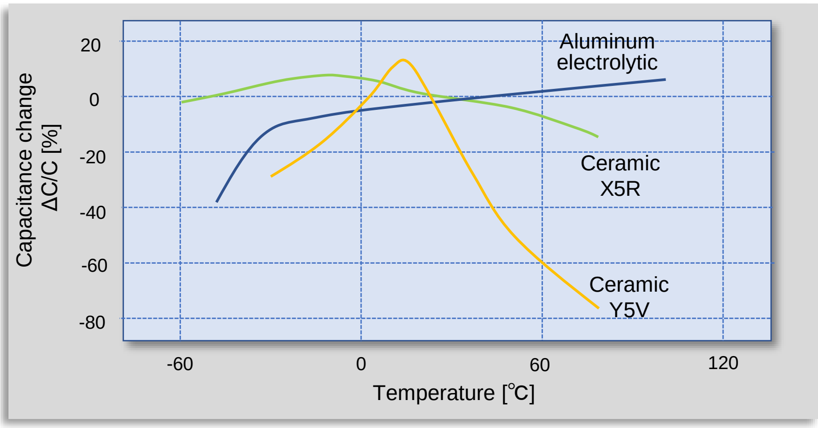


Fig. 1-10
Capacitance change ratio versus temperature, Ceramic capacitors of high dielectric constant type(X5R, Y5V)[*1-21,1-22] **and Aluminum electrolytic capacitors**[*1-23, *1-24]

*1-21 https://www.eeweb.com/multi-layer-ceramic-capacitors-mlcc/

*1-22 X5R : EIA code, Capacitor change within ±15% at -55～+85℃ range
Y5V : EIA code, Capacitor change within +22～-82% at -30～+85℃ range

*1-23 AICtech's type HL snap-in capacitor 500V 560μF

*1-24 20℃ as reference temperature

$$\frac{\Delta C}{C} = \frac{C_T - C_{T0}}{C_{T0}} \times 100 \ [\%] \quad \dots \quad (1\text{-}15)$$

C_T : capacitance at T℃
C_{T0} : capacitance at reference temperature T_0℃

(3) Capacitance versus Frequency

The higher frequency, the smaller capacitance. This is because the dielectric constant becomes smaller under high frequencies. As mentioned in section 1.2, a capacitor can store an electric charge when an external electric field causes polarization in the dielectric. However, it takes time to polarize. In alternating electric field, where the electric field reverses periodically, the polarization and relaxation are repeated. In low frequency alternative field (e.g., 50Hz or 60Hz alternating current for household use), the polarization barely can catch up with the electric field changes, so the dielectric constant does not decrease much and capacitance does not decline[*1-25].

*1-25
At DC voltage, it polarizes instantaneously in less than a nanosecond.

However, when the electric field changes 1 million times per second (1 MHz) or hundreds of millions of times per second (in the radio frequency range), the polarization cannot keep up with the changes in the electric field, and the field reverses before a perfect polarization state is reached. As a result, the dielectric constant becomes smaller (Figure 1-11).

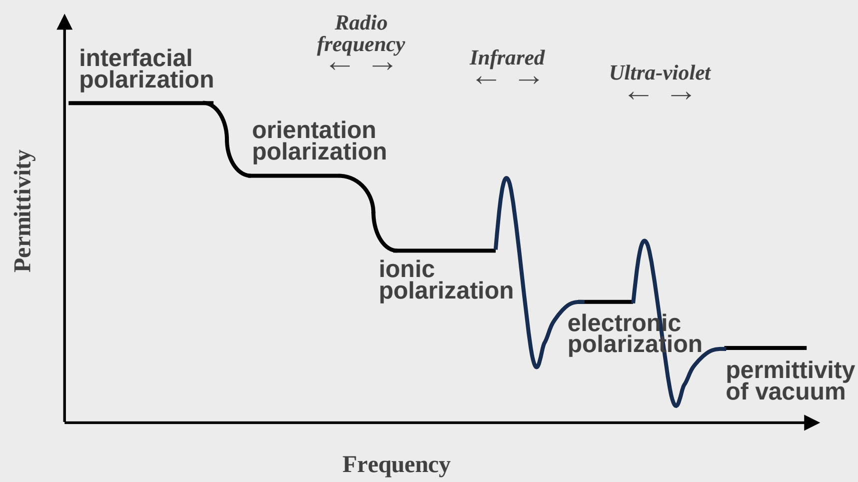


Fig. 1-11 Schematic diagram of permittivity versus frequency [*1-26]

*1-26
http://www.ieice-hbkb.org/
Dielectrics are made up of components that have different responses to frequency, and therefore different possible frequencies. Therefore, the permittivity is frequency dependent.

The magnitude of the capacitance decrease also depends on the electrodes and structure of the capacitor. In general, ceramic and film capacitors with metal electrodes have a small capacitance change, while aluminum electrolytic capacitors with electrolyte have a larger change (Figures 1-12 and 1-13).

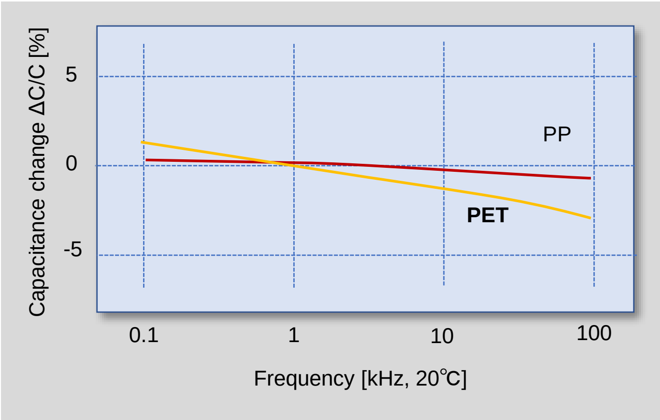


Fig. 1-12 Capacitance versus frequency of metalized film capacitor

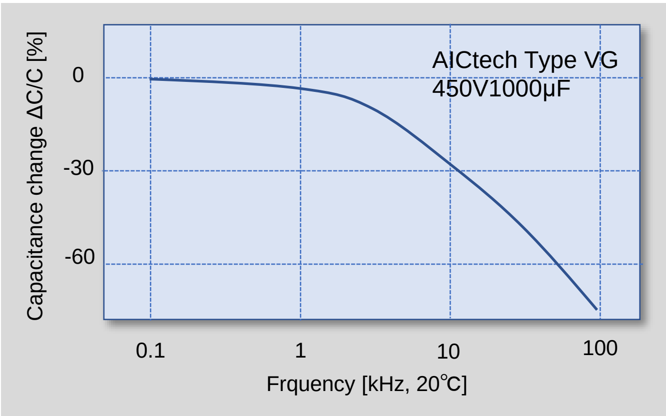


Fig. 1-13 Capacitance versus frequency of aluminum electrolytic capacitor

(4) Capacitance deterioration over time

Capacitance may decrease over a long period of time when capacitors are used. For this reason, each capacitor has a specified capacitance change rate for various life tests. For our screw terminal type aluminum electrolytic capacitors, we guarantee that the capacitance change will be within ±15% of the initial value when the rated voltage is applied for the specified time [*1-27] under the atmosphere of upper category temperature (Figure 1-14). The change in capacitance over time is due to the decrease in electrolyte and increase in conductivity caused by temperature and voltage.

The metalized film capacitors have the self-healing action [*1-28]. It causes the metalized electrode to evaporate, reducing the surface area of the electrode and lowering the capacitance.

*1-27
Capacitors are tested at DC voltage or ripple voltage superimposed on DC voltage in an atmosphere at the upper category temperature limit.

*1-28
In this self-healing action, an electric current flows into a defective spot in the dielectric film, and a thin electrode adhering to the dielectric is transpired by an arc. Details are explained in section 3.2 (4).

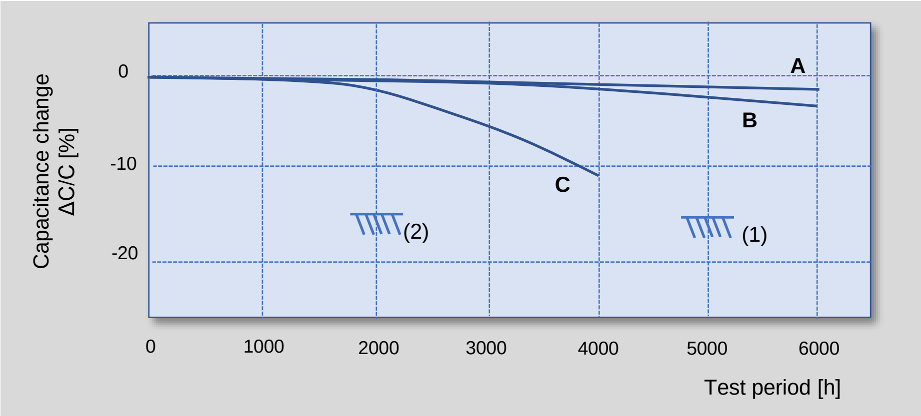


Fig. 1-14 Capacitance change at ripple charged life test of our aluminum capacitors

A : Type FXW 400V30000μF (ΔC/C < ±15% @5000h ,85℃ (1))
B : Type VGLR 450V 6800μF (ΔC/C < ±15% @5000h ,105℃ (1))
C : Type HCGW 450V32000μF (ΔC/C < ±15% @2000h, 85℃ (2))

Key Takeaway

- The nominal capacitance CN is a design value. The capacitance shown on the capacitor body is the nominal value, not the actual.
- There is a difference between the actual capacitance value*1-15 and the nominal, which is called the tolerance.
- Capacitance varies with temperature.
- The magnitude of capacitance change depends on the type of capacitor.
- The higher frequency, the smaller capacitance.
- Capacitance may decrease over a long period of time when capacitors are used.

1.5 Capacitance of Aluminum Electrolytic Capacitors[*1-29]

(1) Element structure and capacitance

The element of an aluminum electrolytic capacitor is a wound body consisting of an anode foil with dielectric, a cathode foil, and a separator soaked with electrolyte (Figure 1-15).

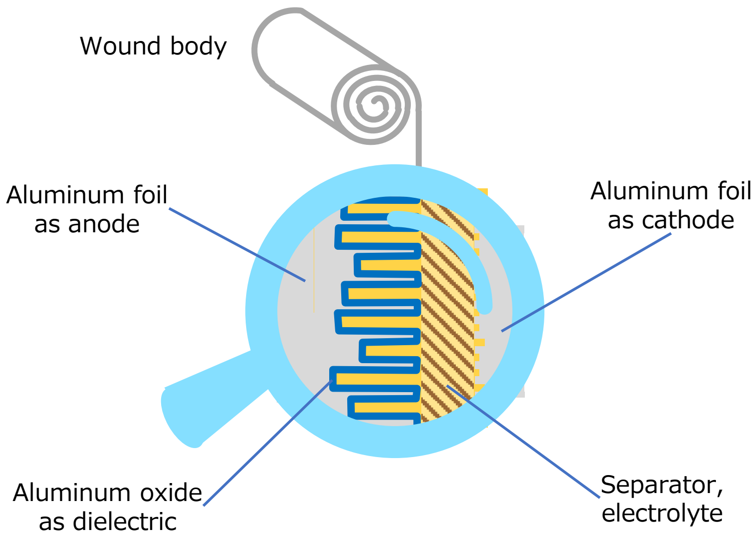


Fig. 1-15
Element structure of aluminum electrolytic capacitor

[Anode foil] The base material, aluminum foil, is a soft foil specially designed for capacitors with a thickness of 40 to 140 μm and a purity of 99.9 to 99.99%. The surface of the anode has large surface area with microscopic holes formed by some electrochemical etching process.

Capacitors with withstand voltages generally below 160 V have a spongy surface with cubic pores connected three-dimensionally, increasing the surface area by a factor of 80 to 100.

For capacitors with withstand voltages exceeding 160V, soft foils with aligned crystal orientation are used to form cylindrical pores (tunnel pits) in the depth direction. The diameter of the tunnel pit is about 1 μm and its length (depth) is about 50 μm. The number of pits per unit area is several tens of millions per cm2, expanding the surface area by a factor of about 30 to 50.

*1-29
To measure the capacitance of an aluminum electrolytic capacitor, set the capacitance bridge or LCR meter to “series circuit” measurement mode, with a sine wave of 0.5 volts rms or less and no DC bias. The measurement value is the equivalent series capacitance (Cs).Rated capacitance is generally measured with a sine wave of 120 Hz at 25° C 120 Hz or 20° C 100 Hz.
The frequency of 120 Hz is derived from the AC power waveform when the power frequency of 60 Hz is full-wave rectified.

[Dielectric]

The dielectric is an aluminum oxide film formed on the surface of aluminum by anodic oxidation[*1-30] . The relative dielectric constant ε_r of this dielectric is 8 to 10, which is about 4 times that of polypropylene film used for film capacitors. The thickness of the dielectric is several tens nm to 1 μm, which is 1/10 to 1/3 of polypropylene film, but the dielectric breakdown voltage per μm thickness is high (>500 V/μm) and it has excellent productivity.

This dielectric has rectifying properties. When a voltage is applied to the aluminum metal side (anode side) as an anode, only a small current flows, but when the opposite side (cathode side) is used as an anode, a large current flows. The mechanism of this rectifying property has been studied for a long time, but nothing definitive has been found [*1-31]. The polarity of aluminum electrolytic capacitors is derived from the nature of the anodic oxide film of the dielectric.

*1-30
Anodic oxidation is one of electrochemical technologies to form an oxide film (anodic oxide film) on the surface of a metal substrate.
In aluminum electrolytic capacitors, a dense barrier-type film is formed in a neutral electrolyte solution.
H. Takahashi et.al M. Seo ; Corros. Sci. 36 677 (1994)

*1-31
There are several theories that explain the insulating and rectifying properties of anodic oxide films.
For example, one theory states that this is because the anodic oxide film is formed from p-type, i-type, and n-type semiconductor layers, forming a pin structure.
Another theory states that hydrogen ions migrate through the film during cathodic polarization and are reduced to hydrogen on the metal side.

[Electrolyte]

Since a dielectric layer is also formed on the surface of the microscopic pores, a conductive electrolyte is impregnated deep into the pores. The electrolyte contacts the dielectric surface and functions as an electric path through which electric charges move. In other words, the electrolyte acts as a cathode, drawing out the capacity of the anode foil without loss, protecting the dielectric, and repairing defective areas.

[Structural features and capacitance]

The large surface area of the anode and the thin dielectric with a large relative dielectric constant are what give the aluminum electrolytic capacitor its high capacitance. On the other hand, capacitance also exists in the cathode foil, which serves as the current collector for the negative electrode. This is because the surface of the cathode foil is slightly etched and covered with an extremely thin natural oxide film. Therefore, the capacitance of an aluminum electrolytic capacitor consists of the capacitances of the anode and cathode foils connected in parallel (Figure 1-16).

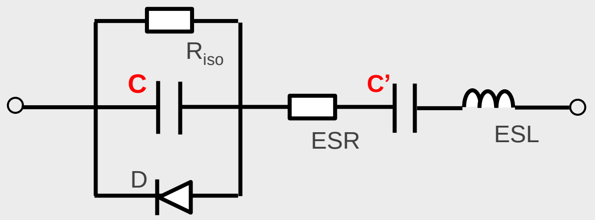


Fig. 1-16 Equivalent circuit of aluminum electrolytic capacitor*1-32

*1-32
Capacitors have not only capacitance but also parasitic resistance and inductance components. Details are explained in the next chapter.

(2) Temperature dependence

The capacitance of aluminum electrolytic capacitors increases at high temperatures and decreases significantly at low temperatures. This is mainly due to the characteristics of the electrolyte. At high temperatures, the viscosity of the electrolyte decreases, allowing it to penetrate deep into the pores, and its conductivity increases, allowing the capacity of the anode foil to be drawn out efficiently. Conversely, at low temperatures, the viscosity of the electrolyte decreases and conductivity decreases, resulting in lower capacitance. Generally, at low temperatures below -20°C, capacitance drops by several tens of percent *1-33 The drop in capacitance is not uniform and depends on the rated voltage of the capacitor. In general, capacitors with higher rated voltage tend to have a larger capacitance drop (Figure 1-17). For this reason, a lower operating temperature limit is specified for each type *1-34 .

*1-33
ESR also deteriorates at low temperatures and may be 10 to 100 times higher than at room temperature.

*1-34
Within the operating temperature range, capacitors whose characteristics have changed at low temperatures will recover their characteristics when brought back to room temperature. However, if the capacitor is rapidly heated when it is returned to room temperature, it may have an abnormal appearance or deteriorate its characteristics.

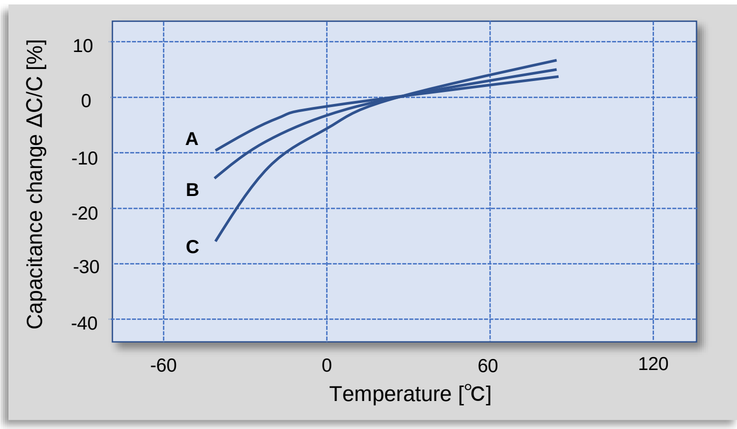


Fig.1-17 Capacitance versus temperature

AICtech's Type VGR
A : 350V 5600μF (Φ77 × 124L)
B : 450V 3300μF (Φ77 × 124L)
C : 500V 5600μF (Φ90 × 167L)

(3) Frequency dependence

As shown in Figure 1-18, an aluminum electrolytic capacitor has a complex circuit consisting of capacitance and resistance. When the frequency of alternating current passing through the capacitor is low, the dielectric constant does not decrease and the capacitive component deep within the microscopic pores functions as a capacitive reactance. However, as the frequency increases, this function is lost and the apparent capacitance decreases[*1-35] . This is even more pronounced at low temperatures because the resistance of the electrolyte increases at low temperatures.

*1-35
See Fig. 1-13.
Capacitors have a resistance factor to AC. Details are explained in the next chapter.

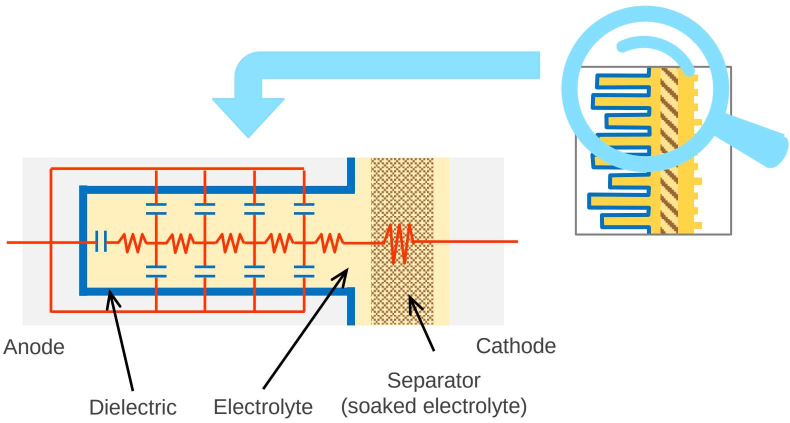


Fig. 1-18 Schematic diagram of fine structure and equivalent circuit of aluminum electrolytic capacitor

(4) Recovery voltage

When the terminals of a fully charged capacitor are shorted, the voltage between terminals instantly drops zero. After that, the short circuit is subsequently released (left open), a voltage is again generated between the terminals. This is called the recovery voltage[*1-36]. High-voltage, high-capacitance type aluminum electrolytic capacitors can generate as much as 40 to 50 V of recovery voltage, which can cause sparking during wiring work, damage to semiconductors, or even electric shock[*1-37].

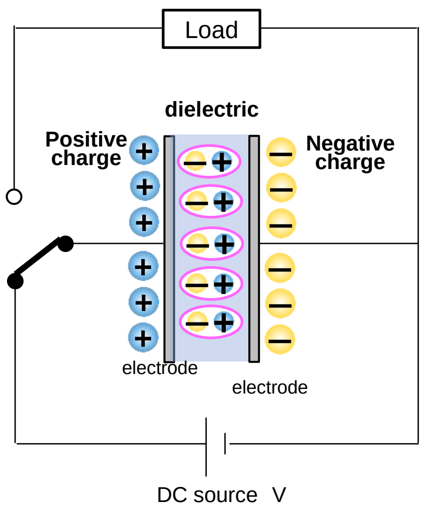


**Fig. 1-19
Fully charged capacitor**

*1-36
Larger recovery voltage might be observed in a capacitor that has been left charged for a long period of time or at high temperatures. Recovery voltage sometimes called “voltage rebound”.

*1-37
Revery voltage is also observed at film and ceramic capacitors.

【Recovery voltage process】

In a charged capacitor, a charge is accumulated on each electrode. This charge orients the molecules of the dielectric, causing dielectric polarization and storing an electric charge in the dielectric[*1-38] (Figure 1-19). When a capacitor is discharged, the charge stored in the electrodes is instantly disappeared and the voltage between the terminals becomes zero. However, dielectric polarization remains (Figure 1-20).

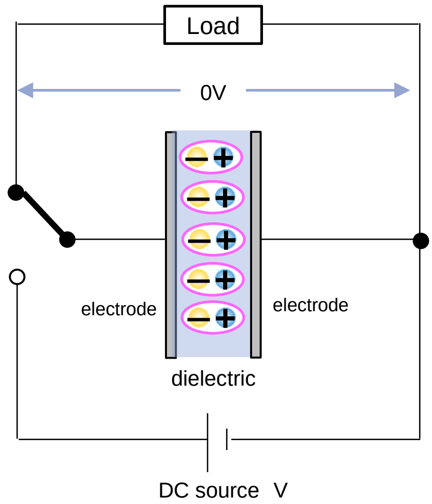


Fig. 1-20
State of charge just after discharge (insufficient discharge)

*1-38
Dielectric polarization does not respond immediately to an external electric field, but is delayed in time and polarizes slowly. This is called dielectric absorption.

When the capacitor is opened (open) with a short discharge time, the dielectric polarization charge remaining in the dielectric will again induce a voltage at the electrodes (Figure 1-21). In other words, the charge stored in the dielectric generates a voltage at the terminals again.

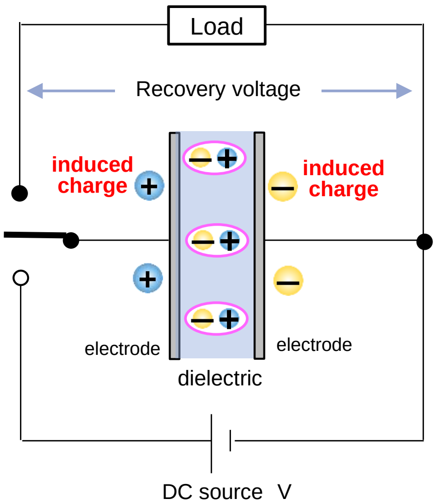


Fig. 1-21
Recovery voltage regeneration

Normally, the recovery voltage peaks at about 1 to 3 weeks, after which the voltage gradually decreases due to leakage resistance. So, polarizaion state is relaxed.

Although we ship capacitors after inspection and discharging, please be aware that recovery voltage may still be generated during the period between shipping and delivery. Therefore, before handling capacitors, connect a 100Ω to 1kΩ resistor between the capacitor terminals to discharge the accumulated charge.

We can also attach a discharge attachment to the terminals or ship the capacitor with a discharge sheet, so please contact us for details.

1.6 Capacitance Summary

A capacitor is an essential device in a circuit, consisting of a dielectric and electrodes, that physically stores electrical energy as static charge.

What is a capacitance?

- The amount of electric charge stored in a capacitor is proportional to applied voltage, and a capacitance is its constant of proportionality.
- In other words, capacitance indicates the amount of charge per unit voltage and is a physical quantity that refers to the ability to store charge.
- When a dielectric is placed between the electrodes, the capacitance can be increased due to dielectric polarization.
- The relative permittivity is the permittivity of a dielectric expressed as a ratio with the electric permittivity of a vacuum.
- The capacitance varies with temperature and frequency.
- Aluminum electrolytic capacitors have large capacitance due to the large surface area of the anode and the thin dielectric with a large relative dielectric constant.

Helpful
TIPS 3

<<<<< What is the difference between a capacitor and a battery? >>>>>

Both capacitors and batteries have the ability to store electricity and are called "energy storage devices. However, there are some basic differences between them as shown below.

	Capacitor	Battery
Storage physics	**Electrostatic charges on electrode surfaces** Capacitors physically store electricity, so no chemical change occurs in the material.	**Chemical reaction of electrodes** The electrodes of a battery change from one substance to another (e.g., ions).
Typical Feature	**Instantaneous power** Capacitors temporarily store and release electric charge in a circuit. Capacitors are used for strobe flashes that only need to shine brightly for a moment (batteries are not used)	**Endurance** A battery provides a continuous DC current to a circuit. A battery is used in a flashlight that keeps the bulb lit (no capacitor is used)
How to use	**Use in combination with other passive components** Capacitors are combined with resistors and coils (inductors) to create time constant or resonance circuits.	**Use alone** The same battery may be used in series or in parallel, but never in combination with other components.

2.1 Definition : The ability to block AC current

Impedance is the resistance to alternating current, measured in ohms. The magnitude of impedance is determined by resistance, capacitance, inductance, and frequency of alternating current. The term "impedance" is derived from the English word "impede," from the Latin "impedire." The name is derived from the fact that resistance, inductance, and capacitance impede the flow of current and voltage in an electric circuit where alternating current flows.

Resistance impedes the flow of current, both DC and AC. Capacitance stores charge and block DC , but allows AC to flow through it. Inductance generates a magnetic field that hinders current changes, but it is difficult for high-frequency alternating current to pass through. Impedance is also used as a parameter to describe the AC characteristics of electronic circuits and materials as well as electronic components[*2-01] .

*2-01
The human body also has impedance. By passing a weak electric current through the body and measuring impedance, the amount of water, body fat, and muscle mass in the body can be indirectly determined.
https://www.jstage.jst.go.jp/article/jsmbe1963/33/3/33_3_184/_article/-char/ja/

(1) Impedance definition

Impedance is expressed as the ratio of AC voltage to current at a given frequency and is defined as a complex number consisting of a real part and an imaginary part as in equation (2-01) [*2-02].

*2-02
Mathematically, impedance is treated as a vector quantity on the complex number plane.

$$\boldsymbol{Z} = R + jX \quad \cdots \quad (2\text{-}01)$$

Z : complex impedance
R : resistance (real part)
j : imaginary unit
X : reactance

[Resistor] A resistor works the same way in both DC and AC circuits, dissipating power as Joule heat. Resistance is always positive, and resistance is directly proportional to impedance (equation (2-02)).

$$\boldsymbol{Z_R} = R \quad \cdots \quad (2\text{-}02)$$

Z_R : Impedance of resistor

[Capacitor] A capacitor has an infinite resistance in a DC circuit, but in an AC circuit, it stores energy as an electric field and behaves like a resistance to the AC current (capacitive reactance[*2-03]). The impedance ($\boldsymbol{Z_c}$) of an ideal capacitor with no parasitic resistance is expressed as the capacitive reactance ($\boldsymbol{Xc}$) in equation (2-03).

*2-03
When an alternating current flows through an inductor or a capacitor, a voltage is generated in these elements, causing them to behave like a resistance. This is called reactance.It is called "inductive reactance" for inductors and "capacitive reactance" for capacitors.

$$\boldsymbol{Z_C} = \boldsymbol{X_c} = -\frac{1}{\omega C} \quad \cdots \quad (2\text{-}03)$$

X_c : capacitive reactance
ω : angular frequency = $2\pi f$
f : frequency
C : capacitance

[Inductor] An inductor is considered to have zero resistance in a DC circuit, but in an AC circuit it stores energy as a magnetic field and behaves like a resistance to AC current (dielectric reactance). The impedance (Z_L) of an ideal inductor with no parasitic resistance is only the inductive reactance (X_L), thus equation (2-04)

$$Z_L = X_L = \omega L \quad \cdots \quad (2\text{-}04)$$

X_L : inductive reactance
L : inductance

(2) Frequency dependence

Considering an equivalent circuit (3-element model) consisting of capacitance, resistance, and inductance (Figure 2-01), the impedance Z of this equivalent circuit can be expressed by equation (2-05), which combines equations (2-01), (2-02), (2-03), and (2-04).

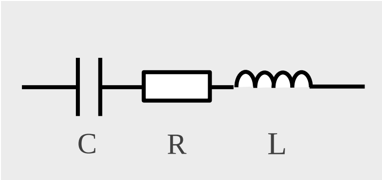


Fig. 2-01 3-element model

$$Z = R + jX = R + jX_C + jX_L$$
$$= R + j\left(\omega L - \frac{1}{\omega C}\right) \quad \cdots \quad (2\text{-}05)$$

The absolute value of impedance, $/Z/$, can be expressed by equation (2-06) as the square root of equation (2-05).

$$/Z/ = \sqrt{R^2 + (jX)^2}$$
$$= \sqrt{R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2} \quad \cdots \quad (2\text{-}06)$$

Replacing the angular frequency ω in equation (2-06) by the frequency f, impedance becomes a function of frequency expressed in equation (2-07). The frequency dependence of impedance can be illustrated using equation (2-07) as shown in Figure 2-02.

$$/Z/ = \sqrt{R^2 + \left(2\pi fL - \frac{1}{2\pi fC}\right)^2} \quad \cdots \quad (2\text{-}07)$$

1 CAPACITANCE
2 IMPEDANCE
3 DC LEAKAGE CURRENT
4 CONCLUTION

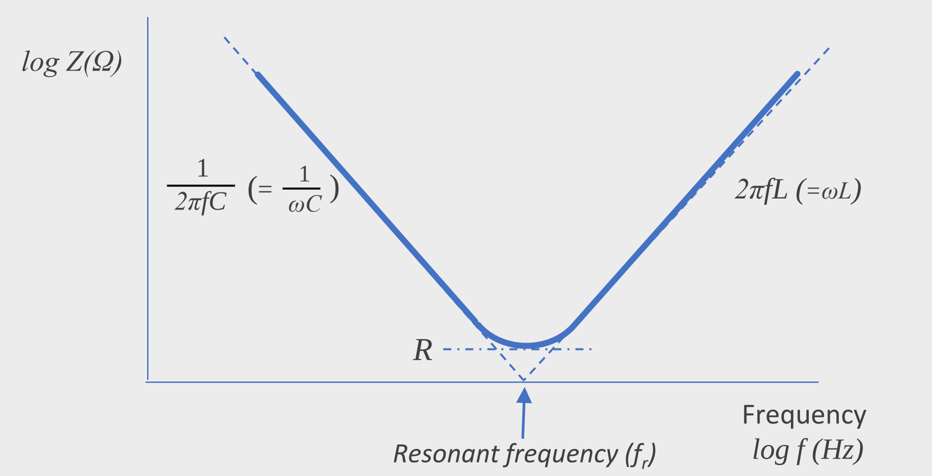


Fig. 2-02 Schematic diagram of impedance versus frequency

The capacitive reactance (X_c : $1/2\pi fC$) in equation (2-07) becomes smaller at higher frequencies and is eventually succeeded by the inductive reactance (X_L : $2\pi fL$). The frequency at which X_c and X_L become equal is called the resonance frequency f_r. The impedance at the resonant frequency is the resistance R [*2-04]. The magnitude of the resistance R greatly affects the frequency response of the impedance.

*2-04
In a decimal circuit, capacitors with different capacitances are connected in parallel to provide a wide range of low impedance from low to high frequencies, and instantaneously supply energy to the semiconductor. (See Section 2.3.2 Equivalent Series Inductance (ESL))

(3) Impedance of real capacitors

Figure 2-3 shows examples of frequency characteristics of impedance for aluminum electrolytic capacitors, leaded linear film capacitors, and chip-type multilayer ceramic capacitors. The graph shows a V-shape or U-shape, but the impedance minima and their frequency ranges vary depending on the type of capacitor and its capacitance.

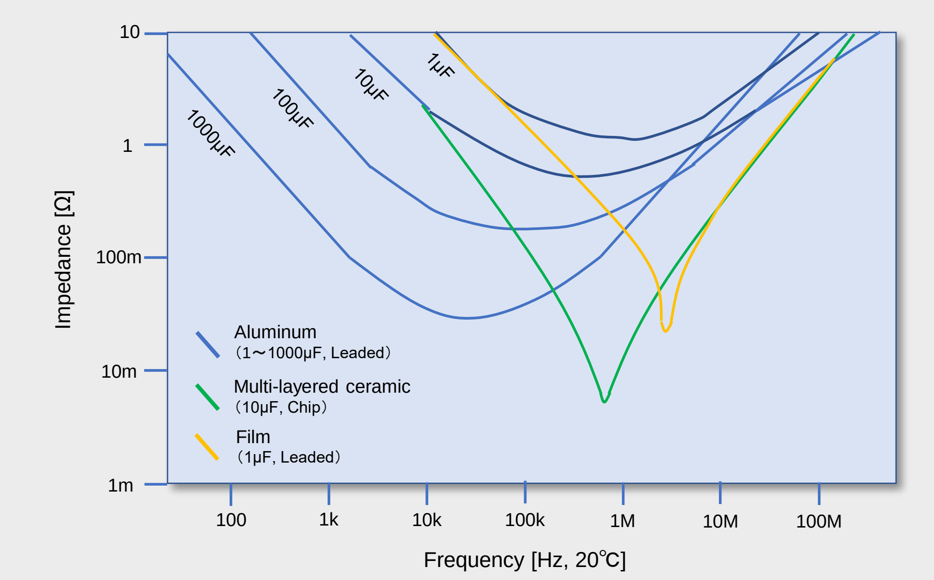


Fig. 2-03 Impedance versus frequency of various capacitors

The resistance of film and ceramic capacitors is smaller than the impedance due to capacitive or inductive reactance, so the impedance curve shows a sharp V-shape. Aluminum electrolytic capacitors have larger capacitance and higher resistance than film and ceramic capacitors, resulting in a smooth U-shaped curve[*2-05] .

In an actual capacitor, resistance due to electrodes and electrolyte and inductance such as lead wires are parasitic in series with the capacitance. These are called “equivalent series resistance (ESR)” and “equivalent series inductance (ESL)”, respectively[*2-06] . In addition to the true capacitance due to the dielectric, double layer capacitance and distributed capacitance between the electrolyte and electrode also exist as parasitic components, which are also components of impedance.

*2-05
By combining the different impedance characteristics of various capacitors, a noise filter with a wide frequency bandwidth can be constructed.

*2-06
“ESR” and “ESL” are preferred to be as small as possible because they cause a (common mode noise to be generated when switching current flows.
Details of "ESR" and "ESL" are explained in section 2.3.

Key Takeaway

- **Impedance is the resistance to alternating current.**
- **The impedance of a capacitor consists of resistance, capacitive reactance and inductive reactance.**
- **The frequency response of the impedance varies from capacitor to capacitor.**

Helpful TIPS 4

<<<<< Impedance and *tanδ* >>>>>

The impedance of an ideal capacitor is only the imaginary component ($1/\omega C$) of the capacitive reactance (X_C) (equation 2-03), but since an actual capacitor has resistance, the resistance (R) is the real component of the impedance[*2-07]. Let δ be the angle when impedance is expressed in terms of resistance R and $1/\omega C$ (Figure 2-04), $\tan\delta$ is expressed by equation (2-08).

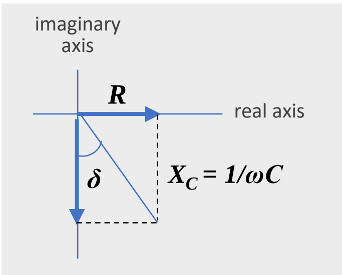


Fig. 2-04 *Vector expression of R and Xc*

$$\tan\delta = \frac{R}{X_c} = \omega CR \qquad \cdots \quad (2\text{-}08)$$

From equation (2-08), we can see that $\tan\delta$ is the ratio of resistance to capacitive reactance. When an AC voltage is applied to the capacitor, the AC current should advance 90°, but due to the equivalent series resistance component, it advances only 90°-δ. The smaller $\tan\delta$ is, the better.

*2-07
The major components of this resistance are the dielectric and the electrodes. When the dielectric cannot follow the direction changes in AC voltage, dielectric losses are generated. This is sometimes referred to as tanδ.

2.2 ESR and ESL as important components of Z

Figure 2-05 shows the frequency characteristics of impedance and ESR of our aluminum electrolytic capacitor (VGR type rated at 4700 μF 400V) As explained in Section 2.1 (3), impedance decreases with frequency at low frequencies (around several kHz) due to capacitive reactance. At frequencies above several tens of kHz, the impedance increases due to inductive reactance caused by ESL. Actual capacitors have parasitic ESR and ESL, which are important components of impedance. This section provides definitions and characteristics of ESR and ESL.

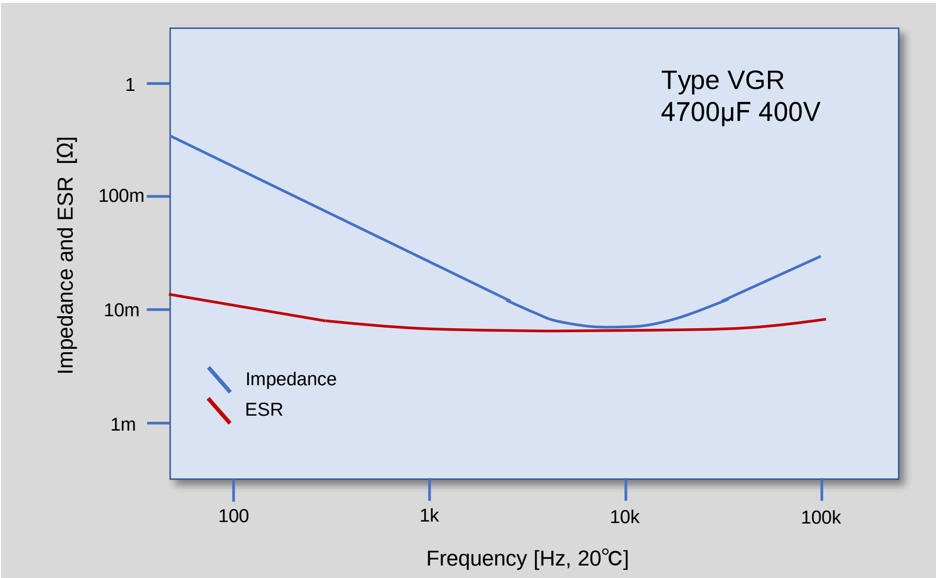


Fig. 2-05 Impedance, ESR versus frequency

(1) Equivalent Series Resistance : ESR

Almost all capacitors have an ESR of a few milliohms to several ohms; as discussed in Section 2.1 (3), ESR is a parasitic resistance in series with capacitance that causes the energy stored in the capacitor to be dissipated as Joule heat. In other words, the higher the ESR of a capacitor, the more power is consumed as heat. For example, in a circuit with a large current flow, such as a power smoothing circuit, the amount of power consumed by the ESR becomes large, causing the capacitor to self-heat and raise its temperature. A significant temperature rise can fatally damage or even break the capacitor. In addition, temperature rise causes aging degradation, which shortens the expected life of the capacitor even if actual damage or destruction does not occur. Thus, ESR of capacitors is an important characteristic along with capacitance and withstand voltage.

1 CAPACITANCE
2 IMPEDANCE
3 DC LEAKAGE CURRENT
4 CONCLUSION

[ESR varies with frequency, why?]

As shown in Figure 2-05, ESR varies with frequency. However, resistance should have no frequency dependence, since resistance works the same way for both DC and AC. This discrepancy can be explained by the equivalent circuit (4-element model, Figure 2-06), which assumes that "a capacitor has not only a resistance parasitic in series with the capacitance but also a resistance parasitic in parallel due to dielectric loss.

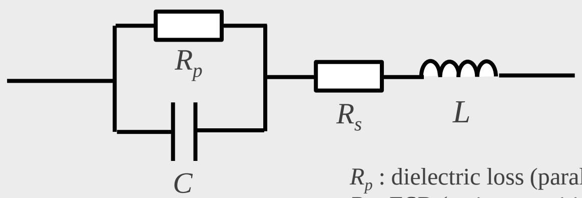


Fig. 2-06 Equivalent circuit, 4-element model *2-08

*2-08
In the equivalent circuit of a capacitor, the parasitic capacitance of the capacitor may be considered in addition to the capacitor's equivalent capacitance C.Parasitic capacitance is the capacitance that occurs between the electrodes of a capacitor and between the electrodes and the surrounding conductors. This parasitic capacitance is expressed as a series capacitance and plays an important role at high frequencies. However, since parasitic capacitance is the smallest capacitance in the equivalent circuit of a capacitor, it is ignored in this section.

(1) Impedance Z_1

In the equivalent circuit shown in Figure 2-06, the impedance Z_1 of the part where the dielectric loss is parasitic in parallel to the capacitance (Figure 2-06a) can be expressed by Equation (2-09) using the impedance Z_C of the capacitance and the resistance R_p due to dielectric loss.

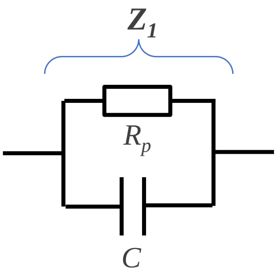


Fig. 2-06a
Impedance Z1 of the part where dielectric loss is parasitic in parallel to the capacitance

$$\frac{1}{Z_1} = \frac{1}{R_p} + \frac{1}{Z_C} \quad \cdots \quad (2\text{-}09)$$

Since the impedance of capacitance Z_C can be expressed as capacitive reactance in Equation (2-10), Z_1 can be expressed as equation (2-11) from equations (2-09) and (2-10).

$$Z_C = -\frac{j}{\omega C} \qquad \cdots \quad (2\text{-}10)$$

$$Z_1 = \frac{R_p \times Z_C}{R_p + Z_C} = \frac{R_p}{1 + j\omega C R_p} \qquad \cdots \quad (2\text{-}11)$$

(2) Impedance Z_2

The impedance Z_2 when a series resistance R_s is parasitic on Z_1 becomes equation (2-12) by adding R_s to Z_1 as shown in Figure 2-06b.

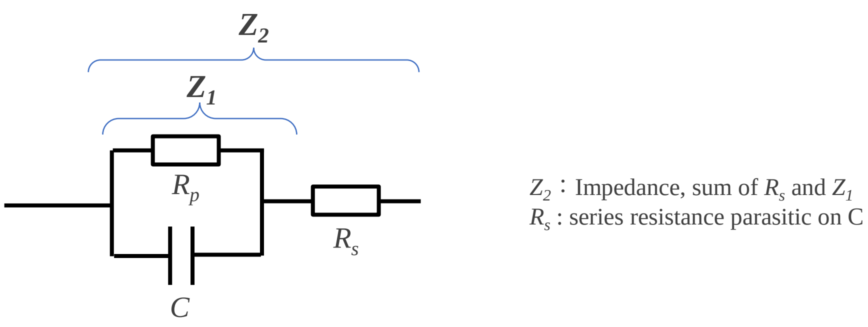


Fig. 2-06b
Impedance Z_2 , sum of R_s and Z_1

$$Z_2 = R_S + Z_1 = R_S + \frac{R_p}{1 + j\omega C R_p}$$

$$= R_S + \frac{1}{1 + (\omega C R_p)^2} - j\frac{\omega R_p^2 C}{1 + (\omega C R_p)^2} \qquad \cdots \quad (2\text{-}12)$$

(3) Impedance Z of 4-element model

The impedance Z of the 4-element model (Figure 2-06c) with inductance L parasitic in series with Z_2 is given by equation (2-13).

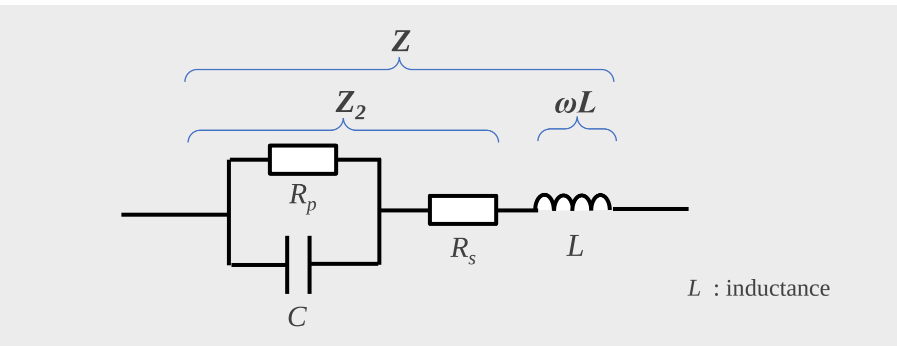


Fig. 2-06c Equivalent circuit of 4-element model and impedance

$$Z = \omega L + Z_2$$

$$= \underbrace{R_S + \frac{1}{1 + (\omega C R_p)^2}}_{\text{real part (ESR)}}$$

$$+ j \underbrace{\left\{ \frac{\omega L + (\omega C R_p)^2 \times \omega L - \omega R_p^2 C}{1 + (\omega C R_p)^2} \right\}}_{\text{imaginary part (reactance)}} \quad \cdots \quad (2\text{-}13)$$

The real part of equation (2-13) is the ESR, and the second term of the real part includes the angular frequency ω . Therefore, the ESR can be considered to have a frequency characteristic.

[Frequency-dependent and frequency-independent ESR]

From Equation (2-13), we can see that ESR is composed of "frequency-independent resistance (R_S)" and "frequency-dependent resistance (R_f)". Then, what are those resistors?

(1) What is a frequency-independent resistance (R_S)?

The metal terminals, electrodes, and internal wiring of a capacitor fall into this category. They behave as resistors to both DC and AC, and their energy loss does not vary much with temperature or frequency. However, at high frequencies, the skin effect of the electrodes increases, and at high currents, the resistance loss of the terminals and internal wiring cannot be ignored.

(2) What is frequency-dependent resistance (R_f)?

There are two types of resistance to this. One is the resistance (R_d) related to dielectric loss, which is related to dielectric polarization and relaxation. In ceramic and film capacitors, the dielectric loss of the dielectric is the main cause of the overall ESR. The other is the resistance (R_o) when the capacitor forms a distributed constant circuit with a complex combination of capacitance and resistance.

The electrodes of aluminum electrolytic capacitors and tantalum capacitors are porous materials with a large surface area[*2-09] and are filled with electrolyte or conductive polymers. As a result, these capacitors form a complex distributed constant circuit with parallel capacitances and series resistances, as shown in Figure 2-07. At low frequencies, all capacitances function, but at higher frequencies, the capacitances in the deeper holes (where the resistance is higher) apparently disappear and the resistance becomes smaller.

*2-09
Please refer to page 15, Section1.5(1) in details.

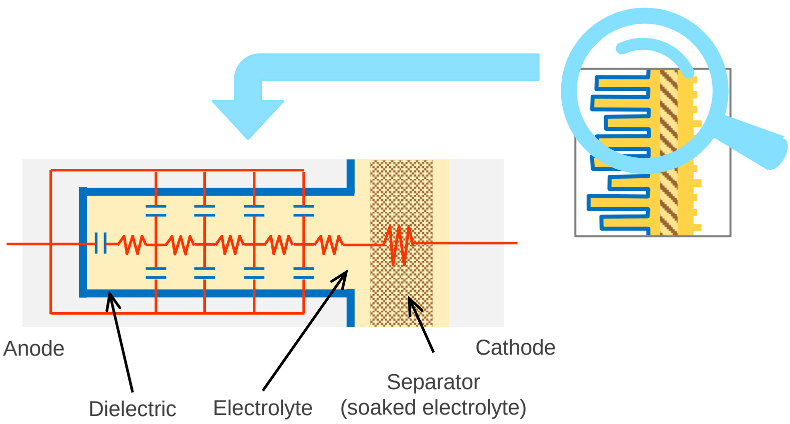


Fig. 2-07 Schematic diagram of fine structure and equivalent circuit of aluminum electrolytic capacitor (Reprint in Fig. 18)

Although it is difficult to explain the frequency dependence of ESR in detail, it is said that the dielectric loss component R_d is dominant at low frequencies from 1kHz to 10kHz, the resistance component R_o due to the distributed circuit is dominant in the intermediate frequency range from tens to hundreds of kHz, and R_S is dominant at high frequencies above 1MHz, as shown in Figure 2-08 [*2-10] .

*2-10
https://www.jstage.jst.go.jp/article/ieejjournal1888/89/970/89_970_1333/_pdf/-char/ja

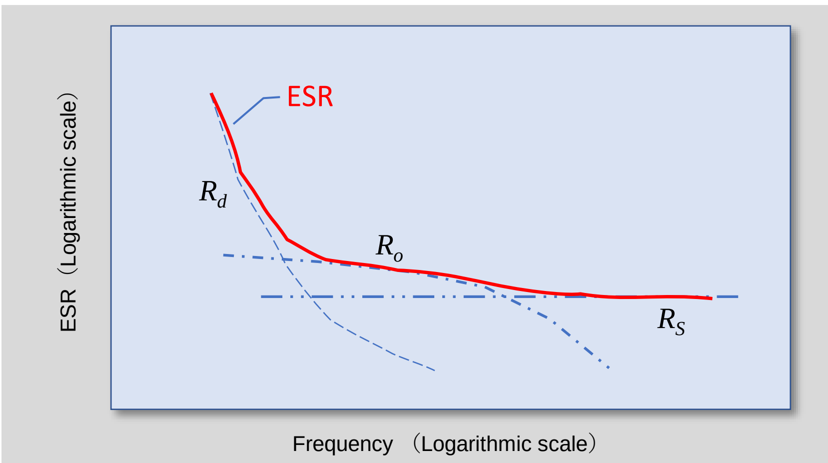


Fig. 2-08
Schematic diagram of ESR of each components versus frequency

1 CAPACITANCE
2 IMPEDANCE
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Figure 2-09 compares the ESR frequency response of various capacitors. The film capacitor shows extremely small ESR characteristics due to its small R_d and R_S and almost no R_0. Ceramic capacitors have large R_d but small R_0 and R_S. Aluminum electrolytic capacitors and tantalum capacitors have a high ESR due to the large size of all three elements.

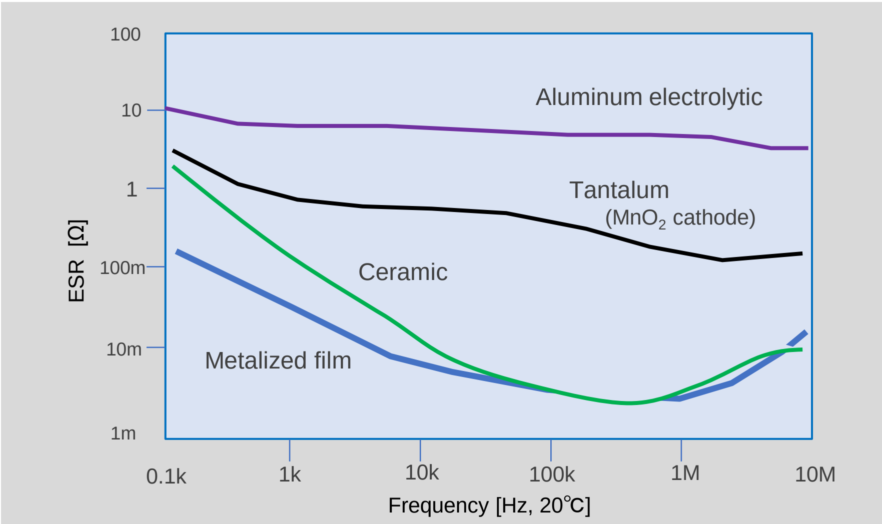

Fig. 2-09
ESR versus frequency of various 10μF capacitors

【ESR varies with temperature】

The ESR of a capacitor varies not only with frequency but also with temperature: if the main factor of ESR is metal, the ESR shows a positive temperature characteristic[*2-11], and if it is a semiconductor, a negative temperature characteristic[*2-12]. The ESR of aluminum electrolytic capacitors using the electrolyte is lower at higher temperatures and is higher at lower temperatures, but the change is larger than that of other capacitors. This detail is explained in section 2.3.

The ESR values in capacitor manufacturer's data sheets are those at a temperature of 20 to 25°C and a frequency of 120 Hz or 100 kHz. However, some capacitor manufacturers or varieties may specify ESR at lower temperatures or at various frequencies. Therefore, it is necessary to contact the manufacturer to select a capacitor with the appropriate ESR for the operating temperature and frequency of the application.

*2-11
The electrodes of ceramic and film capacitors are made of copper, precious metals, or aluminum. The ESR of these capacitors exhibits a positive temperature characteristic that is low at low temperatures and high at high temperatures.

*2-12
Manganese dioxide used as cathode of tantalum capacitors has semiconducting property. Therefore, tantalum capacitors exhibit a negative temperature characteristic with a low ESR at high temperatures.

(2) Equivalent Series Inductance : ESL

[At high frequencies, pay attention to ESL]

Inductance acts like resistance to AC current. Each of the electrodes, external / internal leads and terminals of a capacitor has some inductance. The sum of such inductances connected in series is called equivalent series inductance (ESL). The effect of ESL is observed only at high frequencies, and above the resonant frequency f_r, the capacitor behaves like an inductor[*2-13]. Since the f_r is the frequency when the capacitive reactance (X_c) and inductive reactance (X_L) are equal, solving equation (2-15), where the imaginary part of equation (2-05) becomes zero, yields equation (2-16), which represents the resonant frequency f_r .

*2-13 Resonant frequency is an important factor in RF circuits.

$$\omega L - \frac{1}{\omega C} = 0 \quad \cdots (2\text{-}15)$$

$$f_r = \frac{1}{2\pi\sqrt{LC}} \quad \cdots (2\text{-}16)$$

f_r : resonant frequency
ω : angular frequency = $2\pi f$
f : AC frequency
C : capacitance
L : inductance

Equation (2-15) shows that the smaller the inductance, the higher the resonant frequency, even if the capacitance is the same. As shown in Figure 2-10, a lower-inductance capacitor has a smaller impedance at higher frequencies and can be used in circuits with higher switching frequencies.

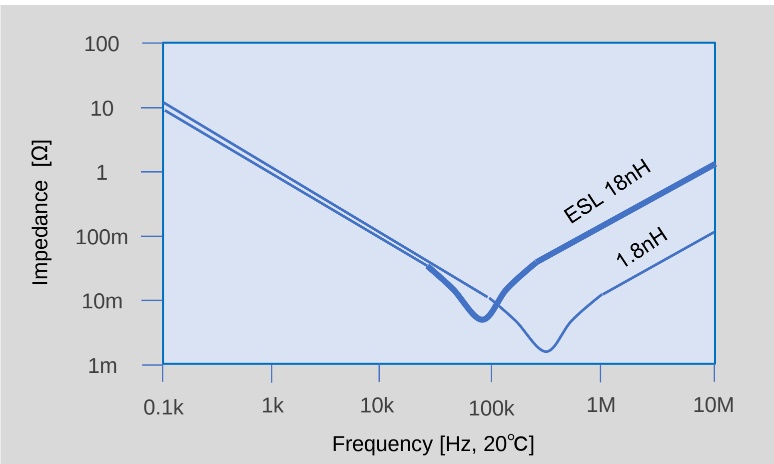

Fig. 2-10
Impedance versus frequency of capacitors with different ESL values[*2-14]

*2-14 https://www.auraauro.com/circuits-simulations/calculating-esl/

【Low ESL type capacitors】

Large inductance causes induced voltage spikes that can damage semiconductors. Furthermore, the interaction between stray inductance and capacitance can generate noise, degrading circuit stability and power quality.

Digital circuits driven at high frequencies are increasingly using low ESL, especially ceramic capacitors. High-speed memory chips and microprocessors use many decoupling capacitors (Figures 2-11 and 2-12). This is to transfer the energy stored in the capacitors instantaneously. The speed at which energy is transferred depends largely on the ESL of the capacitor; the higher the ESL, the slower the speed. Today's digital circuits require high switching speeds and low ESL capacitors. As switching speeds increase, the demand for capacitors with low inductance will continue to increase.

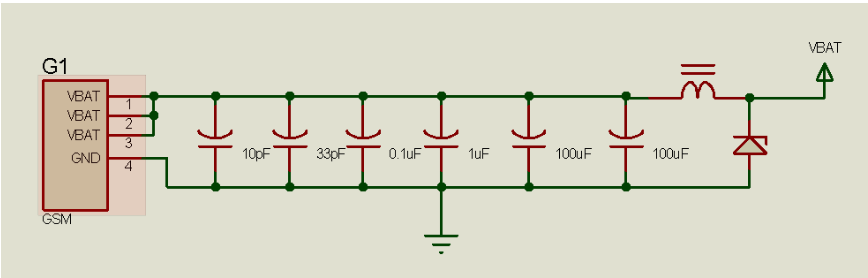

Fig. 2-11
Schematic diagram of decoupling capacitor configuration for microprocessor[*2-15, 2-16]

*2-15
Aluminum electrolytic or tantalum capacitors are often used together with ceramic capacitors.。

*2-16
https://www.labcenter.com/blog/pcb-decoupling-caps/

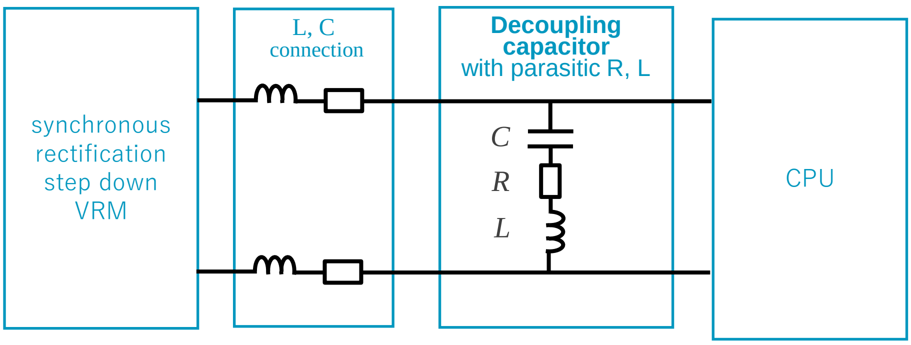

Fig. 2-12
Block circuit diagram of CPU、Decoupling capacitor、VRM[*2-17, 2-18, 2-.19]

CPU : Central Processing Unit
VRM : Voltage Regular Module

*2-17
Decoupling Capacitor - an overview | ScienceDirect Topics

*2-18
https://electronics.stackexchange.com/questions/452798/how-to-determine-the-decoupling-capacitor-values-for-the-power-bus-of-an-rf-devi

*2-19
Low ESR and low ESL are essential factors for decoupling capacitors.

In power electronics technology field, as the application of next-generation power semiconductors[*2-20] such as silicon carbide (SiC) and gallium nitride (GaN) expands, capacitors with low ESL are also required. This is due to the need to suppress self-heating while enhancing the protection of power semiconductors, especially in DC links for high-frequency switching and industrial inverters. Furthermore, capacitors with low ESL reduce peak voltage spikes, allowing the use of lower rated power semiconductors. Noise is also reduced, which improves the output quality of switching power supplies.

*2-20
While silicon, Si, is a single substance, SiC is a compound of carbon and silicon, and GaN is a compound of gallium and nitrogen, and these are called compound semiconductors.
SiC and GaN have high breakdown field strength and can achieve the same breakdown voltage as silicon with a thiner insulation layer.

ESL is primarily due to the internal construction and connections of the capacitor element, and these improvements can reduce ESL. To lower the inductance, it is necessary to make the conductor wider and shorter in length, and to improve the structure of the lead wires and external terminals and the method of connection with the capacitor element. Capacitor manufacturers are making progress in technological development for lower ESL.

Key Takeaway

- **ESR is a parasitic resistance in series with capacitance that causes the energy stored in the capacitor to be dissipated as Joule heat.**
- **While a lower ESR may be better, it should be noted that ESR varies with frequency and temperature.**
- **Since ESL can cause spike voltages and noise at high frequencies, a type of capacitor with reduced ESL should be used if necessary.**

2.3 ESR and ESL of Aluminum Electrolytic Capacitors

As shown in Section 2.2.1, Figure 2-07, aluminum electrolytic capacitors using electrolytic solution are characterized by a larger ESR than other capacitors. In addition, cylindrical aluminum electrolytic capacitors have external leads and leads (lead tabs) inside the capacitor, resulting in a larger impedance at high frequencies.

For this reason, in recent, there are products that apply conductive polymers to lower ESR and chip-type products that achieve low ESR and low ESL by stacking multiple elements on a flat plate.

(1) ESR Features of electrolyte-type aluminum capacitors

Aluminum electrolytic capacitors with low ESR are also required in power electronic circuits, because using capacitors with low ESR suppresses power loss and internal heat generation, and thus longer life can be expected.

Aluminum electrolytic capacitors with electrolytic solution are often used in power electronics circuits. These capacitors consist of an anode, cathode, separator, electrolyte, and lead tabs (Figure 2-13). Of these, the separator and electrolyte have a significant effect on ESR.

The separator prevents direct contact between the anode and cathode foils and at the same time maintains the function of the electrolyte by holding the electrolyte. For this reason, a low-density separator that can easily store electrolyte is suitable for low ESR[*2-21].

*2-21
The separator is made of a special paper with low impurities and high water absorbency. The thickness of the separator is approximately 30 to 75 μm, and it is used according to the rated voltage of the capacitor. For high-voltage capacitors, several layers of paper or high-density paper may be used. Kraft paper made of wood fiber and manila paper made of vegetable fiber are used for separators.

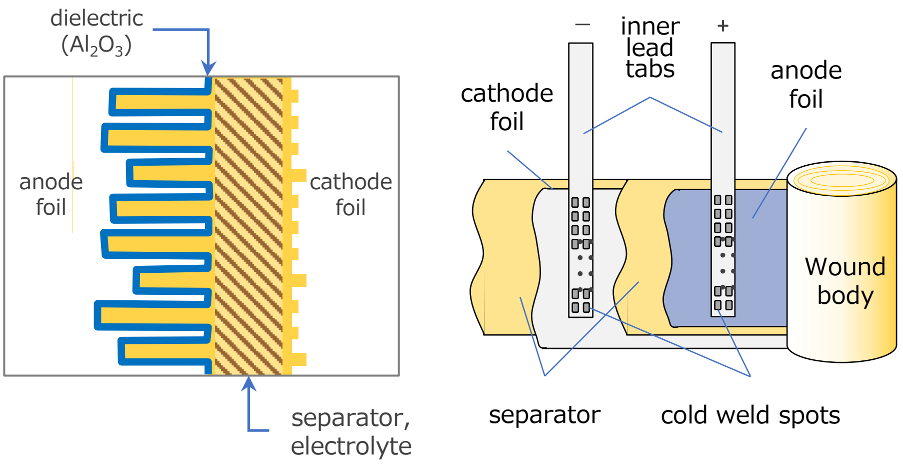

Fig. 2-13
The structure and materials of aluminum electrolytic capacitor element

The viscosity and conductivity of the electrolyte also have a significant effect on ESR[*2-22]. The lower the viscosity of the electrolyte, the easier it is to penetrate the anode and separator, and the higher the conductivity, the smaller the ESR. However, low viscosity and high conductivity electrolytes risk compromising withstand voltage and service life, so capacitor manufacturers address this tradeoff with various technologies.

*2-22
The conductivity of an electrolyte is highly dependent on its concentration and viscosity. Electrolytes with high solubility and high ionization will have a high charge density. Solvents with small viscosity η [Pa・s] and electrolytes with small ionic radius have larger mobility μ [m^2/V・s].

The viscosity and conductivity of electrolyte are highly dependent on temperature, with higher viscosity and lower conductivity at lower temperatures resulting in a larger ESR of the capacitor (Figure 2-14). Depending on the type of solvent and the ionic radius of the solute, the conductivity of electrolyte at temperatures below -20°C decreases significantly to 1/10 to 1/100 of room temperature.

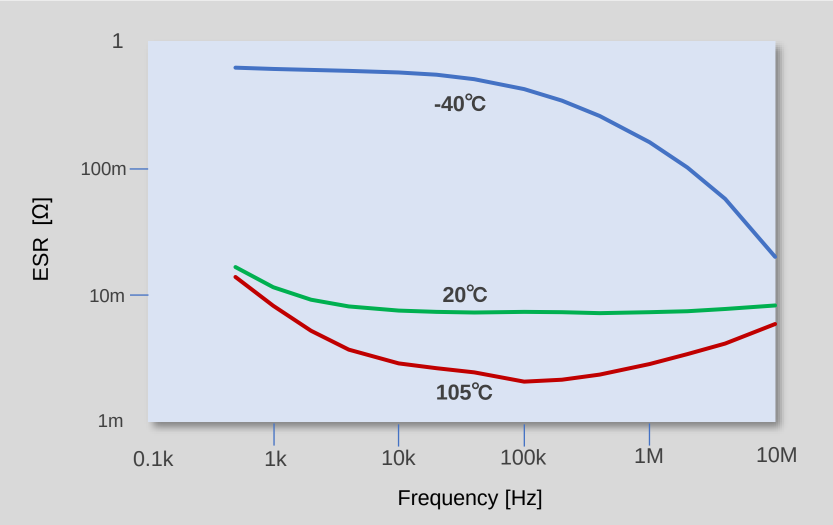

Fig. 2-14
ESR versus frequency at various temperature
(AICtech Type VGR 400V 4700μF)

(2) Low ESL aluminum capacitor

The ESL of an aluminum electrolytic capacitor element is usually less than 2 nH, but when ESL is measured between external terminals, it is 10 to 30 nH for radial leaded aluminum electrolytic capacitors, 20 to 50 nH for screw terminal type, and about 200 nH for axial leaded type (Figure 2-15). Therefore, aluminum electrolytic capacitors have a large impedance at high frequencies.

In DC link applications such as high-frequency switching and industrial inverters, low ESL capacitors are required to reduce self-heating while providing enhanced protection for power devices. Since capacitor ESL, along with other connections and cables, can cause voltage spikes, snubbers must be placed in each phase of the inverter. Lowering the ESL of the capacitor can reduce the overall inductance and possibly eliminate the need for snubber circuits in each phase of the inverter.

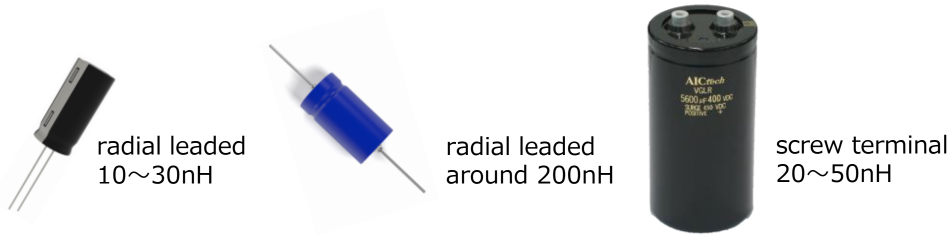

Fig. 2-15
Typical ESL of aluminum capacitor by type

To reduce ESL, it is effective to optimize the internal structure so that all magnetic fields generated by the current flowing through the capacitor are cancelled out. Specifically, this can be achieved by shortening the distance between the winding element and the terminals, as well as between the internal lead tabs of the winding element and the external terminals.

2.4 Impedance Summary

A capacitor is not an ideal capacitive element having only capacitance; it has parasitic resistance and inductance. Therefore, capacitors have an impedance

- Impedance is the resistance of an AC circuit and is measured in ohms (Ω).
- The impedance of a capacitor consists of capacitive reactance, equivalent series resistance (ESR), and inductive reactance (ESL).
- The smaller the ESR, the more desirable the characteristic, since the energy stored in the capacitor is dissipated as heat. Note, however, that it varies with frequency and temperature.
- ESL is mainly caused by the internal structure of the capacitor element and its connections, which can cause spike voltages and noise at high frequencies.
- Aluminum electrolytic capacitors have a larger ESR than other capacitors, and ESL is caused by lead wires and other factors.
- Low ESR and low ESL capacitors have been developed to meet market requirements.

Helpful
TIPS 5

<<<<< Low ESR is the norm, now low ESL !? >>>>>

Capacitors with reduced ESL are now used in digital circuits, especially in capacitors for decoupling. In power electronics, power semiconductors with fast switching in the high power range are now used in DC links, requiring lower inductance in circuits and peripheral components. This is due to the many performance and cost advantages offered by lower ESL. In the future, film capacitors and aluminum electrolytic capacitors will continue to be made with lower ESL[*2-23] .

*2-23
What are the main reasons why low ESL is required for capacitors?The ability to use higher DC link voltages reduces voltage peaks during switch-off and short-circuit conditions. Power semiconductors that can be driven at lower voltages can be used, thus reducing the cost of power semiconductors.High-speed switching becomes possible and switching losses are reduced.The number of capacitors connected in parallel can be reduced without increasing the inductance of the capacitor bank (ripple current characteristics of capacitors are improved).The number of capacitors used can be reduced, which in turn reduces assembly man-hours, space requirements, and weight, enabling smaller systems and lower costs.This is because of such advantages as the following.

3 DC Leakage Current

Leakage current is an electrical current that leaks from insulated areas in a circuit where current does not normally flow. Leakage current can cause problems such as circuit malfunctions, increased power consumption, and heat generation. Leakage current is a major problem in semiconductors consisting of minute circuits and elements[*3-01]. Capacitors also have leakage current. However, this includes not only the current that passes through the dielectric, which is an insulator, but also the current caused by dielectric polarization. In addition, when the insulation between the terminals is degraded by humidity or foreign matter adhering to the terminals, current may flow between the electrode terminals, bypassing the dielectric. This chapter explains the mechanism and properties of leakage currents and the precautions that should be taken.

*3-01
The leakage current of MOS transistors includes,
・Diffusion current from drain to source (sub-threshold current)
・Tunneling current from gate to source and drain (gate tunneling current)
・Junction leakage current (GIDL: Gate Induced Drain Leakage) that flows from the drain to the substrate

3.1 DC current through a capacitor

(1) Insulation resistance and leakage current

There are two parameters that describe the insulation properties of a capacitor: "insulation resistance" ($\boldsymbol{R_{iso}}$) and "leakage current" ($\boldsymbol{i_{leak}}$). The former is used for film and ceramic capacitors with very low leakage current, while the latter is used for electrolytic capacitors with high leakage current. The relationship between leakage current and insulation resistance can be expressed by the following simple equation[*3-02] .

$$\boldsymbol{i_{leak}} = \frac{\boldsymbol{V}}{\boldsymbol{R_{iso}}} \quad \cdots \quad (3\text{-}01)$$

i_{leak} : leakage current
V : voltage
R_{iso} : insulation resistance

*3-02
The relationship between applied voltage $\boldsymbol{V}$, insulation resistance $\boldsymbol{R_{iso}}$ and leakage current $\boldsymbol{i_{leak}}$ is expressed as the following equation,
$\boldsymbol{V = i_{leak} \times R_{iso}}$

Leakage current can be regarded as an insulation resistance (IR) connected in parallel to the capacitance (Figure 3-01) and is therefore sometimes referred to as resistance (leakage resistance) rather than current.

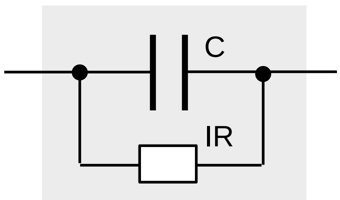

Fig. 3-01 Schematic diagram of capacitance and insulation resistance

(2) Dc current through an ideal capacitor

When an ideal capacitor C_0 is charged from power supply V_0 through external resistor R_0 (Figure 3-02), the charging current $\boldsymbol{i_{charge}(t)}$ decreases with time and the voltage $\boldsymbol{v(t)}$ across the capacitor terminals increases exponentially (Figure 3-03)

1 CAPACITANCE
2 IMPEDANCE
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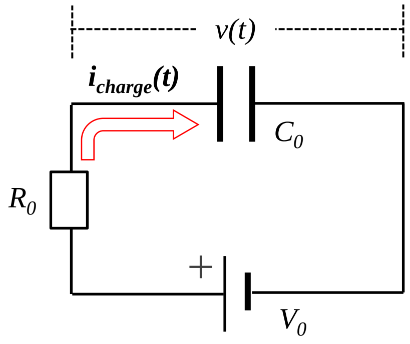

Fig. 3-02
An ideal capacitor is charged through external resistor

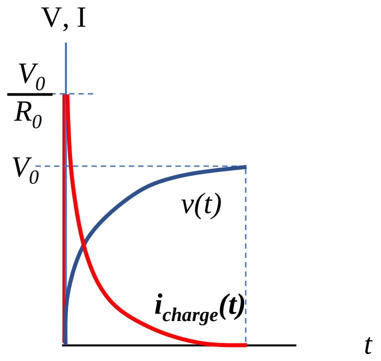

Fig. 3-03
Voltage, current versus time during capacitor charging

The charging current $\boldsymbol{i_{charge}(t)}$ and the charging voltage $\boldsymbol{v(t)}$ are expressed by equations (3-02) and (3-03), respectively[*3-03], where is the ratio between the supply voltage $\boldsymbol{V_0}$ and the resistance $\boldsymbol{R_0}$ at the start of charging ($t = 0$).

$$i_{charge}(t) = \frac{V_0}{R_0} \times exp(- \frac{t}{\tau_0}) \qquad \cdots \quad (3\text{-}02)$$

$$v(t) = V_0 \times \left[1 - exp(- \frac{t}{\tau_0}) \right] \qquad \cdots \quad (3\text{-}03)$$

Charging continues until $\boldsymbol{v(t)} = \boldsymbol{V_0}$. τ_0 is the product of resistance and capacitance and is called the time constant (Equation (3-04))[*3-04] .

$$\tau_0 = R_0 \times C_0 \qquad \cdots \quad (3\text{-}04)$$

If $\boldsymbol{R_0}$ is at the kilo-ohm (kΩ) and $\boldsymbol{C_0}$ is at the microfarad (μF) level, $\boldsymbol{\tau_0}$ is on the order of milliseconds (ms). At this time ($t = \tau_0$) the voltage is 63.2% of equilibrium, i.e., $\boldsymbol{v(t)} = \boldsymbol{0.632 \times V_0}$. The time for $\boldsymbol{v(t)}$ to reach $\boldsymbol{V_0}$ can be calculated using equation (3-05), a variant of equation (3-03). At three times the time constant ($t = 3\tau_0$), the voltage is approximately 95% of $\boldsymbol{V_0}$.

$$\frac{v(t)}{V_0} = 1 - exp(- \frac{t}{\tau_0})$$

$$= 1 - exp(- \frac{3\tau_0}{\tau_0}) = 95.0\% \qquad \cdots \quad (3\text{-}05)$$

In the cases of $t = 5\tau_0$ and $t = 10\tau_0$, the voltages can be calculated by equation (3-06) and (3-07). Therefore, The charging voltage is expected to reach almost the set voltage in about 5 to 10 times the time constant. At the same time, the current will be reduced to a negligible level.

*3-03
This formula represents the charging current and charging voltage of a capacitor in an RC circuit.

*3-04
The time constant is a measure of the speed of transients during charging and the time it takes to reach equilibrium.

$$1 - exp(-\frac{5\tau_0}{\tau_0}) = 99.3\% \quad \cdots \quad (3\text{-}06)$$

$$1 - exp(-\frac{10\tau_0}{\tau_0}) = 99.995\% \quad \cdots \quad (3\text{-}07)$$

(3) DC current through a real capacitor

Figure 3-04 shows the current behavior when a 1kΩ series resistor is connected to our aluminum electrolytic capacitor (4700μF rated capacitance) and the rated DC voltage is applied[*3-05]. A large current flows immediately after the start of charging, but it appears to decrease instantaneously and remain constant.

*3-05
The time constant of this RC circuit is 4700μF x 1kΩ = 4.7s.

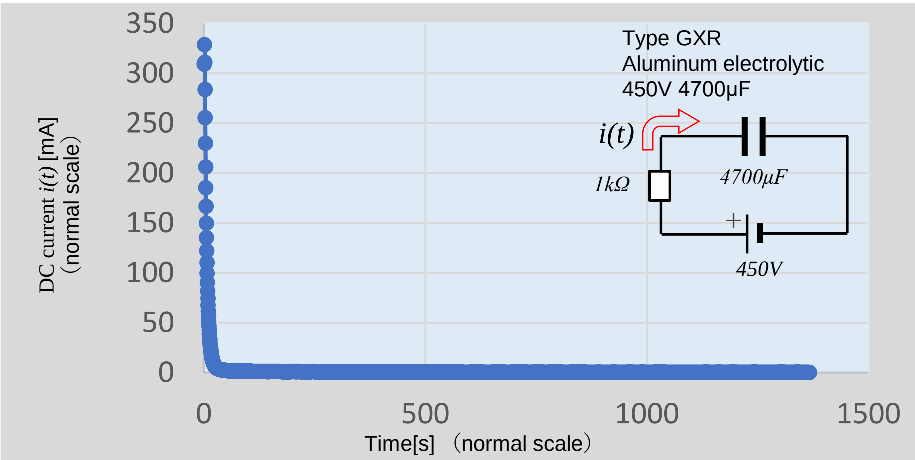

Fig. 3-04
DC current through type GXR capacitor[*3-06]

*3-06
The data was measured using a digital recorder with a sampling speed of 500 ms.

Replacing the current scale (vertical axis) in Figure 3-04 with a logarithm, we can see that the current decreases significantly for several tens of seconds after the start of charging, and then the current decreases slowly (Figure 3-04a).

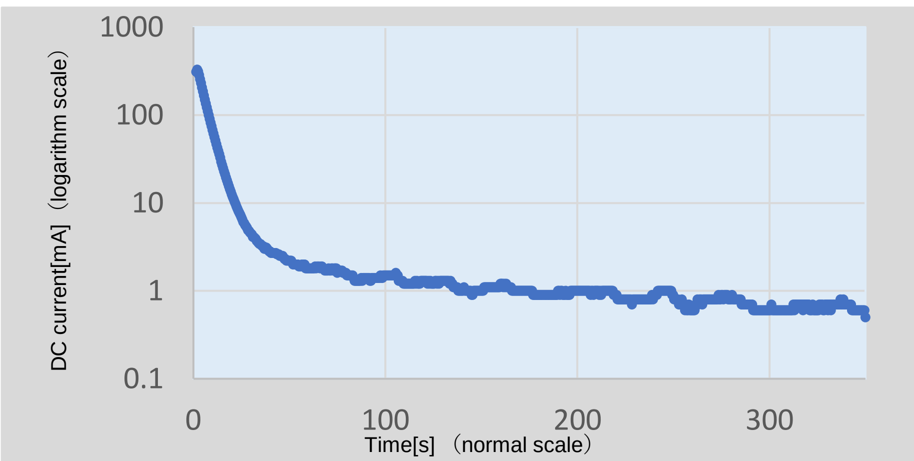

Fig. 3-04a
DC current through type GXR capacitor
（The vertical scale in Figure 3-04 is rewritten in logarithm.）

When the time axis (horizontal axis) of Figure 3-04a is set to logarithmic scale, an inflection point in the plot appears around 35 seconds[*3-07]. Thereafter, the current progressively decreases linearly over 1000 seconds (about 17 minutes) (Figure 3-04b).

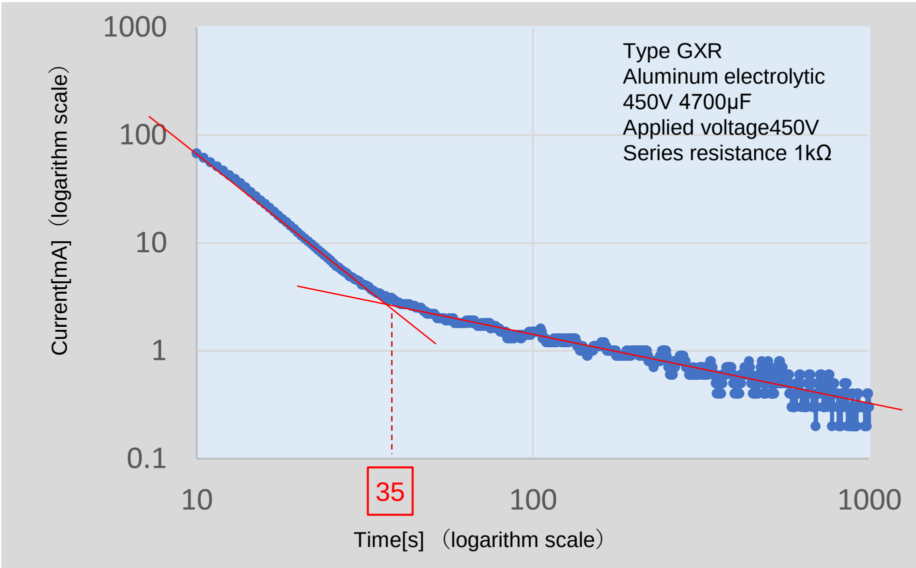

Fig. 3-04b

DC current through type GXR capacitor[*3-08]

(The horizontal scale in Figure 3-04a is rewritten in logarithm.)

This gradual decrease in current over tens to hundreds of seconds is also seen in other capacitors. Figure 3-05 shows data on the relationship between DC current and time when a ceramic capacitor is charged[*3-09]. The same behavior can be seen with ceramic capacitors, which have smaller capacitance than aluminum electrolytic capacitors.

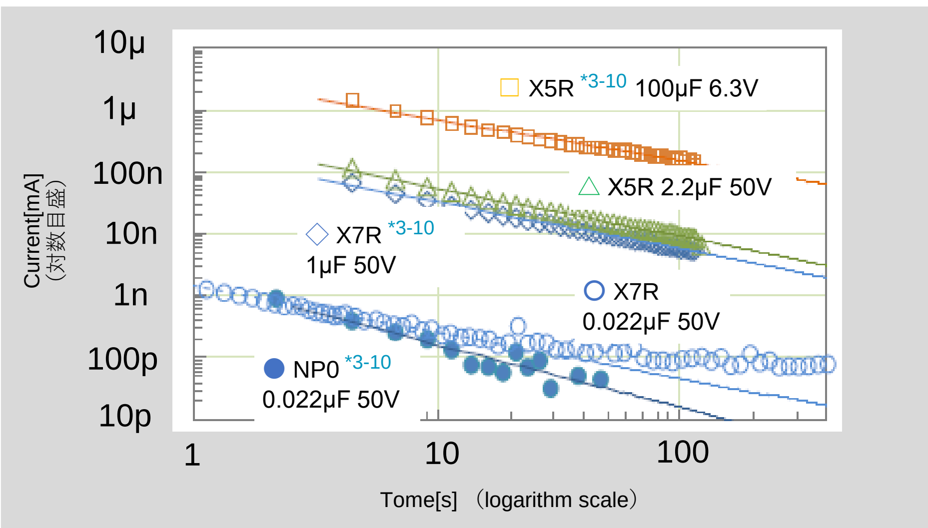

Fig. 3-05

DC current through various ceramic capacitors

*3-07
In this case, the time of about 35 seconds is about 7.4 times the time constant of this charging circuit (4.7s).

*3-08
The currents below 1 μA show fluctuations in measurement due to the fact that the measurement range was fixed at 100 mA.

*3-09
Alexander Teverovsky NASA Electronic Parts and Packaging (NEPP) Program, Screening Techniques for Ceramic Capacitors with Microcracks, Part II. Leakage and Absorption Currents and Voltages in Ceramic Capacitors 2013

*3-10
Figure 3-05 shows data for ceramic capacitors with various temperature characteristics. The symbols in the figure are names according to the EIA standard (EIA-198). Each is defined as follows
・X7R: Capacitance change within ±15% from -55 to +125° C
・X5R: Capacitance change within ±15% in -55 to +85° C
・NP0: Temperature coefficient within 0±30ppm/°C in -55 to 150°C.

(4) Absorption current

The slow, linear, gradual decrease in current with time during charging a capacitor can be explained as the absorption of charge by the dielectric.

As described in Chapter 2, Impedance, actual capacitors have not only capacitance but also parasitic resistance and inductance in series or parallel (Figure 3-06)[*3-11]. Dielectrics also exhibit various behaviors in response to external electric fields. Dielectrics contain electrically polarized dipoles[*3-12] and dipoles are oriented according to the strength of the electric field. As time passes, the dipoles align in chains, and the dielectric material becomes polarized and stores an electric charge (Figure 3-07).

*3-11
The characteristics due to these parasitic components are described in the capacitor manufacturer's data sheet. Parameters for parasitic elements include tanδ, impedance, ESR, and ESL.

*3-12
http://www.ieice-hbkb.org/ Chapter 9, Section 1-1

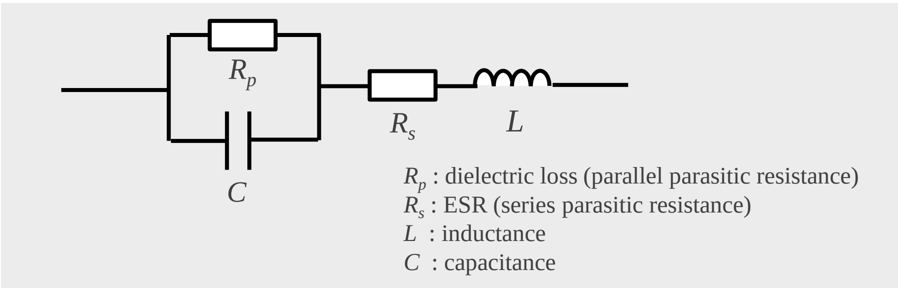

Fig. 3-06 Equivalent circuit, 4-element model
(Reprint Fig. 2-06)

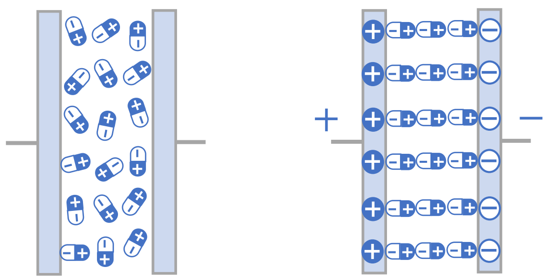

Fig. 3-07
Schematic drawings of dipole conformation
Left: no bias, Right: with bias

The rate at which a dipole responds to an external electric field is called the relaxation time. This relaxation time ranges from a few seconds to tens of seconds for electron-dependent dipoles and up to several hours for large molecular complexes. In other words, a current continues to flow in the dielectric depending on the relaxation time. This current, also called absorption current or polarization current, can be approximated by the time power function in equation (3-08)[*3-13, 3-14, 3-15]

*3-13
Takashi TETSUTANI et.al. Relaxation Spectroscopy of the Dielectric Jl-Relaxation in Poly(n-alkyl methacrylate)s by Absorption-Current Measurements. II. Dielectric Relaxation Spectrum for Isotactic Poly(methyl methacrylate) , Polymer Journal, Vol. 14, No. 6, pp 471-476 (1982)

*3-14
Namika, et.al., J. Ceram. Assoc. Japan 76 [3] 1968

*3-15
Shiraishi et.al., IEEJ Transactions on Electrical and Electronic Engineering 86-1, No. 928, pp 75-84 (1966)

$$i_{abs}(t) = A \times t^{-n} \quad \cdots \quad (3\text{-}08)$$

A, n : constant

$i_{abs}(t)$ in equation (3-08) represents the absorbed current as a function of time, and A and n are constants that depend on temperature. For dielectrics used in ordinary capacitors, the value of n ranges from 0.3 to 1.2. The value of n for each capacitor can be obtained from the data in Figures 3-04b and 3-05, as shown in Table 3-01.

Table 3-01 Parameter n of various capacitors in Fig. 3-04b and 3-05

	Aluminum electrolytic	Multi-layered ceramic capacitor (chip type)		
Supplier	AICtech	A	B	C
Type	GXR	2220, X5R	2225, X7R	2223, NP0
Rated voltage	450V	6.3V	50V	50V
Capacitance	4700μF	100μF	2.2μF	0.022μF
n	**0.73**	**0.65**	**0.75**	**1.01**

*3-15 Shiraishi et.al., IEEJ Transactions on Electrical and Electronic Engineering 86-1, No. 928, pp 168-177 (1966)

The absorption current $i_{abs}(t)$ is closely related to the dielectric loss $\varepsilon''(f)$ of the dielectric. This relationship can be expressed using Hamon's approximation[*3-15] as in equation (3-09).

$$\varepsilon''(f) = \frac{i_{abs}(0.1/f)}{2\pi f \times C_0 \times V} \quad \cdots \quad (3\text{-}09)$$

$\varepsilon''(f)$: permittivity at low frequency
f : frequency

where f is the frequency, $\varepsilon''(f)$ is the dielectric loss factor at frequency f (s^{-1} : inverse of time t), C_0 is the capacitance, and V is the applied DC voltage. $i_{abs}(0.1/f)$ is the absorption current at $t = 0.1/f$ [sec]. For example, ε'' at $f = 0.1$ [c/s] can be calculated from the current value at $t = 0.1/f = 1$ [s] using equation (3-09).That is, the absorption current $i_{abs}(t)$ is used to polarize the dielectric and depends not only on time t but also on capacitance C and voltage V. From this, $i_{abs}(t)$ can be rewritten as the following approximate expression.

$$i_{abs}(t) = k \times C \times V \times t^{-n} \quad \cdots \quad (3\text{-}10)$$

k : constant
C : capacitance
V : voltage

(5) What is capacitor leakage current?

In Figure 3-05, a small capacitor, 0.022 μF 50V, began to have a time-independent steady current flow about 100 seconds (about 1.7 minutes) after the start of charging. This current is different from the charging current or absorption current, which inhibits charge accumulation and causes energy loss. This is called "leakage current i_{leak}". However, leakage current has the following elements

(1) Inherent current caused by the conduction of electrons through the bulk of the dielectric layer.

(2) Current associated with structural or mechanical defects such as cracks or delamination in the dielectric.

(3) Current that bypasses between electrodes without going through the dielectric.

As mentioned in the previous section, to accurately measure pure leakage current that does not include absorption current, it is necessary to confirm that the measured current is the true leakage current by allowing sufficient time for charging. At room temperature and rated voltage, however, measurement can take many hours.

For this reason, the IEC standard specifies a charging time of 1 or 5 minutes for measuring leakage current, depending on the type of capacitor, and the MIL standard specifies 2 minutes or more.

Therefore, it should be noted that the leakage current indicated by the capacitor manufacturer is not the true leakage current, but the current including the absorption current.

(6) Three components of DC current flowing through a capacitor

As mentioned above, the actual DC current flowing through a capacitor consists of three elements: charging current, absorption current, and leakage current. The role and characteristics of each element are summarized in Table 3-02.

Table 3-02 Three components of DC current flowing through a capacitor

	Charging $i_{charge}(t)$	Absorption $i_{abs}(t)$	Leakage i_{leak}
Feature	electric charge for electrodes	dielectric polarization	passing through dielectric or bypassing
Periods	m-sec to μ-sec	a couple of minutes to several days	no dependence on time
Factors[*3-16]	voltage, capacitance, series resistance	voltage, capacitance, dielectric loss, temperature	voltage, capacitance, temperature, humidity

*3-16 The three components are discussed in next section.

As shown in Figure 3-08, the DC current flowing through a capacitor varies with time. That is, when voltage is applied to the capacitor, a charging current flows instantaneously, accumulating charge on the electrodes. When the charge to the electrode ends and the charging current decays, an absorption current flows and dielectric polarization begins. When dielectric polarization ends, a leakage current appears.

Using equation(3-02) and (3-10), the DC current $\boldsymbol{i(t)}$ flowing through the capacitor can be expressed in a mathematical formula as shown in equation (3-11).

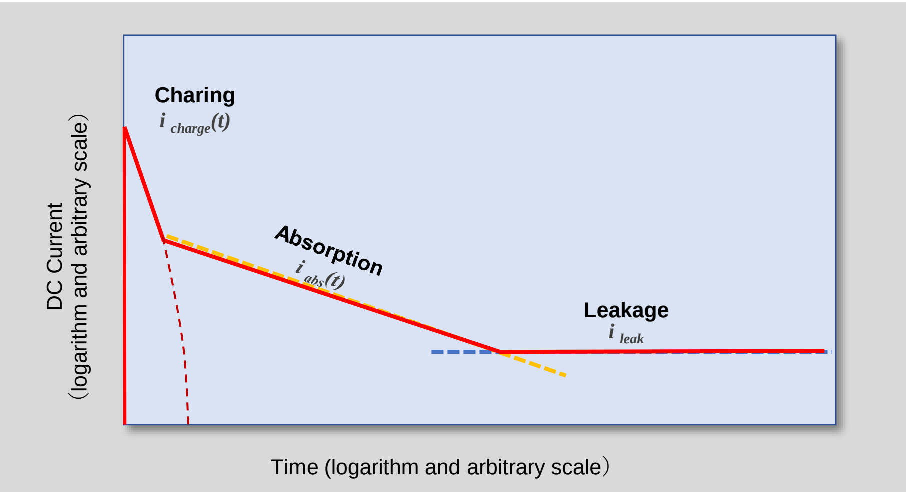

Fig. 3-08
Schematic diagram of DC current flowing through capacitor

$$\begin{aligned} i(t) &= i_{charge}(t) + i_{abs}(t) + i_{leak} \\ &= \frac{V_0}{R_0} exp\left(-\frac{t}{\tau_0}\right) + k\,C\,V\,t^{-n} + i_{leak} \qquad \cdots \quad (3\text{-}11) \end{aligned}$$

Key Takeaway

- **The actual DC current flowing through a capacitor consists of three elements: charging current, absorption current, and leakage current..**
- **The "pure" leakage current is not only a current that is passing through the bulk of the dielectric layer, but also bypassing between electrodes without going through the dielectric.**
- **It should be noted that the leakage current indicated by the capacitor manufacturer is not the true leakage current, but the current including the absorption current.**

3.2 Characteristics of Leakage Current

(1) Voltage dependence（I-V characteristics）

The higher the applied voltage, the larger the leakage current, and the leakage current increases rapidly when the rated voltage is exceeded. Figure 3-09 shows the I-V characteristics of our aluminum electrolytic and film capacitors.

Normally, the I-V characteristics of a capacitor are expressed with a logarithmic scale for the current and a normal scale for the voltage (Figure 3-09), but it is possible to estimate a model of electronic conduction by plotting them in different coordinates.

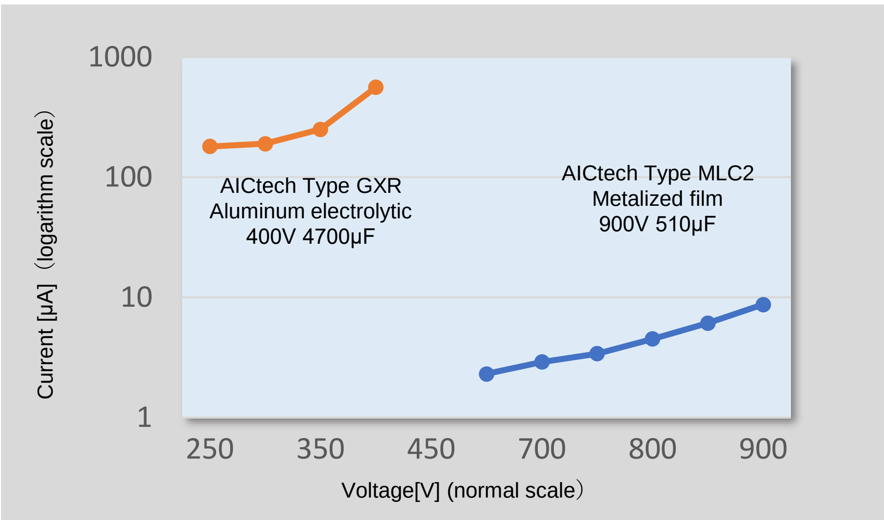

Fig. 3-09 Voltage versus Current

1 CAPACITANCE
2 IMPEDANCE
3 DC LEAKAGE CURRENT
4 CONCLUTION

[Current flow consideration]

It has been confirmed that the current through the dielectric is related to the electron conduction injected by the metal electrode into the insulator[*3-17, 3-18]. There are various views on the model of electron conduction, but the Schottky emission, Poole-Frenkel, space-charge limited, etc. are typical mechanisms have been proposed.

Schottky coordinates[*3-19, 3-20, 3-21] that plot current in logarithms and voltage in square roots, Poole-Frenkel coordinates[*3-22, 3-23] that use the logarithm of current divided by voltage [$\ln(I/V)$] and the square root of voltage ($\sqrt{V}$), or linearization in both logarithmic coordinates [$\ln(I)$ vs. $\ln(V)$] [*3-24, 3-25] are used to prove the model. The slope is then the parameter of the model.

Since these models include an Arrhenius-like temperature dependence characterized by the activation energy E_a, a more detailed examination of the I-V characteristics and their temperature dependence is necessary to clarify the conductive mechanism of the leakage current in the capacitor.

(2) Temperature dependence

The leakage current shows a positive temperature characteristic. The temperature dependence differs depending on the type of capacitor. The leakage current of film capacitors is more temperature sensitive than that of aluminum electrolytic capacitors, and the leakage current increases approximately 2 to 4 times when the temperature increases by 10 degrees Celsius(Fig. 3-10).

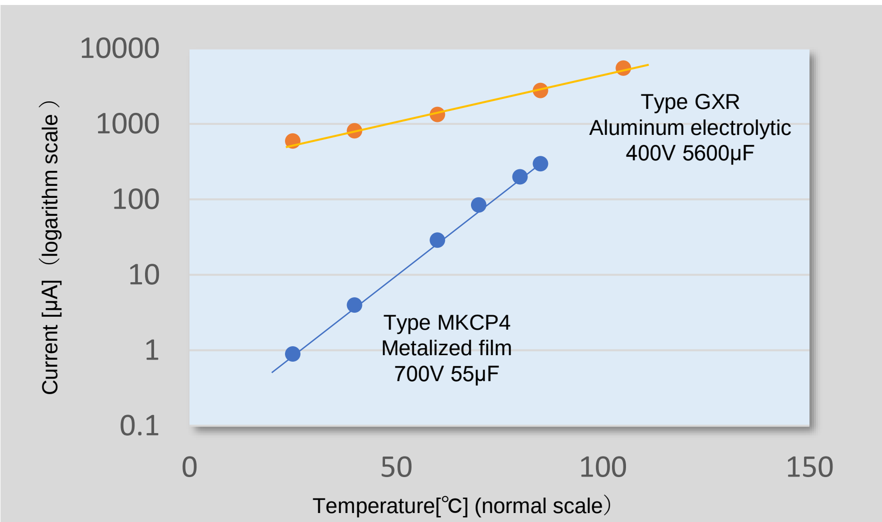

Fig. 3-10 Leakage current versus temperature

*3-17
H. Y. Lee, et al, IEEE Transactions on Components Hybrids and Manufacturing Technology, vol. 7, pp. 443-453, 1984.

*3-18
M. Dawber, et al, Reviews of Modern Physics, vol. 77, pp. 1083-1130, Oct 2005.

*3-19
J. H. Koh, et. al, Integrated Ferroelectrics, vol. 39, pp. 1361-1368, 2001.

*3-20
L. Pintilie, et. al, Physical Review B, vol. 75, Mar 2007.

*3-21
J. C. Shin, et. al, JOURNAL OF APPLIED PHYSICS, vol. 86, pp. 506-513, Jul 1999.

*3-22
E. Loh, et. al, Journal of Applied Physics, vol. 53, pp. 6229-6235, 1982..

*3-23
P. Zubko, et. al, Journal of applied physics, vol. 100, Dec 2006.

*3-24
L. C. Burton, Virginia Polytechnic Inst. and State Univ., Blacksburg, VA, ADA199113, 1998.

*3-25
F. D. Morrison, et al, Applied Physics Letters, vol. 86, Apr 2005.

Leakage current of aluminum electrolytic capacitors tends to increase more in the high temperature range than in the low temperature range.

Using the results in Figure 3-10, an Arrhenius plot of the leakage current is plotted, and the activation energy ***Ea*** of the leakage current is compared as shown in Figure 3-11.

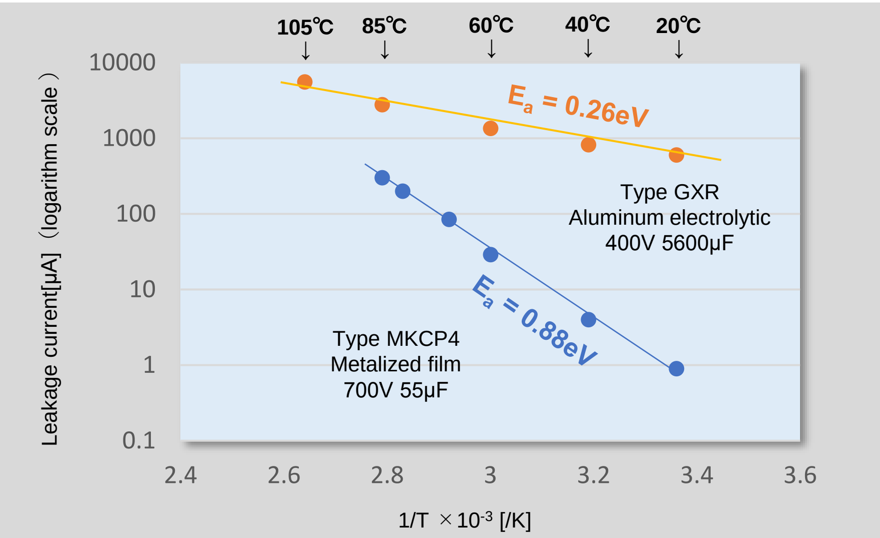

Fig. 3-11 Arrhenius plot of leakage current

Since the activation energy ***Ea*** of film capacitors is 3 to 4 times larger than that of aluminum electrolytic capacitors, so some care might be taken when using film capacitors at high temperatures[*3-26] . Since the activation energy of aluminum electrolytic capacitors is not uniform across the temperature range, the conductive mechanism is considered to be different at low and high temperatures.

Leakage current varies with temperature and voltage. However, it is difficult to clearly define and predict the trend in actual capacitors. On the other hand, knowing the I-V characteristics and temperature characteristics of leakage current in advance is extremely important not only for capacitor selection, but also for circuit design and quality assurance. For this reason, we recommend that you contact the capacitor manufacturer for the temperature and voltage characteristics of the leakage current, if necessary.

*3-26
The activation energy of ceramic capacitors is reported to be 0.55 to 1.1 eV in the following literature
Alexander Teverovsky, NASA Electronic Parts and Packaging (NEPP) Program, Screening Techniques for Ceramic Capacitors with Microcracks, Part II. Leakage and Absorption Currents and Voltages in Ceramic Capacitors 2013

(3) Dielectric Absorption（DA）

When the capacitor is fully charged, an absorbing current flows for a long time and the dipoles in the dielectric form a dipole chain (Figure 3-07). When the capacitor is discharged, it takes a corresponding amount of time to restore the dipole chain to its original state. And most capacitors do not release all of their charged charge. Assume that the capacitor is charged, then momentarily short-circuited, and finally opened (Figure 3-12). When shorted, the charge on the electrodes is discharged and instantly dissipated, but the dipole chain remains aligned with the captured charge.

When the capacitor is opened, the alignment of the dipole chain begins to break down, again inducing a charge on the electrodes. This voltage is called dielectric absorption*[3-27] . Dielectric absorption is observed not only in aluminum electrolytic and ceramic capacitors, but also in tantalum and film capacitors. Dielectric absorption depends mainly on the properties of the dielectric material itself, but can also be affected by the capacitor manufacturing process and electrode material.

*3-27
This is also called “recovery voltage”. It’s discussed in Chapter 1.

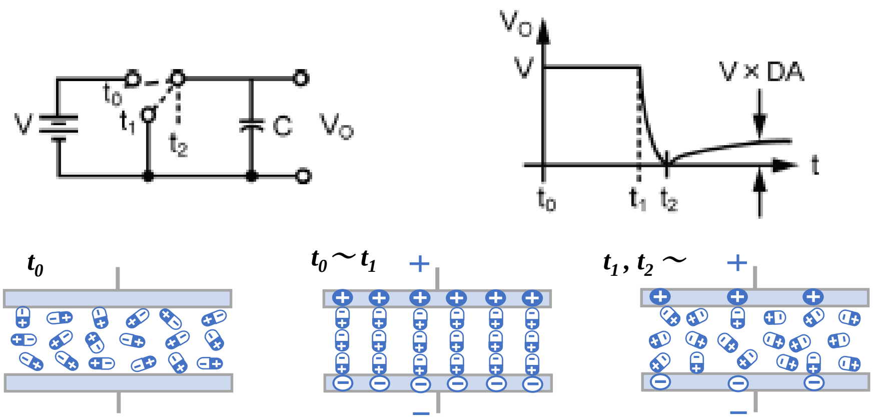

Fig. 3-12 Charging and discharging of capacitor

The measurement of dielectric absorption (DA) is specified in MIL-PRF-1978 as follows (1) Charge the capacitor at rated voltage for 1 hour. (2) Discharge the capacitor for 10 seconds. (3) Measure the recurrent voltage with a voltmeter having an input resistance of 10,000 MΩ or more at the maximum voltage within 15 minutes. (4) Calculate the ratio of the maximum recurrence voltage to the charging voltage as DA.

Film capacitors made of polypropylene or polyphenylene sulfide show very small DA[*3-28]. On the other hand, ceramic capacitors[*3-29], aluminum electrolytic capacitors, and tantalum capacitors with high dielectric constant show large values.

High dielectric absorption can degrade accuracy and cause errors in analog circuits such as sample-and-hold circuits, analog-to-digital converters, and active filters[*3-29]. Dielectric absorption can also cause errors in voltage-to-frequency conversion circuits of voltage-controlled oscillators (VCOs) [*3-29]. Special compensation circuits have been applied to reduce the effects of dielectric absorption in some high-sensitivity, high-precision applications[*3-30, 3-31]. Table 3-03 summarizes the DA of major capacitors.

*3-28
http://www.national.com/rap/Application/0,1570,28,00.html

*3-29
X. Xu, et al. "Advances in Class-I C0G MLCC and SMD Film Capacitors," in The 28th symposium for passive components, CARTS'07, Newport Beach, CA, 2008.

*3-30
J. C. Kuenen and G. C. M. Meijer, "Measurement of dielectric absorption of capacitors and analysis of its effects on VCOs," Instrumentation and Measurement, IEEE Transactions on, vol. 45, pp. 89-97, 1996.

*3-31
C. Iorga, "Compartmental analysis of dielectric absorption in capacitors," Dielectrics and Electrical Insulation, IEEE Transactions on, vol. 7, pp. 187-192, 2000.

Table 3-03 Dielectric Absorption (DA) of various capacitors

Capacitor type	dielectric	DA [%]
Ceramic capacitor	Class1, NP0 Class2, X7R	0.6 2.5
Film capacitor	polypropylene(PP) polyethylene terephthalate (PET) polyphenylene sulfide(PPS) polyethylene naphthalate(PEN)	0.05 ～ 0.1 0.2 ～0.5 0.05 ～ 0.1 1.0 ～ 1.2
Tantalum capacitor Aluminum capacitor	tantalum oxide (Ta_2O_5) aluminum oxide (Al_2O_3)	2 ～ 10% 10 ～ 15%
EDLC	–	～30%

(4) Leakage current and self-healing

Defective areas or spots in the dielectric can cause leakage current. However, when a charging current rushes into that area, the current energy makes repair or intercept that area and the electrode layer, returning it to a normal state. This is called self-healing. However, this healing mechanism varies from capacitor to capacitor. This section outlines self-healing in metalized film capacitors, aluminum and tantalum capacitors.

【Metalized film capacitor】

Self-healing is frequently observed in evaporated-electrode film capacitors. These capacitors contain defects in the film and mechanical damage from the manufacturing process. When a voltage is applied to the film capacitor, current is concentrated in these defective spots and a localized arc is generated.

The energy of the arc evaporates a small area of the deposited metal layer around the defect, physically separating the defect from the low insulation (Figure 3-13). The capacitor thus returns to its electrically normal state, and the leakage current originating from the defect is reduced[*3-32]. However, if self-healing occurs frequently, the capacitance will decrease[*3-33, *3-34].

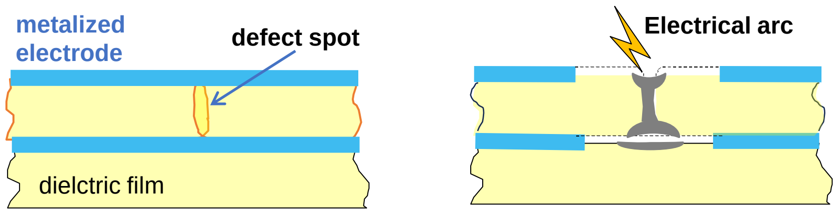

Fig. 3-13 Self-healing at metalized film capacitor

【Polymer cathode aluminum, and tantalum capacitor】

In aluminum electrolytic and tantalum capacitors using conductive polymers as the cathode, when current flows through a defective spot in the dielectric, Joule heat is generated and the defective spot is heated to about several hundred degrees Celsius. As a result, the conductive polymer loses its conductivity and becomes insulating, blocking the current to the defective spot. [*3-35, 3-36]

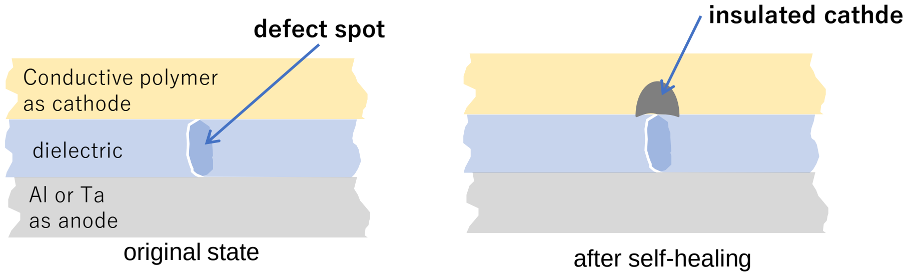

Fig. 3-14
Self-healing of Polymer cathode aluminum, and tantalum capacitor

【Electrolyte cathode aluminum capacitor】

Self-healing of aluminum electrolytic capacitors, electrolyte cathode, is a process in which defective spots are electrochemically repaired by ions in the electrolyte. In other words, the defective spot is anodized and remolded into a new dielectric[*3-37]. In the manufacturing process of this capacitor, there is a process that uses self-healing to stabilize the leakage current[*3-38].

*3-32
The magnitude of this energy is not enough to break down or carbonize the film.

*3-33
J.H. Tortai, N. Bonifaci, A. Denat, C. Trassy, Diagnostic of the Self-healing of Metallized Polypropylene Film by Modeling of the Broadening Emission Lines of Aluminum Emitted by Plasma Discharge, J. Appl. Phys. (2005), pp.053304.

*3-34
G. Picci, M. Rabuffi, Status Quo and Future Prospects for Metallized Polypropylene Energy Storage Capacitors, Ieee T. Plasma Sci. (2002), pp.939-1942

*3-35
https://nepp.nasa.gov/docs/tasks/003-Evaluation-Polymer-Tantalum-Capacitors-for-Space-Applications/2020-NASA-TM-Teverovsky-MnO2-Polymer-Tantalum-Capacitors-20205011704.pdf

*3-36
15K.S. Jang, B. Moon, E.J. Oh, H. Lee, Characteristics of tantalum electrolytic capacitors using soluble polypyrrole electrolyte, J. Power Sources (2003), pp. 338-442

*3-37
This process is also called "reformation" or "aging".

*3-38
In this process, a DC voltage greater than the rated voltage but less than the anodizing voltage is applied to the capacitor at the rated temperature. Appropriate re-generating reduces the probability of infant mortals.

Self-healing has the effect of reducing the leakage current of the capacitor. The mechanism, however, depends on the type of capacitor (Table 3-04). Although self-healing is essential to improve capacitor reliability, it should be noted that self-healing may not function under conditions such as a defect spot that is too large to repair, high temperatures exceeding the maximum operating temperature, overvoltage, or high currents.

Table 3-04 Self-healing (SH) features by capacitor type

	Electrolyte cathode Aluminum capacitor	Polymer cathode Al, Ta capacitor	Metalized Film capacitor
Charge carriers for SH	ion（OH^-）	electron	electron
Healing spot	electrode/ dielectric interface and inside dielectric	electrode/ dielectric interface	NA
Process	Electrochemical (anodization)	Physical (Joule heat)	Physical (Joule heat)

Key Takeaway

- **Leakage current increases at high temperatures and high voltages.**
- **Since the behavior and changes in leakage current vary depending on the type of capacitor, it is extremely important to understand the trend in advance.**
- **The higher the capacitance of a capacitor, the greater the dielectric absorption, so care must be taken when using it.**
- **Self-healing reduces leakage current.**
- **However, self-healing has different mechanisms depending on the type of capacitor and may not work under harsh conditions**

3.3 Leakage Current of Aluminum Electrolytic Capacitors

Aluminum electrolytic capacitors are critical components that have a significant impact on the performance of desiccant and power electronic equipment. In these applications, the characteristics of aluminum electrolytic capacitors directly affect the life and reliability of the equipment. This section focuses on the leakage current of aluminum electrolytic capacitors, providing an overview of the technology, characteristics of leakage current, and reliability.

(1) Dielectric of aluminum electrolytic capacitor

The aluminum oxide dielectric formed on the surface of the anode is in almost complete contact with the electrolyte of the cathode (Figure 3-15). The dielectric is formed as an ultrathin film on the aluminum surface by an electrochemical process called anodic oxidation or anodization. The dielectric not only affects capacitance, but also has a significant impact on withstand voltage and leakage current characteristics, which directly affects the reliability of aluminum electrolytic capacitors. The anodic oxide layer of aluminum can be roughly classified into a porous type produced in an acidic (or basic) solution and a barrier type produced in a neutral electrolyte bath, the latter being used in aluminum electrolytic capacitors[*3-39] .

*3-39
Barrier-type layers are thinner than porous one and are used for aluminum electrolytic capacitors and insulating substrates, taking advantage of their electrical properties such as dielectric and insulation properties.

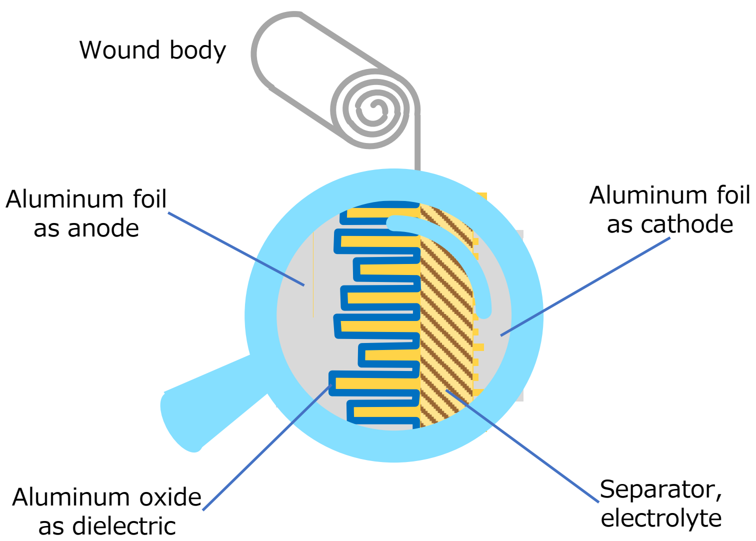

Fig. 3-15
Element structure of aluminum electrolytic capacitor (Reprint of Fig. 1-15)

Figure 3-16 shows a cross-sectional schematic of the dielectric layers. A layer of amorphous aluminum oxide directly contact to aluminum foil anode, followed by a layer of crystalline aluminum oxide, with a layer of hydrated oxide (aluminum hydroxide) on the top surface[*3-40, *3-41, *3-42] 。

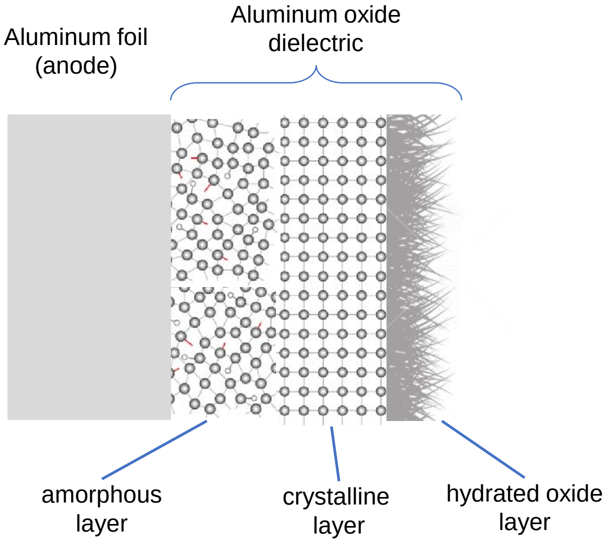

Fig. 3-16
A cross-sectional schematic of the dielectric layers

*3-40
The formation of aluminum oxide involves multiple steps of hydration, anodization, heat treatment, and phosphating, and this process is believed to create the structure shown in Figure 3-15.

*3-41
Tanaka, et.al., Journal of the Surface Finishing Society of Japan, **69**, (12) pp542- 543, (2018)

*3-42
Sining Pan et.al, "Microstructure evolution for oxide film of anodic aluminum foil used in high voltage electrolytic capacitor ".Journal of Alloys and Compounds Volume 823, 15 May 2020, 153795

Amorphous layers do not have the translational symmetry of crystals, and molecules are loosely bound to each other with little interaction. This feature results in less heat generation due to fluctuations in the electric field caused by alternating current. Molecules in the crystalline layer are more densely arranged and strongly bonded, resulting in high insulation resistance and low leakage current. Molecules in the hydration layer are easily polarized and generate relatively large losses. At high temperatures, water molecules dissociate from the hydration layer and the layer becomes brittle, which is thought to increase leakage current. Therefore, in order to create a good quality dielectric layer, it is important to stabilize the hydration layer and to use technology to thicken the amorphous and crystalline layers. We have excellent features in anode foil and dielectric formation technology.

(2) Leakage current, its specification and actual values

We apply the standard in accordance with JIS C 5101-4:2019 (IEC 60384-4:2016). Table 3-05 shows an example of the specified values of leakage current for our aluminum electrolytic capacitors.

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2 IMPEDANCE
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4 CONCLUTION

Table 3-05 The leakage current specifications of AICtech aluminum capacitor

Type	Screw terminal VFR	Screw terminal HCGW3	Snap-in HU3
specification	0.01CV or 5mA	0.01CV or 7mA	0.02CV or 3mA

Leakage current is measured after 5 minutes of applying the rated voltage at 20°C. However, for capacitors with large capacitance or high rated voltage, the leakage current is not constant because the absorption current continues to flow even after 5 minutes. In other words, the specified value of leakage current is not the pure leakage current, but the value including the absorbed current.

In principle, the standard value of leakage current is obtained by multiplying the product of capacitance and voltage by a coefficient. This coefficient can be thought of as the constant k in equation (3-11), with the unit being μA / (μF x V). Leakage current, which are industrial products, varies widely. For this reason, the standard value of leakage current is set with a margin to the actual value in consideration of economic efficiency. The margin varies depending on the type of capacitor, but is generally 1/10 to 1/100 of the specified value.

(3) Notification

The main cause of leakage current in aluminum electrolytic capacitors is dielectric defects. However, defects can be caused by a variety of factors, including manufacturing damage (e.g., foil cutting, tab crimp connections), various lattice defects in the crystal, the presence of dissimilar atoms in the aluminum substrate layer, mechanical stress, and partial dissolution of the oxide film into the electrolytic solution. As shown in Figure 3-04b, the current flowing through an aluminum electrolytic capacitor when charged decreases almost exponentially immediately after the application of voltage, and after dielectric absorption, a leakage current of almost constant value finally appears. If the capacitor is manufactured by a controlled process, the effects of bypass current[*3-43] and tunneling effect[*3-44] on the leakage current can be ignored. As mentioned above, the leakage current of aluminum electrolytic capacitors depends on time, magnitude of applied voltage, and temperature, but there are additional considerations that must be taken into account when using these capacitors.

*3-43
This is a current that does not pass through the dielectric but bypasses between the electrode terminals.

*3-44
It is a phenomenon in which an electron passes through the dielectric insulating potential (potential energy) of a dielectric.

【Reverse voltage】

Since aluminum electrolytic capacitors are polarized, reverse voltage must not be applied. When a reverse voltage is applied, i.e., a forward voltage to the cathode of the electrolyte and a negative voltage to the dielectric layer, hydrogen ions collected in the dielectric layer pass through the layer as proton current, reach the boundary between the layer and the metal layer, and are converted to hydrogen gas (Figure 3-17). The expansion force of this hydrogen gas causes the dielectric layer to peel off, and after the electrolyte decomposes, a current flows through the capacitor and the capacitor fails[*3-45]. Therefore, when a reverse voltage is applied, a large leakage current continues to flow, gas is generated inside the capacitor, pressure rises, and the pressure relief vent may open and fail (Figure 3-18).

*3-45
The mechanism of applying reverse voltage to aluminum electrolytic capacitors has been reported in many papers. The following paper is a review.
J. W. Diggle, Thomas C. Downie, and C. W. Goulding, Chem. Rev., 1969, 69 (3), 365-405

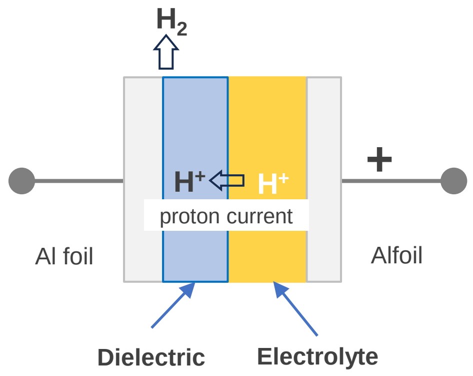


Fig. 3-17
A cross-section of capacitor element

Reverse voltage was applied and hydrogen gas was generated, causing the internal pressure of the capacitor to increase and the pressure relief vent to open.

Fig. 3-18
Opened vent due to reverse voltage

The reverse voltage allowed by aluminum electrolytic capacitors is very small, only a few volts for those with electrolyte. jis c 5101-4:2019 (IEC 60384-4:2016) The reverse voltage test condition specified in JIS C 5101-4:2019 (IEC 60384-4:2016) is 1 V at the upper category temperature (Condition A; test duration 125 hours).[*3-46]

*3-46
The reverse voltage of conductive polymer type capacitors without electrolyte is 0.15 times the rated voltage

【Storage】

When aluminum electrolytic capacitors are stored for a long period of time without a load (without applying DC voltage), the leakage current increases.

Fig. 3-19 Storage（image）

The higher the storage temperature, the more pronounced this phenomenon becomes. Therefore, care should be taken when using aluminum electrolytic capacitors that have been stored for a long time as maintenance parts.

This is said to be because the high temperature degrades the insulating property of the oxide film of the dielectric[*3-47]. The same thing also happens to capacitors that have been transported for a long period of time, even if they have just been delivered from the manufacturer. Low-voltage capacitors using organic solvent electrolytes (rated voltage up to 100V) are relatively stable, but high-voltage capacitors using ethylene glycol electrolytes (rated voltage from 160V), especially capacitors of so-called “low ESR specifications” using water-based electrolytes, may show increased leakage current. Unless otherwise specified, our aluminum electrolytic capacitors are not suitable for this purpose. Unless otherwise specified, our aluminum electrolytic capacitors can be stored without voltage for 3 years at temperatures from +5 °C to +35 °C and relative humidity below 75%[*3-48] . Within this period, the capacitors can be used at their rated voltage without modification after they are removed from storage. Figure 3-20 shows the results of a study of changes in leakage current after long-term storage of our screw terminal type aluminum electrolytic capacitors. The leakage current increased by a factor of 2 to 3 regardless of the type and rating of the capacitor.

*3-47
Some reports state that dielectric films dissolve to some extent depending on temperature and electrolyte composition, but that oxide films do not regenerate (self-heal) unless voltage is applied.
Thiesbürger, K.H., Der Elektrolytkondensator, Roederstein, Landshut (1991)

*3-48
For capacitors that are soldered to the board, the capacitors must be mounted within 2 years to prevent soldering problems.

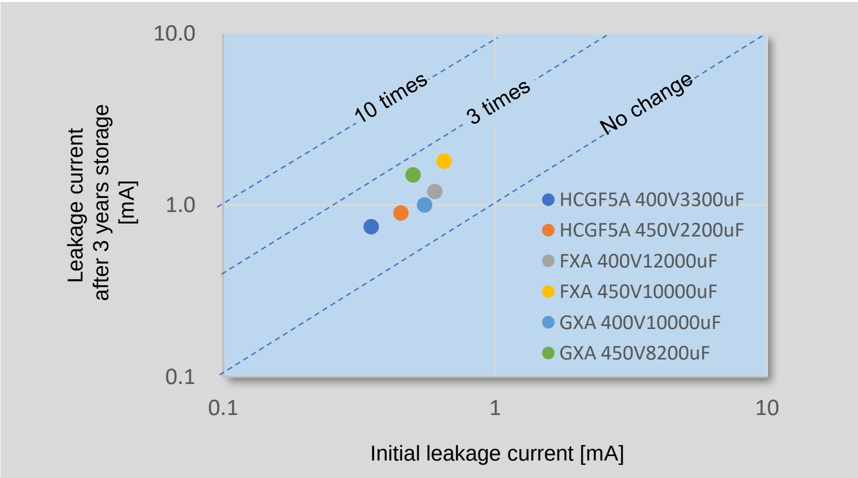


Fig. 3-20
Leakage current change of aluminum capacitor at initial and after 3-years storage

【Capacitor bank and voltage blancing】

In AC drive systems (Figure 3-21), welding converters, and switching-mode power supplies for telecommunications equipment, the DC voltage link between converter and inverter is connected to a 400/500 V three-phase supply. In these applications, two aluminum electrolytic capacitors may be placed in series together with a voltage divider resistor. The reason for the series connection is that the DC link voltage level of the converter is typically 500-800 V, while the maximum voltage rating of the aluminum electrolytic capacitors is only 500-600 V, making it difficult to design with a single capacitor.

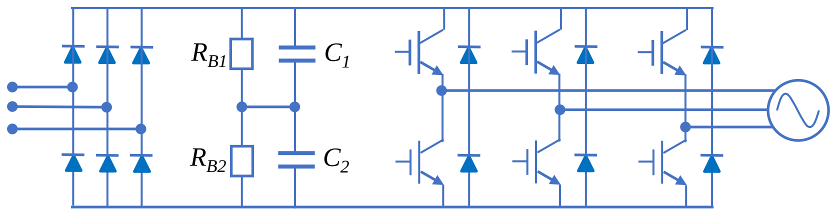
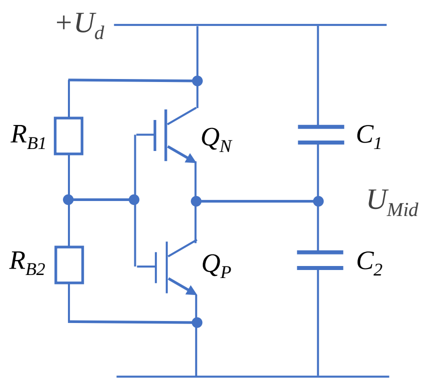


Fig. 3-21
AC drive system with two electrolytic capacitors connected in series. Circuit topology of a three-phase power converter

In a series connection of capacitors, the voltage across the individual capacitors is divided according to the ratio of the capacitor's insulation resistance (or the ratio of the capacitor's leakage current)[*3-49]. However, if the divided voltages are unequally balanced, the overall efficiency of the equipment will be reduced and the life of the capacitors will be shortened [*3-50]. For this reason, it is important to divide the voltage evenly.



U_d : line voltage, U_{Mid} : Middle voltage
R_B : High impedance divider
Q_N, Q_P :Emittor follower

Fig. 3-22
Stabilizes the midpoint voltage U_{Mid} and improves power dissipation Improved voltage balancing circuit[*3-51]

It is necessary to optimize the resistance of the voltage divider resistor or to design the current through the resistor so that it exceeds several times the leakage current, and technologies to solve these problems have been reported in recent years (Figure 3-22)[*3-51].

*3-49
CLC/TR 50454:2008, Guide for the application of aluminium electrolytic capacitors, CENELEC, Brüssel (2008)

*3-50
When converters are constantly connected to the main power supply, as in industrial equipment, the losses due to the voltage divider resistors cannot be ignored in terms of energy and cost. In addition, the voltage divider resistors are often installed close to the capacitors as a heat source, posing a risk to the capacitors and other de-energizers.

*3-51
H. Ertl et al, "Active voltage balancing of DC-link electrolytic capacitors" https://www.pes-publications.ee.ethz.ch/uploads/tx_ethpublications/ertl_IET-PE_2008_.pdf

Since the leakage current of aluminum electrolytic capacitors varies depending on operating conditions and long-term use, it is effective to reduce the deviation of leakage current of capacitors connected in series by combining capacitors of the same production lot or using capacitors with low leakage current specifications.*3-52

*3-52 Since aluminum electrolytic capacitors have a capacitance tolerance of ±20% and voltage sharing is performed according to the capacitance deviation in the initial stage of charging, consideration must also be given to capacitance in series connection.

3.4 Leakage Current Summary

[Leakage Current]

- Leakage current inhibit the accumulation of electric charge and cause energy loss.
- The magnitude of leakage current is affected by dielectric composition and defects, time, voltage, and temperature.
- Under normal conditions (normal temperature and short charge time), the leakage current is observed as a combined current with the absorption current.

[Leakage Current of Aluminum Capacitor]

- Since it is highly dependent on the physical properties of the oxide film that is the dielectric, the leakage current can be optimized by properly controlling the process of forming the dielectric.
- If a reverse voltage is applied, a large leakage current will continue to flow, leading to failure. Leakage current also increases when voltage is left unapplied.
- Since there is variation in leakage current, care must be taken when using series connection.

The model and applicability of the leakage current described in this chapter vary depending on the conditions of use, type of product, and application. Therefore, in applications where the magnitude of the leakage current greatly affects the performance of the equipment, counseling by the capacitor manufacturer is recommended.

CONCLUTION

Capacitors come in a variety of types and characteristics depending on the dielectric, and are essential devices used in both digital and analog circuits.

The unique properties and performance of each capacitor, such as operating voltage, capacitance, dissipation and frequency response, leakage current, device size, and frequency response, allow customers to select the best capacitor for their application.

However, a real capacitor is not an ideal component with capacitance alone. There are parasitic resistors and inductances in series with the capacitance, as well as resistors in parallel with the capacitance. These can cause losses.

For this reason, this report describes the most basic and important characteristics of capacitor performance: capacitance, impedance, and leakage current.

We continues to improve its dielectric performance, capacitor construction, and manufacturing technology to provide compact, low-loss, and highly reliable products. At the same time, we ask our customers to properly select capacitors with quality and reliability that meet the requirements of their applications, to take safety design and safety measures, and to conduct thorough evaluations in advance.

We hope that this report will be of help to you in selecting the right capacitors, improving the functionality of your application, and maintaining your capacitors.

Thank you for taking your time to read this report. If you have any questions, please do not hesitate to contact us.

Bibliography

Editorial supervision／Kazuyuki Iida
General Advisor, AIC tech Inc.

【Background】

Born in the Tokyo area in 1956
M.S. of Sc, Sophia University, Tokyo, Japan. 1982
Over 35 years experience with knowledge on capacitor technology, i.e. R&D for high-performance capacitor and its materials, marketing activities at Hitachi Chemical Co, Ltd. and Hitachi AIC Inc. and Contributed articles on capacitors to public relations magazines, trade journals, and various handbooks.
Instructor of capacitor technology at the Technical Training Institute of Hitachi, Ltd. from 2005 to 2015.
General advisor to AIC tech Inc. from 2020.

【 Major Contributions and Lectures 】

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AIC tech Inc.
1065, Kugeta, Moka, Tochigi 321-4521, Japan
https://aictech-inc.com