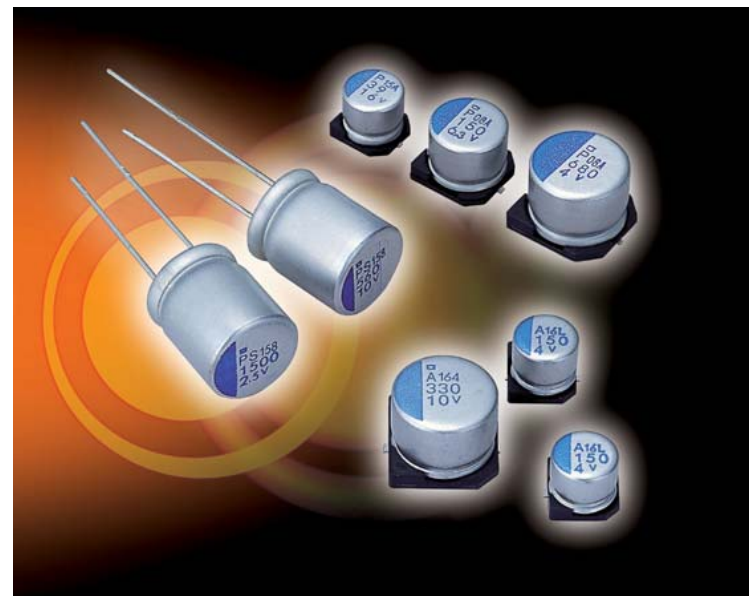# Conductive Polymer Aluminum Solid Capacitors

Application Note

The data which this application note shows are typical values, and they are not guaranteed values. Contents in this application note are subject to change without notice.

Conductive polymer aluminum solid capacitors, which will be abbreviated to "polymer capacitors" in the following, have been recently extending in their applications. The polymer capacitors as well as conventional aluminum electrolytic capacitors are featured by large capacitance and excellent bias characteristics which multilayer ceramic capacitors can never compete with. In addition to these advantages that aluminum electrolytic capacitors have as well, the polymer capacitors have extremely low ESR characteristics. Regarding ESL, which it is determined by inside structure and terminal configuration of the capacitors, by making structural improvements the polymer capacitors have low ESL compared with the conventional aluminum electrolytic capacitors.

Also, concerning the dry-out of electrolyte in service life and the changes of characteristics at a range of low temperatures that have been regarded as disadvantages in aluminum electrolytic capacitors, the polymer capacitors have realized very high reliability and superior low temperature characteristics by using solid polymer materials as an electrolyte.

The polymer capacitors having these features have been demonstrating their capabilities in various fields. Their common uses are described in this application note.

Large Capacitance

Low ESR／ESL

High Reliability

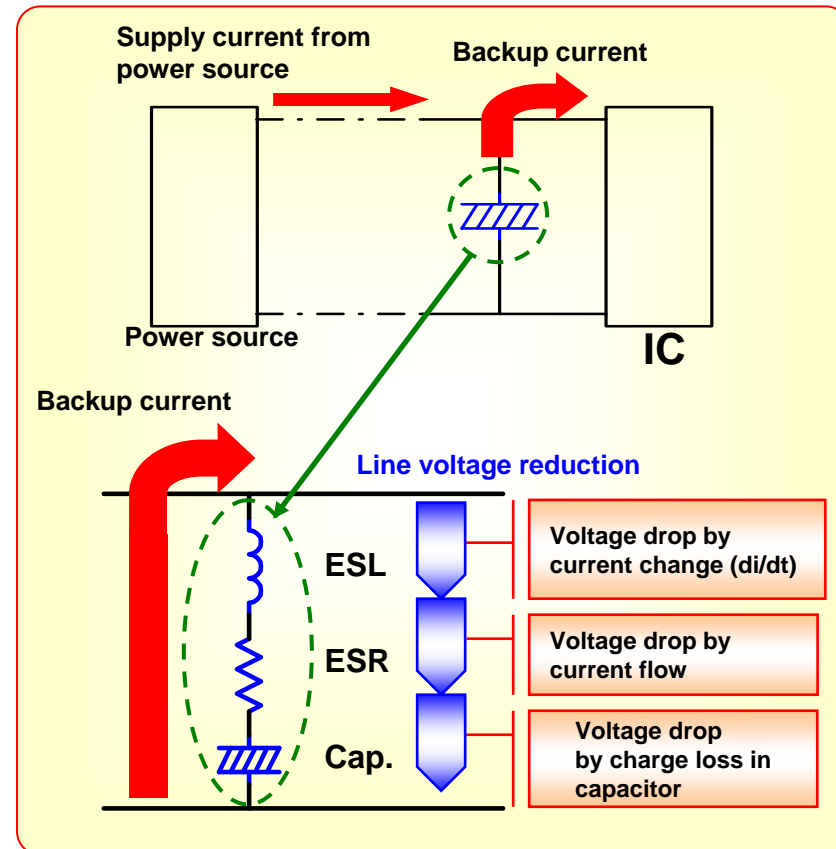**Excellent characteristics at low temperatures**
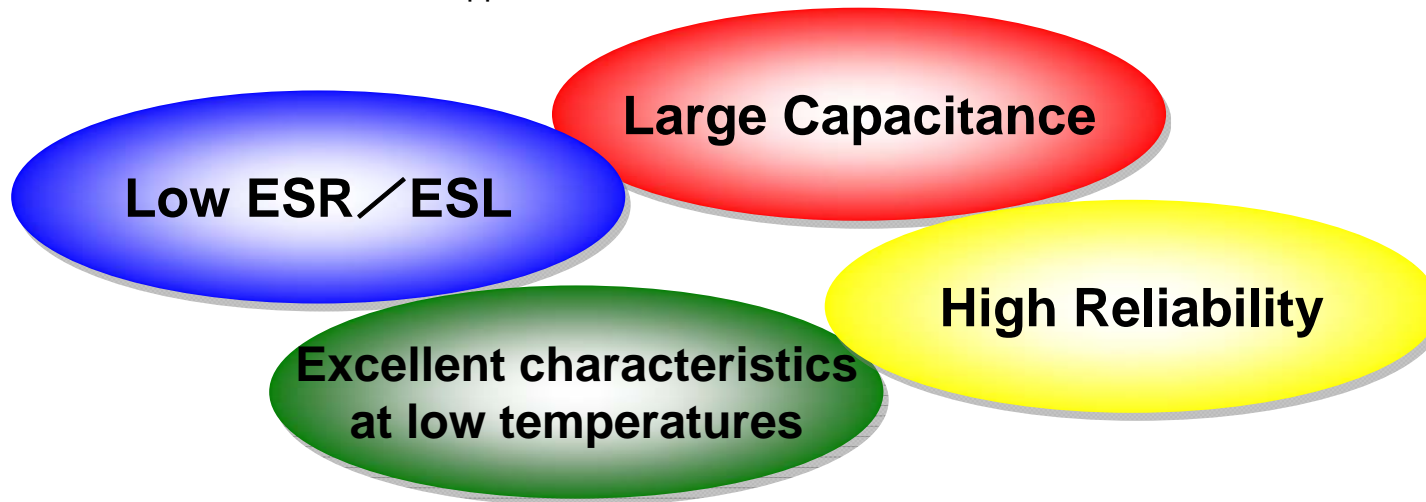
1. Uses: For backup

Load currents in ICs, etc. are not constant and always change with its operation. As the load rapidly changes, the power supply unit cannot supply a sufficient amount of current to the ICs, etc., causing line voltage to drop with the result of malfunction or stoppage of IC operation.

Capacitors for backup as used here can mitigate the drop in line voltage by playing a role of power supply temporarily. However, a capacitor contains equivalent components of resistance and inductance in series, called ESR and ESL respectively. These affect the capacitor's backup function.

ESR causes a drop in line voltage in proportion to the current that capacitor discharges. ESL causes another drop in the voltage in proportion to the change amount of current as a rapid change in current occurs. Also, since the capacitor keeps discharging until the power supply unit will respond to the load change, the voltage that capacitor discharges and supplies will decrease. For this reason, the capacitors used for backup need to have large capacitance rating as well as low ESR and low ESL.

Since polymer capacitors have low ESR, low ESL and large capacitance, they have excellent response to a change in the load, thereby being able to support a change in the load in ICs, etc.

Supply current from power source — **Backup current**

Power source — **IC**

Backup current

Line voltage reduction

ESL — Voltage drop by current change (di/dt)

ESR — Voltage drop by current flow

Cap. — Voltage drop by charge loss in capacitor

Low ESL ⟹ Support rapid current change

Low ESR ⟹ Voltage drop is small even through large current flows

Large capacitance ⟹ Reduce voltage drop for a long period of time

1. Uses: Bypass and decoupling

■**Bypass capacitors**

There may be noises in current (voltage) which will be supplied into an IC, etc. through a power supply line. The noises come to cause the IC, etc. to malfunction in their operation. The AC noises can be shunted to the ground by bypassing the power supply lines by a capacitor.

■**Decoupling capacitors**

Spike containing harmonic current, which IC generates by its operation, flows into a power supply line. A decoupling capacitor functions to circulate the harmonic current in a short loop. If the decoupling capacitor is unable to handle an ample amount of harmonic current, a long loop of harmonic current is formed and the harmonic current flows into the power supply unit. This forms an antenna and becomes the cause of emission noise.

It is said that capacitors used here should have low impedance and sufficient capacitance. Therefore, polymer capacitors are very effective as decoupling and bypass capacitors for power supply lines and so forth.
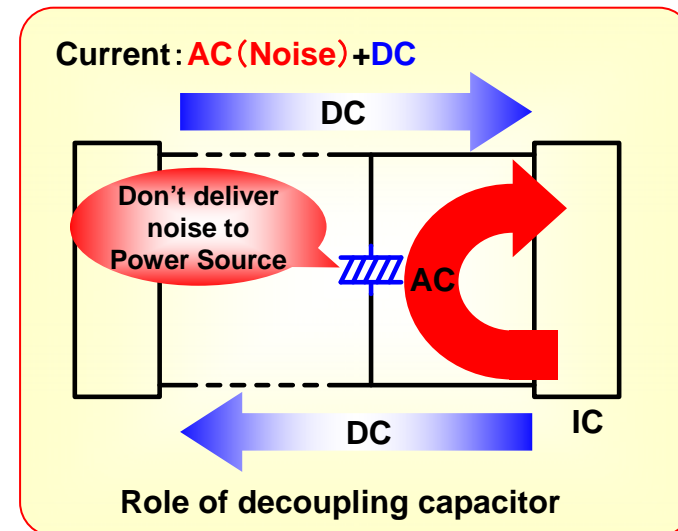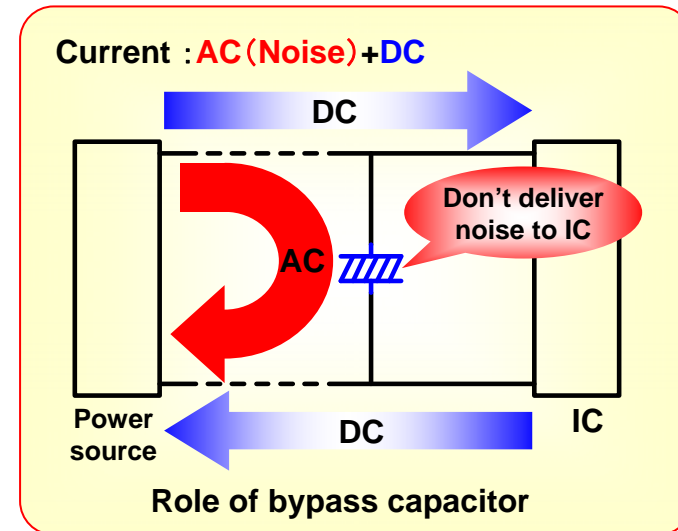
Bypass capacitor ⟹ Don't deliver noise from power source to IC

Decoupling capacitor ⟹ Don't deliver noise on IC to power source, etc.

Current：AC（Noise）+DC

DC

Don't deliver noise to IC

AC

Power source

DC

IC

Role of bypass capacitor

Current：AC（Noise）+DC

DC

Don't deliver noise to Power Source

AC

DC
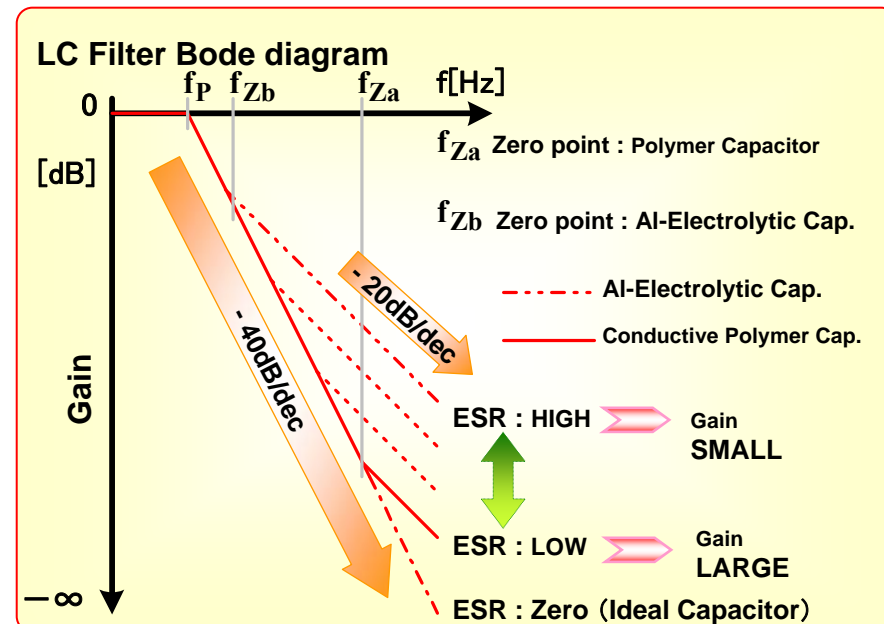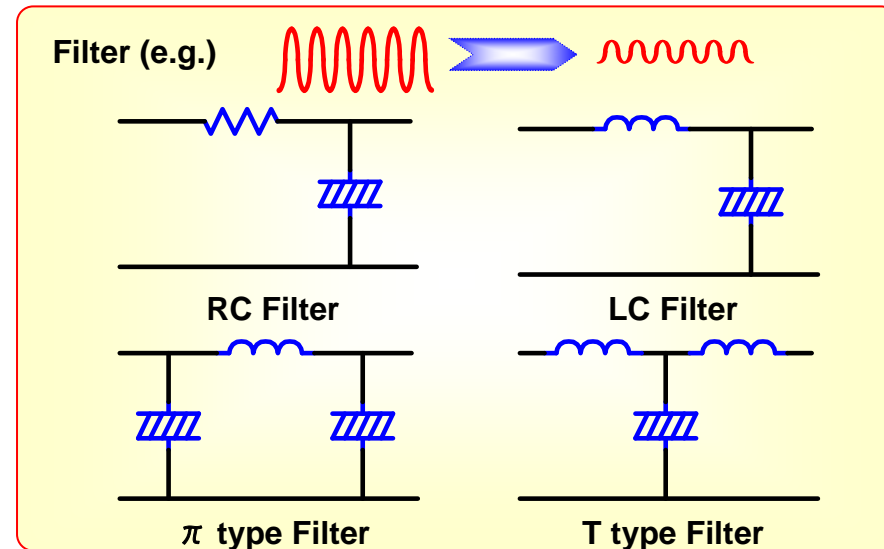
IC

Role of decoupling capacitor

1. Uses: Filtering

When using a capacitor in the low-pass filter to reduce switching noises or to separate a power supply line in a mixed digital-analog circuit, polymer capacitors are the optimum choice because of their advantages of large capacitance, good temperature characteristics and long-life performance. The polymer capacitors especially have characteristics of low ESR. Therefore they have extremely high gain characteristics in the filter at a range of high frequencies.

As an example, the gain characteristics of an LC filter is shown in the chart on the lower right. Based on the transfer function, the LC filter has each frequency called "pole" and "zero point" as shown in the equations below. The zero point depends on the ESR of the capacitor.

Pole $f_{P} = \dfrac{1}{2\pi\sqrt{LC}}$ Zero point $f_{z} = \dfrac{1}{2\pi R_{ESR}C}$

The pole in the LC filter is the frequency that gives a gain slope of -40dB/dec. And the zero point in the LC filter is the frequency that gives a gain slope of -20dB/dec. In the case of an ideal capacitor having no ESR, the gain changes by a -40dB/dec slope at the pole frequency fp and higher. However, actual capacitors have ESR, so that the gain characteristics come to switch from the -40dB/dec slope to a -20 dB/dec slope at the zero point frequency fz. The zero point frequency fz is inversely proportional to the resistance (ESR) as the equation shows. Therefore, using polymer capacitors featuring low ESR come to shift the zero point frequency fz to the higher frequency area, and eventually noise removal characteristics are improved at a range of high frequencies.

Filter (e.g.)

RC Filter   LC Filter

π type Filter   T type Filter

LC Filter Bode diagram

fP   fZb   fZa   f[Hz]

0

[dB]

f_{Za} Zero point : Polymer Capacitor

f_{Zb} Zero point : Al-Electrolytic Cap.

- 20dB/dec

------- Al-Electrolytic Cap.

——— Conductive Polymer Cap.

- 40dB/dec

Gain

ESR : HIGH ⟹ Gain SMALL

ESR : LOW ⟹ Gain LARGE

−∞

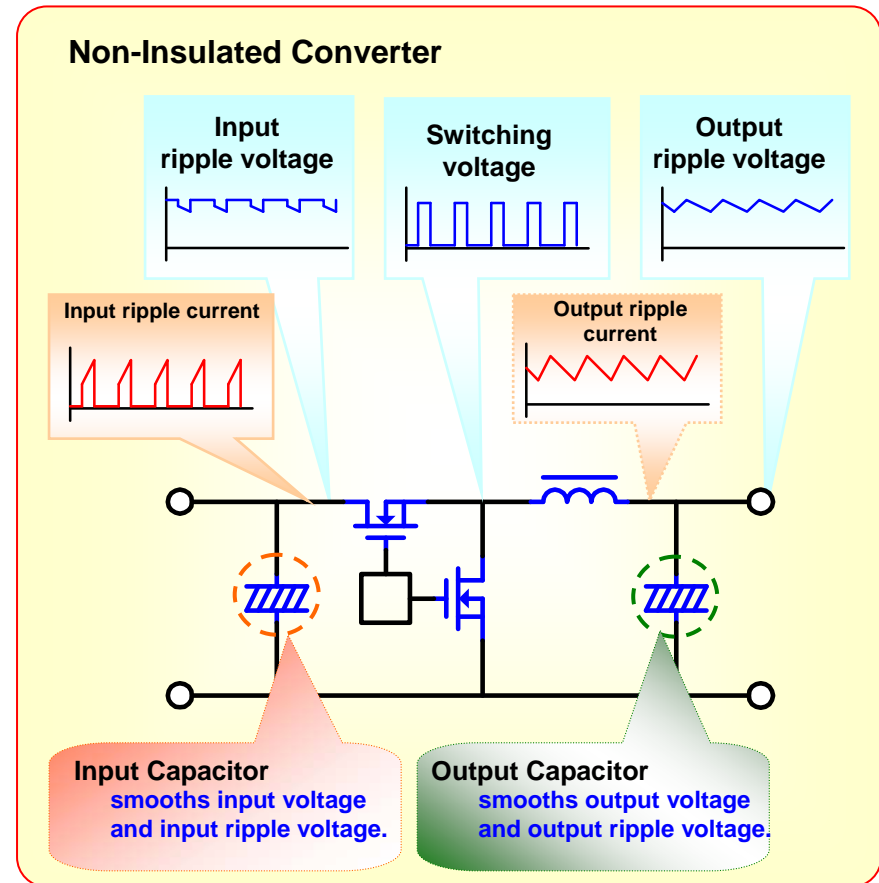ESR : Zero (Ideal Capacitor)

1. Uses: Smoothing

Since polymer capacitors have low ESR, using them as input and output smoothing capacitors can downsize power supply units.

A smoothing capacitor for the switching power supply units can suppress ripple voltage better as its ESR becomes lower. At the output side of the converter shown on the left, an output ripple current in a triangular waveform is generated with a switching waveform synchronized, thereby an output ripple voltage being generated as well. A capacitor at the output side functions to smooth the ripple. Smoothing the output ripple voltage provides stable operation for ICs, etc. at the output side.

As for the input ripple current, pulse-shaped current is synchronized with the switching waveform. The pulse current becomes one of the causes of noise if it flows in the wiring. For this reason, sufficient consideration is required for smoothing capacitors at the input side as well.

Since smoothing capacitors require sufficient capacitance, large capacitance aluminum electrolytic capacitors have been used. Nowadays polymer capacitors, which have greater ripple current capability and lower ESR than aluminum electrolytic capacitors, are available and therefore ripple voltage can be suppressed with the smaller quantity of capacitors.

Non-Insulated Converter

Input ripple voltage	Switching voltage	Output ripple voltage

Input ripple current

Output ripple current

Input Capacitor
smooths input voltage and input ripple voltage.

Output Capacitor
smooths output voltage and output ripple voltage.

Smooth Input ⟹ influences noises.

Smooth Output ⟹ influences the stability of IC

Polymer capacitors are capacitors with lower ESR as compared with the conventional aluminum electrolytic capacitors. They also have stable characteristics over a wide range of temperature.

Since the smoothing capacitors (backup capacitors) require sufficient capacitance for the input and output portions of switching power supply units, the aluminum electrolytic capacitors have been generally used for such purpose. However, for the aluminum electrolytic capacitors, the specifications of ESR and rated ripple current should be especially considered. Depending on use conditions, a multiple number of capacitors are connected in parallel.

Advantages of polymer capacitors are stable characteristics independence on temperature and low ESR and high ripple current capability, so that the switching power supply can be downsized by reducing the number of capacitors.

In the meantime, the downsizing can be made by reducing the size of the output inductor. However, reducing the output inductance leads up to an increase in the ripple current, which comes to increase in the load on the smoothing capacitors. Although the ripple current can be reduced by increasing the switching frequency, a higher switching frequency makes switching loss increase proportionally, the loss affecting efficiency and becoming a cause of noise generation.

Low ESR capacitors as output capacitors can suppress the ripple voltage increased by the reduced output inductance. Comparison and evaluation of the dynamic characteristics of the capacitors are made here by actually using an evaluation circuit board for step-down buck converters.

■ **Reduction in space of capacitors**
■ **Available for coil downsizing**
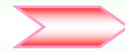
**Practicable in downsizing switching power supply**

Ripple removing capability

In pursuing miniaturization of switching power supply units, to what an extent components with a large volume can be reduced becomes one of the tasks. In determining output capacitors, the maximum value of output ripple voltage is one of the factors to be considered. With ICs, etc. taking a shift to lower operation voltage, the maximum values of the ripple voltage should be naturally reduced for stable operation.

Also, the conventional aluminum electrolytic capacitors change their characteristics such as ESR at lower temperatures, and it affects ripple voltage. For this reason, power supplies, etc. had to be designed by assuming the worst cases considering not only ripple voltage at normal temperature but also their changes at the lower temperatures.

Here is a simple explanation of the principle of the ripples and comparison of the polymer capacitors with the other capacitors in term of quantity. In addition to this, measurement of ripple voltage will be done at a low temperature environment, thereby verifying the temperature characteristics of the capacitors. Actual operation results of step-down buck converters will verify the excellent ripple removal capability of polymer capacitors.
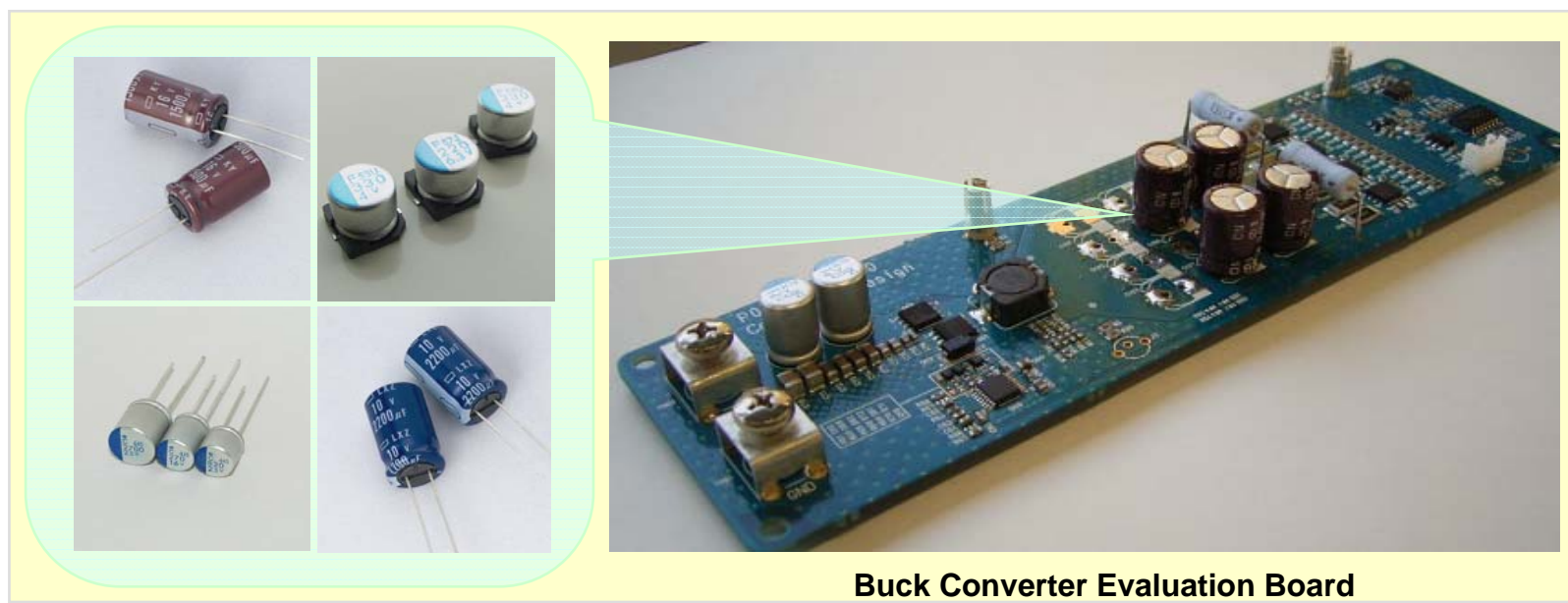
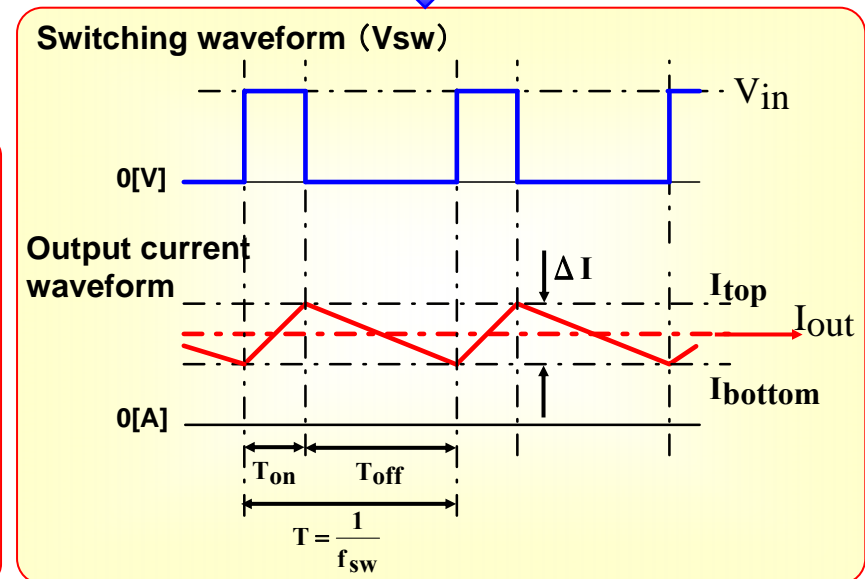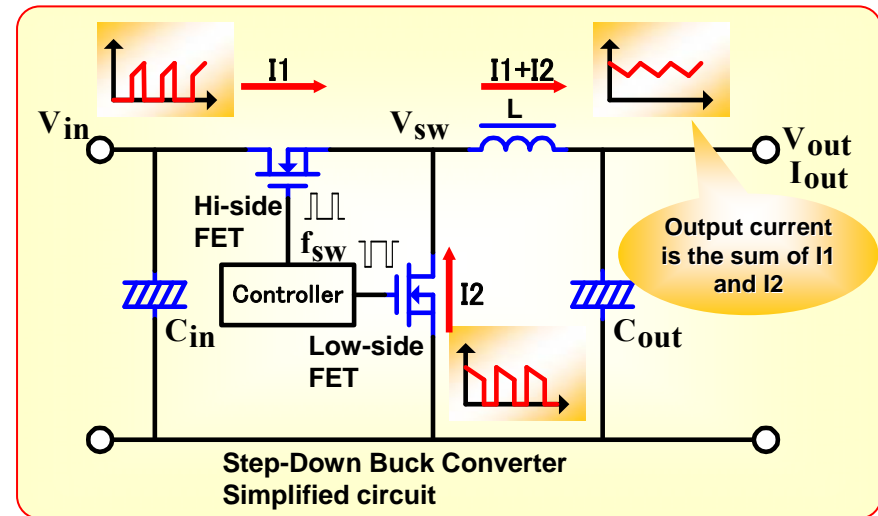

Buck Converter Evaluation Board

Illustrated on the right is a simplified circuit diagram of a synchronous buck converter. By turning on and off each FET at the high and low sides alternately, pulse-shaped voltage (switching waveform) is generated with its constant amplitude. The output voltage value is determined by adjusting the duty cycles in the high voltage (power supply voltage) portion and the low voltage (GND) portion and then by means of the smoothing function of an LC filter.

The L as inductive reactance generates a triangular waveform current based on the switching waveform (see graph on lower right), this is the ripple current. Its peak value ΔI is determined by inductance (L), output voltage (Vout) and turn-off time (Toff).

For the capacitors, the rated ripple current is specified with regard to the ripple current above. When using capacitors, attention needs to be paid to the specifications of the rated ripple current.

Step-Down Buck Converter Simplified circuit

Output current is the sum of I1 and I2

Switching waveform (Vsw)

Output current waveform

Ripple current equation

$$\Delta I = \frac{V_{out} \times T_{off}}{L} \quad \dots \text{ converted from } L \times I = V \times T$$

Where,

$$T_{off} = \frac{V_{in} - V_{out}}{V_{in}} \times \frac{1}{f_{sw}} \qquad T_{off} = (1 - Duty) \times T$$

$$T_{on} = \frac{V_{out}}{V_{in}} \times \frac{1}{f_{sw}} \qquad T_{on} = Duty \times T$$

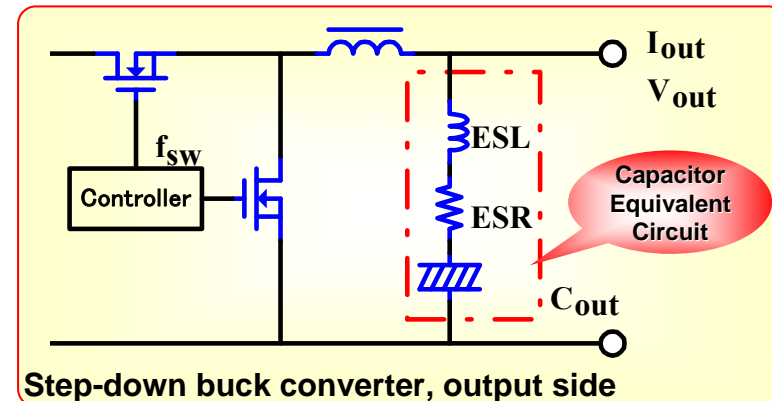$$Duty[\%] = \frac{T_{on}}{T} = \frac{V_{out}}{V_{in}}$$

2. Examples of capacitor use:
Ripple characteristics of smoothing capacitors

Ripple voltage (1)

Next, output ripple voltage is considered. The output ripple voltage is basically determined by an output capacitor. As shown on the right, an actual capacitor includes parasitic components such as ESR and ESL, and these affect ripple voltage very much.

It is generally thought that the output ripple voltage is determined by the capacitance and ESR of a capacitor. A calculation equation of the peak value of output ripple voltage △Vripple in the worst case is expressed as equation (1) on the right. △I is the ripple current mentioned previously, and fsw is the switching frequency. It is an equation in which each of ESR and capacitance is a parameter with the ripple current. Then, the ripple voltage comes to be affected dominantly by ESR. What superimposed spike-shaped noises to the △Vripple is called "ripple noises".

I_{out}
V_{out}

ESL

ESR

Capacitor Equivalent Circuit

C_{out}

f_{sw}

Controller

Step-down buck converter, output side

Ripple voltage equation（1）

$$\Delta V_{ripple} = \Delta I \times \left(ESR + \frac{1}{8 \times C_{out} \times f_{sw}} \right)$$

20mV/div

470μF φ10 (1piece)
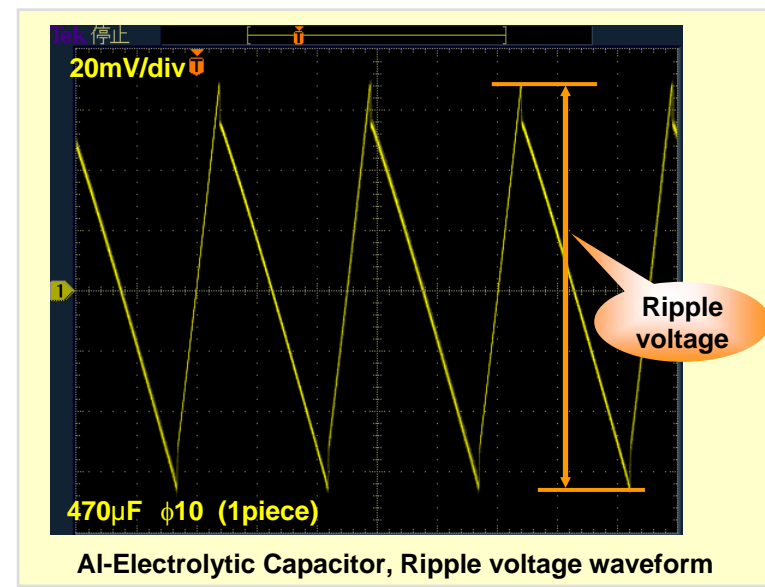
Ripple voltage

Al-Electrolytic Capacitor, Ripple voltage waveform

ESR：Large

➢ **Large in ripple voltage**

➢ **Becomes triangular-like waveform**

※**The equation on this page is only for reference.**
   Result depend on the actual equipment because of
   other factors to influence it.

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Ripple voltage (2)

In the meantime, since polymer capacitors have low ESR, the influence of ESR becomes small in the equation (1) and therefore the ripple voltage becomes extremely small as a whole. However, an influence of ESL should be considered in this case.
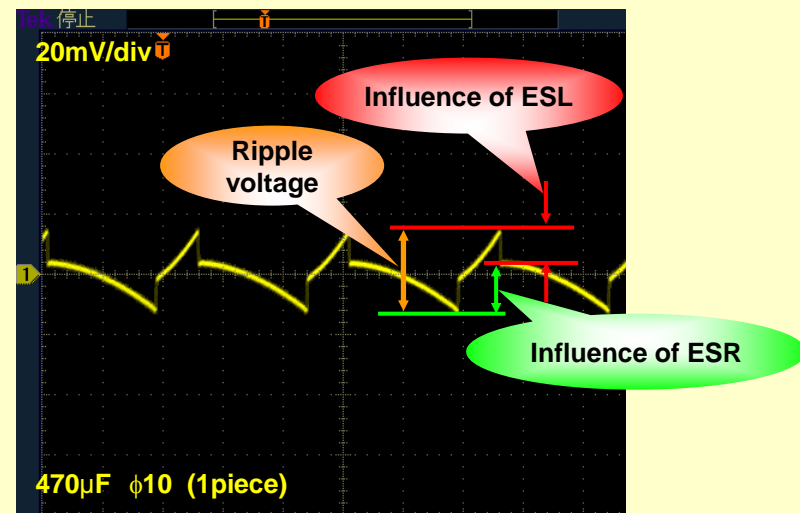
The waveform shown on the right is the ripple waveform when using a polymer capacitor with low ESR. Ripple current measurement has been done under the same conditions as those for the aluminum electrolytic capacitor on the preceding page. Although the ripple voltage value becomes the smaller as a whole, there appear bounces in the waveform of the ripple voltage.

The bounces are caused by ESL and appeared in the ripple voltage waveform of the said aluminum electrolytic capacitor as well. On the aluminum electrolytic capacitor, the bounces caused by ESL become comparatively inconspicuous as the ESR noticeably influences the waveform very much.

Therefore, when using low ESR capacitors, the equation (2) that includes the influence of ESL may be used to calculate the ripple voltage.

Ripple voltage equation（2）

$$\Delta V_{ripple} = \Delta I \times ESR + \Delta I \times \left(\frac{1}{T_{on}} + \frac{1}{T_{off}} \right) \times ESL$$

20mV/div

Influence of ESL

Ripple voltage

Influence of ESR

470μF φ10 (1piece)

**Conductive Polymer Al-Solid Capacitors
Ripple voltage waveform**

ESR：Small ➡ ➤ **Small ripple voltage**

➤ **Influence of ESL is noticeably on ripple waveform.**

※ **On high ESR capacitors, ESL influences the waveforms as well.**

※**The equation on this page is only for reference.
Result depend on the actual equipment because of other factors to influence it.**

2. Examples of use:
Ripple characteristics of smoothing capacitors

### Measurement conditions for the ripples

Ripple voltages are reviewed by means of a buck converter as an evaluation circuit board. The ripple characteristics are measured to compare three types of capacitors; the polymer capacitors, conventional aluminum electrolytic capacitors and high-aqueous electrolyte aluminum electrolytic capacitors.

Ripple voltage is measured on the polymer capacitors, aluminum electrolytic capacitors and high-aqueous electrolyte aluminum electrolytic capacitors at a normal temperature, and then it is reviewed how many of each capacitor are equivalent in ripple voltage to a single polymer capacitor.

Also, for comparison with lower temperature characteristics, ripple voltage is measured at the lower temperature with the same numbers as above in each capacitor.

Test Conditions
● SW Regulator : DC-DC Buck Type
● SW Frequency : 100kHz
● Input/Output Voltage : 12V/5V
● Temperature : 25℃ and -20℃

Test Circuit
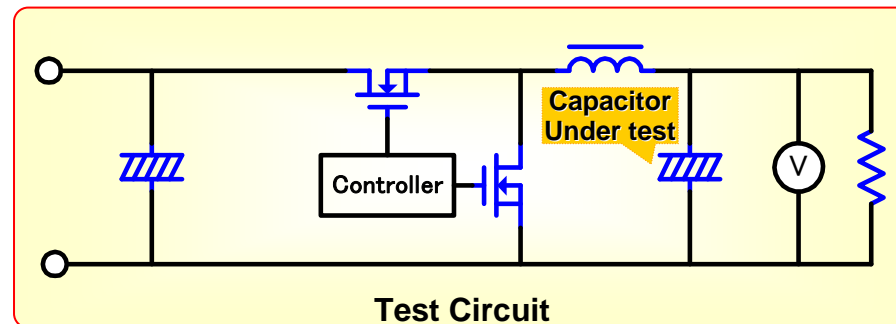
Capacitor Type	Voltage-Capacitance	Qty.	Image
Conductive Polymer Aluminum Solid Capacitors (PS_ series)	16V - 470µF	1	
Low Z, Aluminum Electrolytic Capacitors (High water contains electrolyte)	16V - 1000µF	3	
Low Z, Aluminum Electrolytic Capacitors (Conventional electrolyte)	16V - 470µF	6	

2. Examples of capacitor use:
Ripple characteristics of smoothing capacitors

Waveform Measurements

The measurement results of ripple waveform are shown on the right. The results on the left side show the comparison in quantity of capacitors at a normal temperature. The single polymer capacitor becomes equivalent to three of the high aqueous electrolyte aluminum capacitors in the smoothing ability, and also becomes equivalent to six of the conventional aluminum electrolytic capacitors.
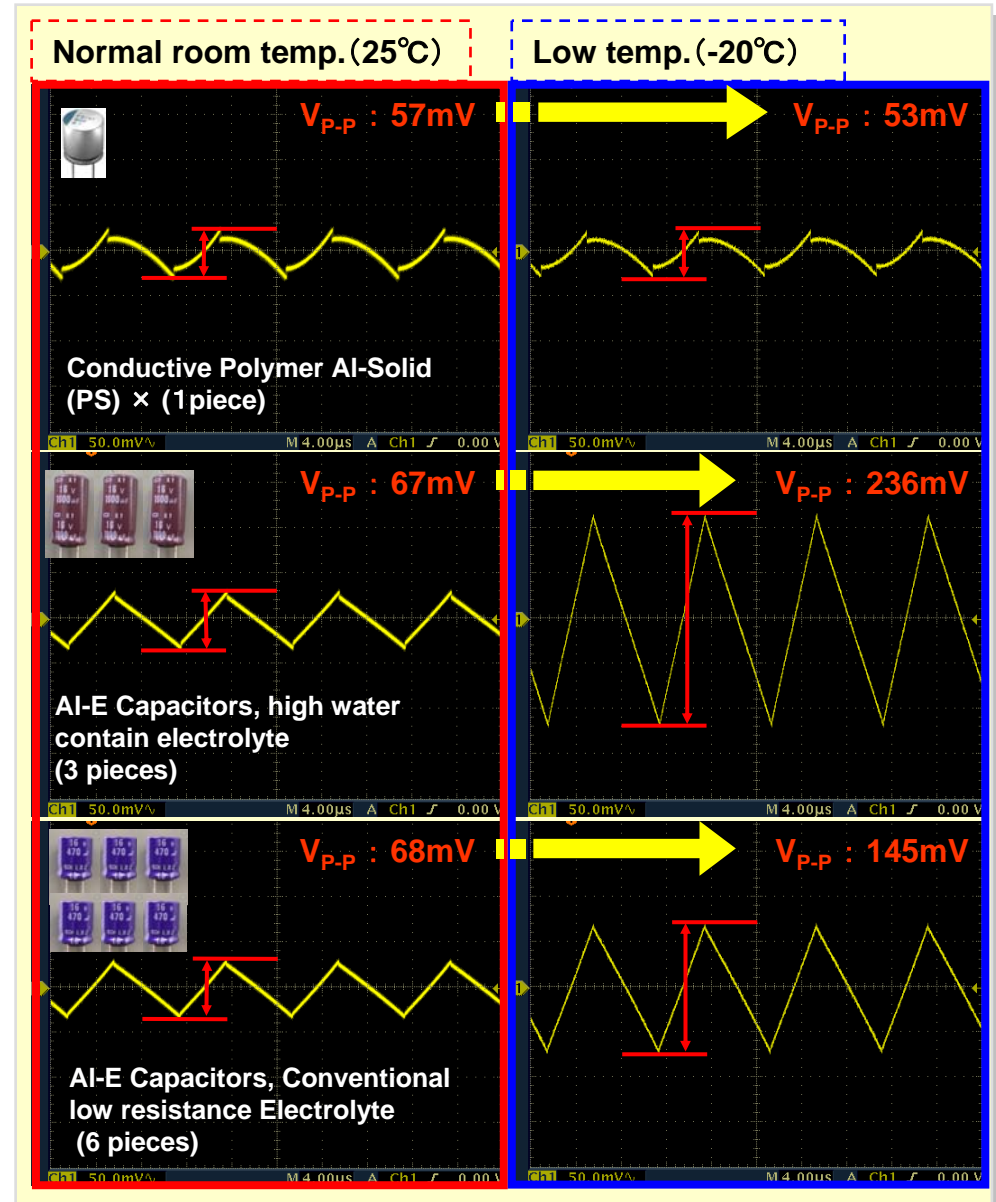
Next, the results on the right side are the lower temperature ripples that were obtained by using the same numbers of capacitors as above. Even at the low temperature, the polymer capacitor gives almost the same ripple voltage as the normal temperature measurement, whereas the high aqueous electrolyte aluminum capacitors give more than 3 times as high as the ripple voltage. Also, the conventional aluminum electrolytic capacitors give more than 2 times.

As can be seen from above, the polymer capacitors can reduce the ripples by a smaller number of capacitors, and they also have stable ripple removal capability even at lower temperatures.

The merit of polymer capacitors

➢ **Can reduce ripple with fewer parts**

➢ **Very high ability to smooth ripples even at low temperature environment**

Contribution to the downsizing and stability of the products that do not depend on a temperature change

Normal room temp.（25℃）   **Low temp.（-20℃）**

V_{P-P} : 57mV V_{P-P} : 53mV

Conductive Polymer Al-Solid (PS) × （1piece)

V_{P-P} : 67mV V_{P-P} : 236mV

Al-E Capacitors, high water contain electrolyte (3 pieces)

V_{P-P} : 68mV V_{P-P} : 145mV

**Al-E Capacitors, Conventional low resistance Electrolyte (6 pieces)**

Transient response characteristics

While DC-DC converters have been required to have high efficiency, low noise and miniaturization, one of recent additional requirements is faster transient response characteristics to the load change. This is because ICs, etc. have been developing into the directions of higher speed, larger current and lower voltage operation. IC operation of the high-speed and large current comes to increase variations in current load, and the low voltage operation comes to require very accurate stability in voltage. All of them require faster transient response for the converter to support the ICs. Power controllers won't work on such transient response due to the limits of their ability, so the backup capacitors come to have an important role for the transient response.

Polymer capacitors with low ESR and low ESL can display the better transient response ability by the smaller number of capacitors as compared with the conventional aluminum electrolytic capacitors. Explanations are given here about the discharge characteristics of capacitors on transient response.

IC operations:
- **Speed up**
- **Larger current**
- **Lower voltage**
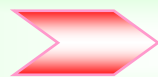
The output capacitors of higher performance are necessary to improve accuracy in output voltage.
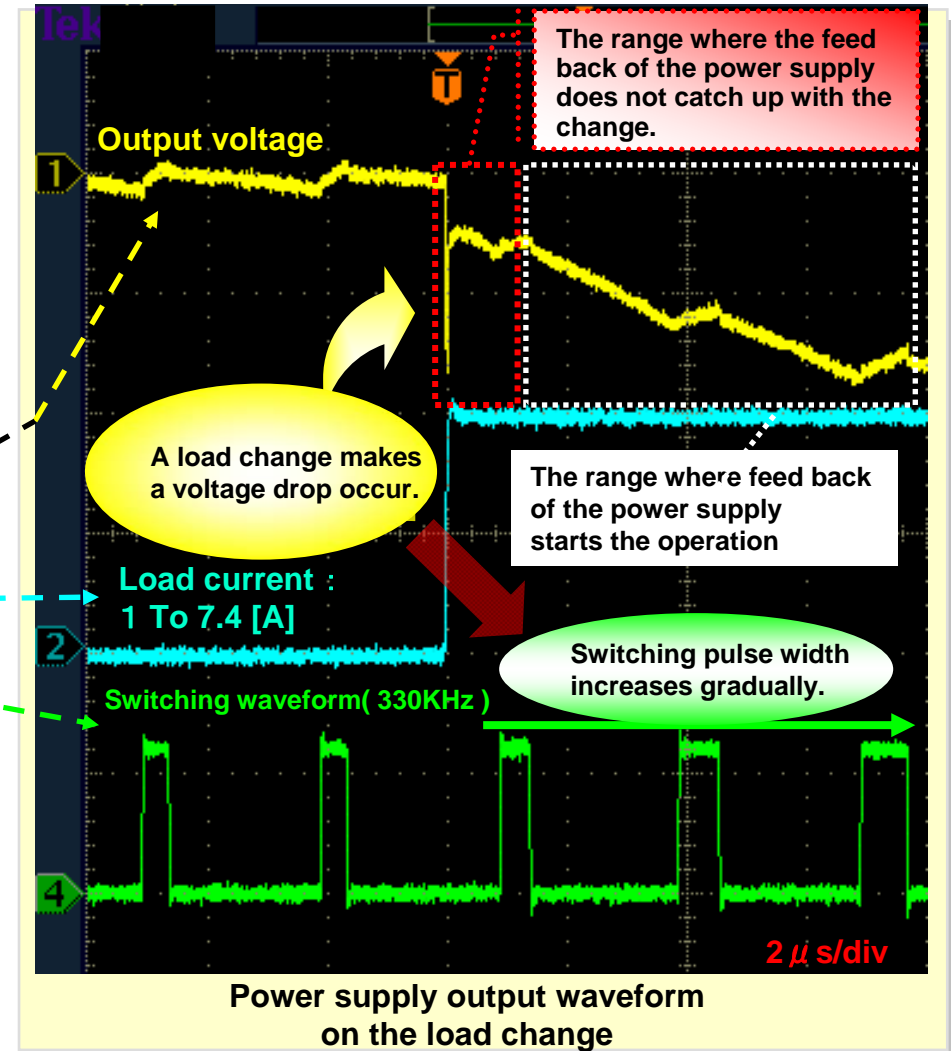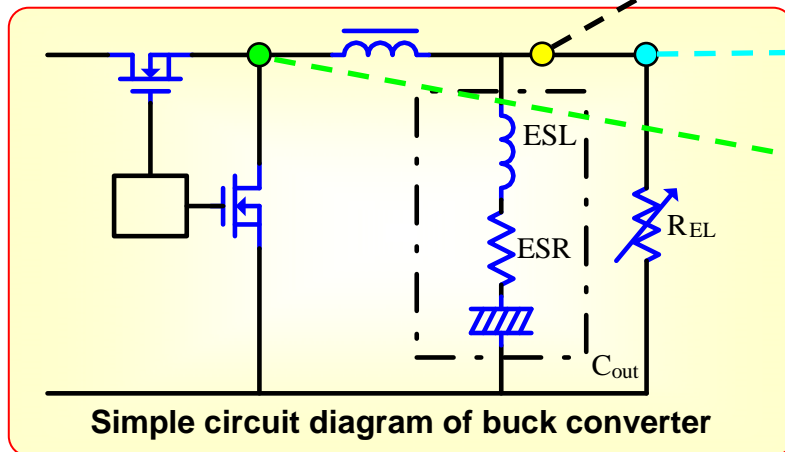
2. Examples of capacitor use:
Transient response characteristics of backup capacitors

Regulator output during load changes

The waveforms on the right are the output current, output voltage, and switching waveform taken while the load of the buck converter was changing from 1 [A] to 7.4 [A]. At the time of a load change, the output voltage droops with a spike-shaped voltage drop at startup. This is because the power controller cannot support the transient response.

A certain period of time is required until the power controller can respond to the load change. In order to compensate for this, the backup capacitor needs to discharge. Therefore, the voltage droop during this transient response is dependent on the characteristics of the output capacitor.

Simple circuit diagram of buck converter

Output voltage

The range where the feed back of the power supply does not catch up with the change.

A load change makes a voltage drop occur.

The range where feed back of the power supply starts the operation

Load current : 1 To 7.4 [A]

Switching pulse width increases gradually.

Switching waveform(330KHz)

2μ s/div

Power supply output waveform on the load change

ESL

ESR

R_{EL}

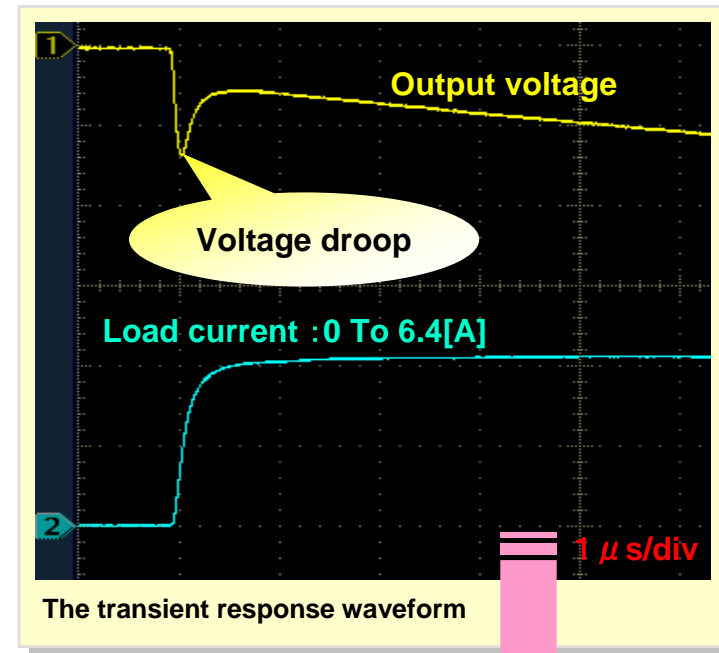C_{out}

Nippon Chemi-Con Corporation

2. Examples of capacitor use: Transient response characteristics of backup capacitors

The transient response characteristics of a switching power supply during the load change are concerned with the capacitance, ESR and ESL of backup capacitors. The graph on the right shows the output waveform of a switching power supply during the period that the load was changing from light load to heavy load. The characteristics of the output capacitor can be confirmed by this output waveform.

Since there arises a change in current as a result of the load change, a voltage drop caused by ESL of the capacitor occurs in the form of spikes. Another voltage drop affected by ESR occurs in proportion to the amount of current. As the load reaches the heavy load current with a constant load, the voltage drop due to ESL resulting from a current change disappears. Also, as the capacitor supplies the discharge current to the load, the last voltage drop arises and increases with the lapse of time. The following equations show the relationship between the voltage drops at the transient response and the ESR, ESL and capacitance of a capacitor.

Output voltage

Voltage droop

Load current : 0 To 6.4[A]

1 μ s/div

The transient response waveform

・**Voltage Drop**

$$\Delta V(t) = \Delta V_C(t) + \Delta V_{ESL}(t) + \Delta V_{ESR}(t)$$
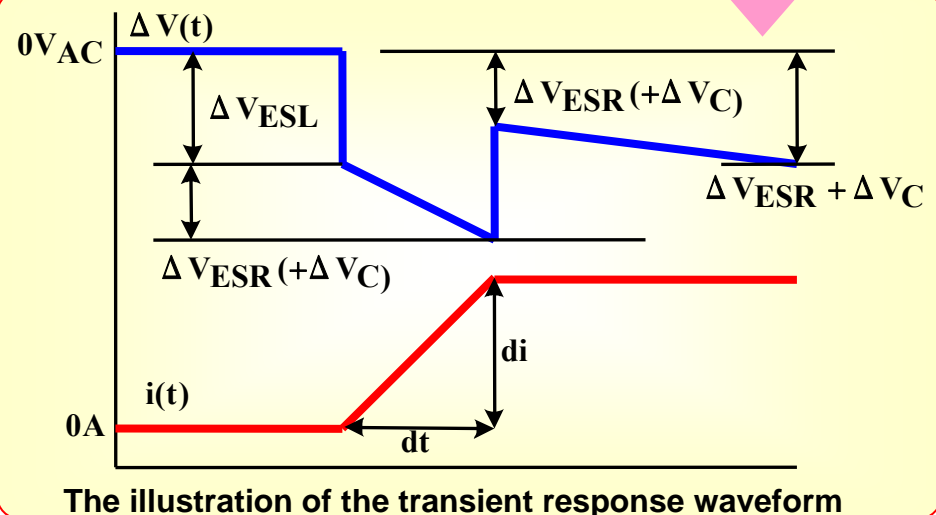
・**Discharge Voltage Drop**

$$\Delta V_C(t) = \frac{1}{C}\sum i(t)$$

・**ESL Voltage Drop**

$$\Delta V_{ESL}(t) = ESL \times \frac{di}{dt}$$

・**ESR Voltage Drop**

$$\Delta V_{ESR}(t) = ESR \times i(t)$$

$0V_{AC}$

$\Delta V(t)$

ΔV_{ESL}

$\Delta V_{ESR}(+\Delta V_C)$

$\Delta V_{ESR} + \Delta V_C$

$\Delta V_{ESR}(+\Delta V_C)$

$i(t)$

$0A$

di

dt

The illustration of the transient response waveform

2. Examples of capacitor use:
Transient response characteristics of backup capacitors
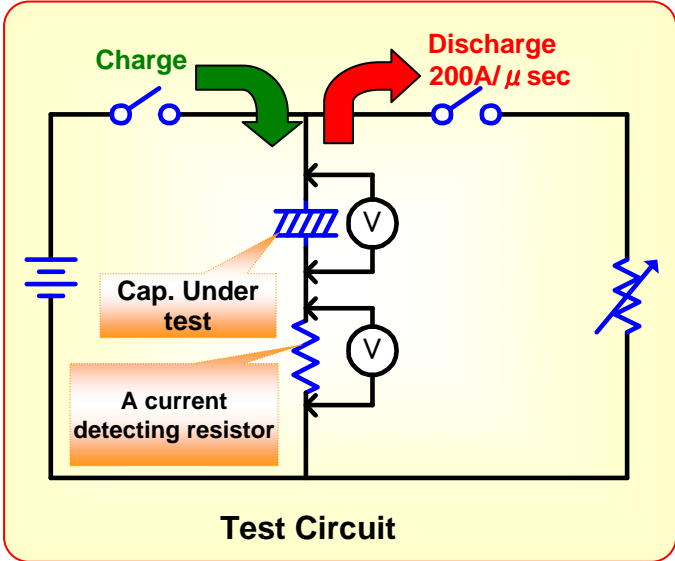
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Measuring conditions for discharge characteristics

Explanations are given here to verify the discharge characteristics of capacitors. As the fully charged capacitor is rapidly discharged, the voltage drops arisen are measured.

The discharge should be made with a large discharge current of high slew rate (200A/µsec.) in order to define the influence by the ESR and ESL of the capacitor.

The transient response characteristics are measured on the polymer capacitor and the high aqueous electrolyte aluminum capacitors for the comparison purpose.

Test Conditions
- ●Input Voltage : 2.5V
- ●Charge : 100msec
- ●Discharge : 10usec
- ●Current : 0A to 40A (Dynamic)
- ●Current Slew Rate : 200A/μsec

Test samples

Charge   Discharge 200A/μ sec
Cap. Under test
A current detecting resistor
Test Circuit

Capacitor Type	Voltage-Capacitance	Qty.	Case size
Conductive Polymer Aluminum Solid Capacitors (PS_ series)	**2.5V-820µF**	**1**	**φ8x10mm**
Low Z, Aluminum Electrolytic Capacitors (High water contains electrolyte)	**6.3V-820µF**	**1**	**φ8x10mm**

Transient response characteristics of backup capacitors

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Waveform of discharge characteristics

The graphs below show the measurement results of transient response characteristics. It can be seen that the single polymer capacitor realized the smaller voltage drops because of the lower ESR and ESL. This means that the plural number of the high aqueous electrolyte aluminum capacitors will be necessary to achieve such small voltage drops.

That is to say, a small number of polymer capacitors can realize equivalent transient response characteristics. This comes to contribute to the miniaturization of power supply units.

Room Temp. (25ºC)

$\Delta V_{ESL} + \Delta V_{ESR}$: 0.69V
ΔV_{ESR}: 0.28V

Output voltage
Load current

Polymer capacitor
(PS) ×1piece

Ch1 500mV ∿ Ch2 200mV M 1.00μs A Ch2 ſ 100mV

$\Delta V_{ESL} + \Delta V_{ESR}$: 1.18V
ΔV_{ESR}: 0.73V

Output voltage
Load current

Aluminum electrolytic capacitors
(High water contains electrolyte) ×1piece

Ch1 500mV ∿ Ch2 200mV M 1.00μs A Ch2 ſ 100mV
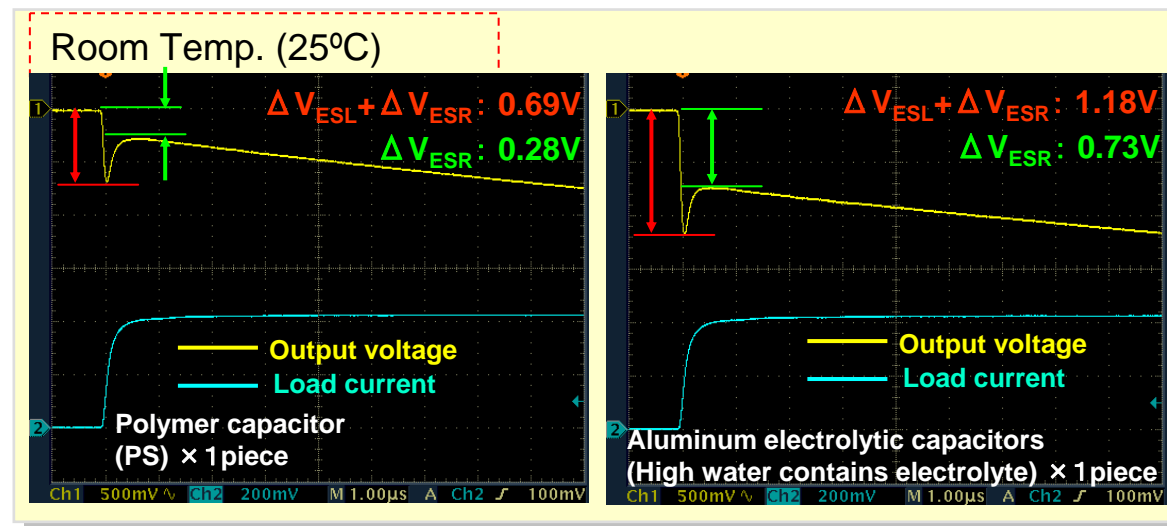
Merit of polymer capacitors

$\Delta V_{ESL} + \Delta V_{ESR}$: **Spike-shaped voltage drop is small.**

ΔV_{ESR}: **Voltage droop is small after the spike-shaped drop.**
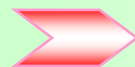
Improvement of the voltage accuracy is available with few components

Nippon Chemi-Con Corporation

Polymer capacitors have lower ESR than the conventional aluminum electrolytic capacitors. Therefore, a smaller number of polymer capacitors can have characteristics equal to or better than that of the latter, greatly contributing to reduction in the number of components and space saving with regard to pc board mounting.

However, because of the low ESR, consideration should be given to the use of polymer capacitors in some respects as compared with the conventional capacitors with large ESR.

Explanations are given here about abnormal oscillation that is found in step-down buck converters (voltage control mode) when using low ESR capacitors, and about anti-resonance caused by the parallel connection of different capacitors. Data shown in the following are obtained through actual measurements by using an evaluation circuit board.
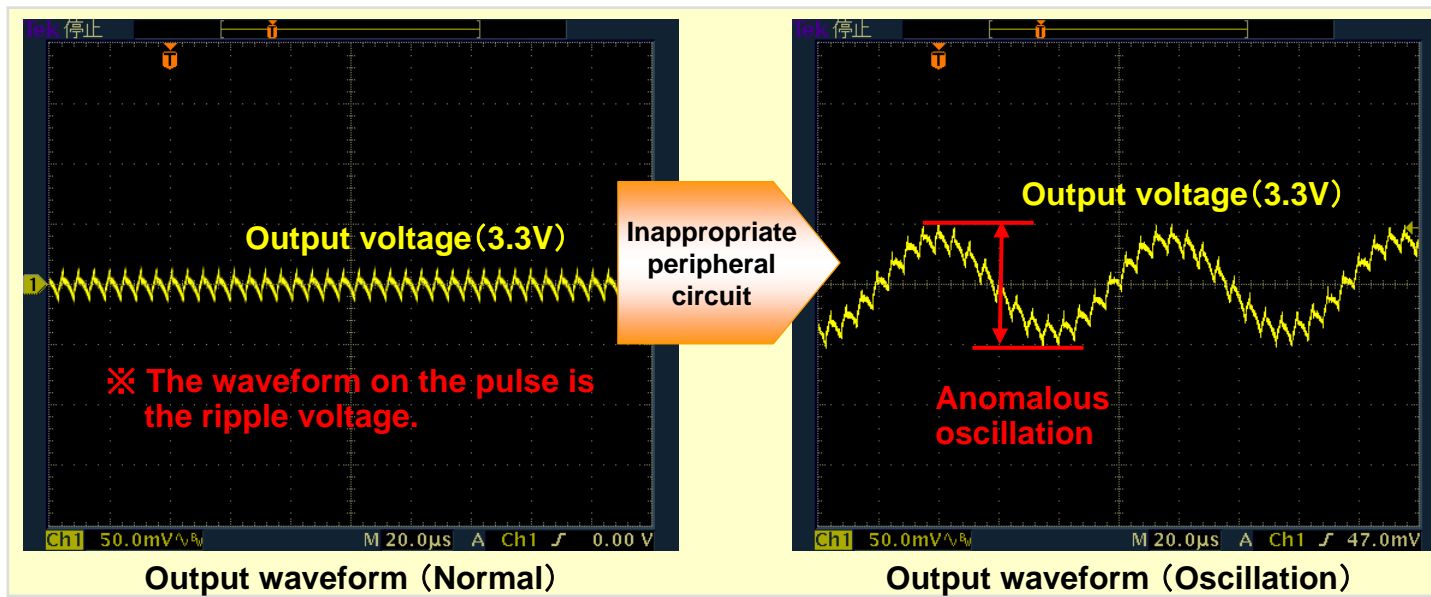
3. Precautions for capacitor use: Abnormal oscillation

Output smoothing capacitors for switching converters have a smaller voltage drop at the time of ripple suppression or transient response as ESR is lower. However, phenomena occur which have not appeared in the conventional electrolytic capacitors. One of such phenomena is that a 180 degree phase shift easily occurs, which gives rise to abnormal oscillation.

The graphs below show the output voltage waveforms obtained by a step-down buck converter. The graph below on the left shows a normal output waveform. Only ripple voltage of dozens of millivolts can be seen in the normal waveform. However in the graph below on the right, oscillation that has superimposed on the ripple voltage can be seen at the frequency different form the switching frequency. This is an output due to abnormal oscillation.

As mentioned earlier, mere replacement of an aluminum electrolytic capacitor as the output capacitor for a step-down buck converter with a polymer capacitor may give rise to such oscillation in some cases. For this reason, when using a polymer capacitor as the output capacitor, its surrounding circuits also need to be taken into account.

Output voltage（3.3V）

※ The waveform on the pulse is the ripple voltage.

Inappropriate peripheral circuit

Output voltage（3.3V）

Anomalous oscillation

Output waveform（Normal）

Output waveform（Oscillation）

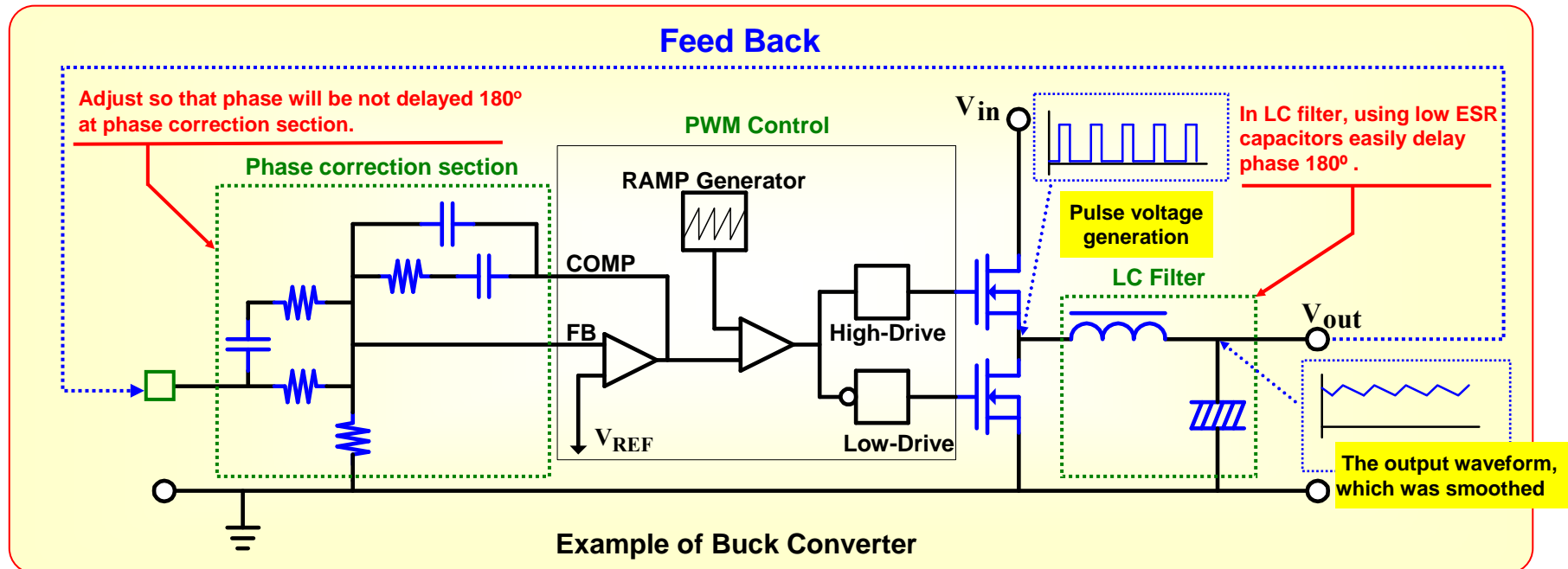**It is necessary to review the factor design of peripheral circuit when changing output capacitors.**

3. Precautions for capacitor use: Abnormal oscillation

The diagram below shows an example of a circuit of a step-down buck converter (voltage control mode). It is generally divided into blocks: PWM control, LC filter and phase correction section. The LC filter is located in the output portion. Pulse voltage with constant amplitude is generated by the PWM control, and output voltage is smoothed by means of the LC filter. And the output voltage is adjusted to an intended constant voltage by negative feedback to the output voltage.

However, if a 180⁰ phase delay occurs in the output voltage loop at this time, positive feedback is created. This positive feedback causes abnormal oscillation.

As for a cause of the 180⁰ delay in phase, the delay may be caused by ESR of a capacitor used in the LC filter in the output portion. This is because, as ESR of the capacitor becomes lower, the phase tends to be delayed by a 180⁰ which is a property of the LC filter. Therefore, in order to prevent abnormal oscillation, the phase correction portion needs to be adjusted properly. For the details of the adjustment method of the phase correction portion, check them with the manufacturer of the power supply control IC or refer to various types of reference literature. control IC or refer to various types of reference literature.

Feed Back

Adjust so that phase will be not delayed 180º at phase correction section.

Phase correction section

PWM Control

RAMP Generator

COMP

FB

V_{REF}

High-Drive

Low-Drive

V_{in}

Pulse voltage generation

LC Filter

V_{out}

In LC filter, using low ESR capacitors easily delay phase 180⁰ .

The output waveform, which was smoothed
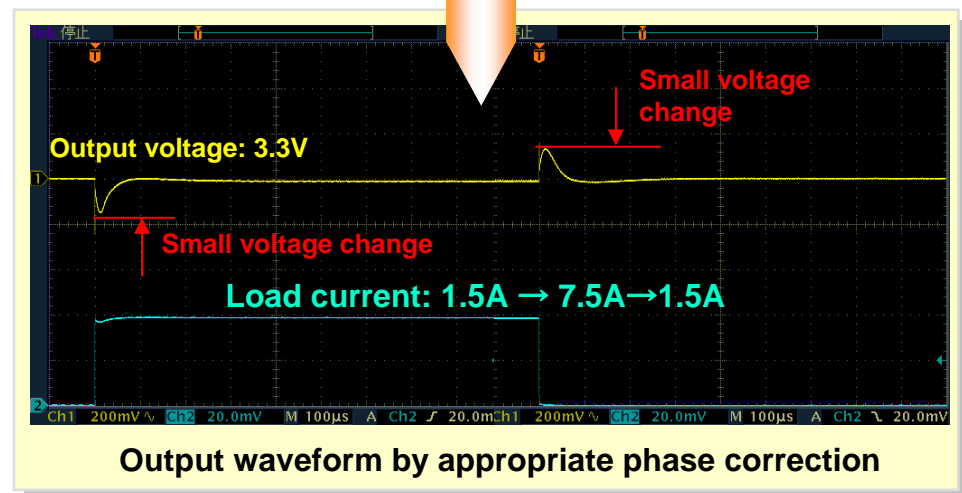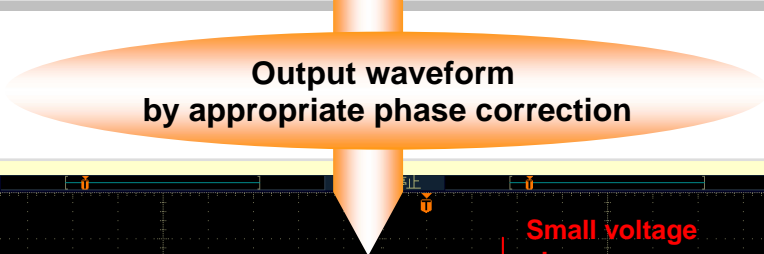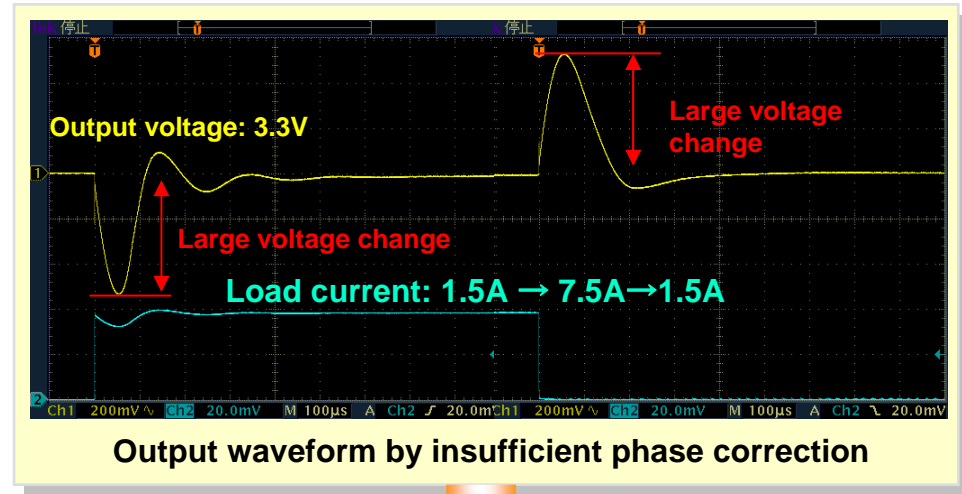
Example of Buck Converter

3. Precautions for capacitor use: Abnormal oscillation

Another thing should be noted with regard to phase correction. It is the response characteristics during a load change. The graphs on the right show the output waveforms of a DC-DC converter whose oscillations are suppressed, in which the responses during the load changes are verified here. In the upper right graph, although there is no abnormal oscillation caused by phase correction, degradation in responses can be seen, and appropriate phase correction has not been done yet. The lower right graph shows the improved waveform of the load change which was made on phase correction. The change in voltage is small during the load change, and the effect of the improvement can be seen.

Making sufficient phase correction comes to suppress oscillation and improve response characteristics during a load change. When using polymer capacitors that have low ESR, their superior characteristics can be optimized effectively by giving sufficient consideration to phase correction. With regard to phase correction, in addition to oscillation control, sufficient consideration needs to be given to response characteristics during a load change as well.

> **The phase correction has to be considered not only for the oscillation restraint but also for response characteristics.**

Output voltage: 3.3V
Large voltage change
Large voltage change
Load current: 1.5A → 7.5A→1.5A

Output waveform by insufficient phase correction

Output waveform by appropriate phase correction

Small voltage change
Output voltage: 3.3V
Small voltage change
Load current: 1.5A → 7.5A→1.5A

Output waveform by appropriate phase correction

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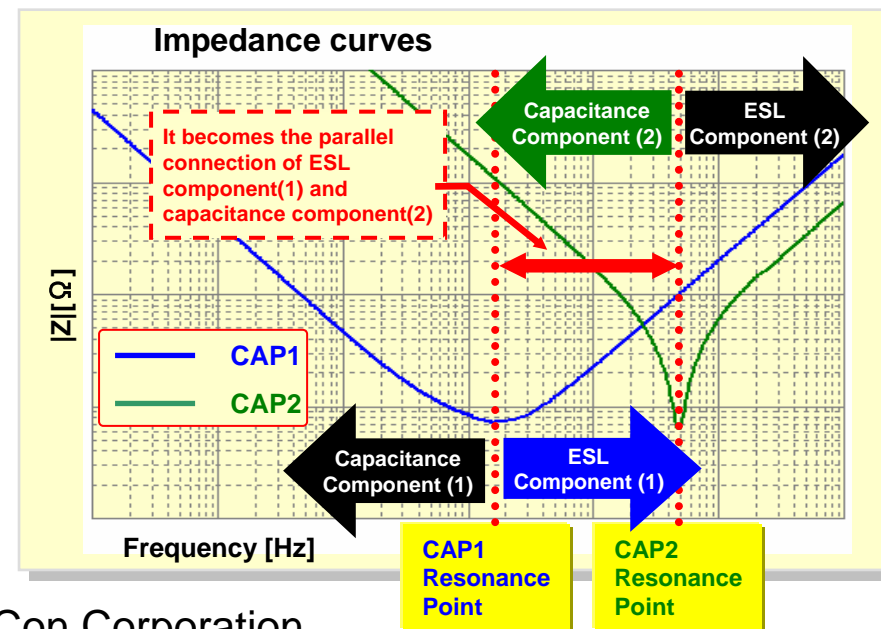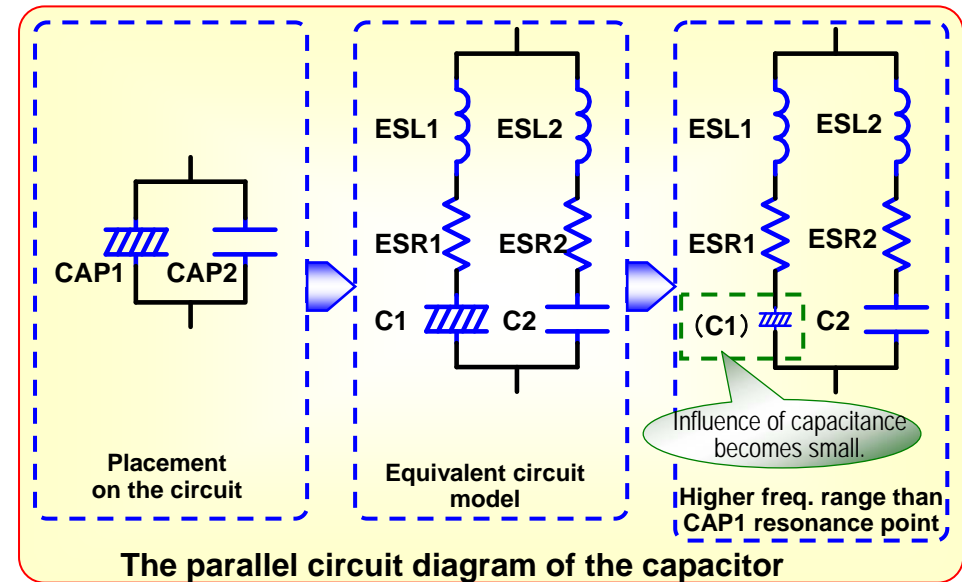# 3. Precautions for capacitor use: Anti-resonance

Connecting capacitors having different capacitance rating or characteristics in parallel reduces impedance over a wide frequencies range, and it has been often used for many applications.

At that time it has to be made sure that the impedance has been lowered at the intended frequency range. This is because the parallel connection of capacitors may cause an increase in impedance at a certain frequency to the contrary.

Let us consider the parallel connection of capacitors in terms of the circuit deployment as shown in the upper right diagram. When the capacitors (CAP1 and CAP2) are connected in parallel, the connection is expressed as shown on the left in the upper right diagram.

However, its indication in an actual equivalent circuit becomes as shown at the center in the upper right diagram due to ESR and ESL that are the parasitic factors of capacitors. Now let us consider a combination of capacitors with C1>C2 and ESL1>ESL2. The lower right graph shows impedance curves of CAP1 and CAP2. CAP1 and CAP2 have their resonance points at different frequencies.

At a range of higher frequency than a resonance frequency, a capacitor behaves as inductance of ESL more rather than capacitance component. In a frequency range between the resonance frequencies of CAP1 and CAP2, CAP1 is greatly behaves as the inductor and CAP2 is the state of the capacitor, and therefore CAP1 and CAP2 form the parallel-connection shown on the right in the upper right diagram. This results in anti-resonance (parallel resonance).

The parallel circuit diagram of the capacitor

- Placement on the circuit: CAP1, CAP2
- Equivalent circuit model: ESL1, ESL2, ESR1, ESR2, C1, C2
- Higher freq. range than CAP1 resonance point: ESL1, ESL2, ESR1, ESR2, (C1), C2 — Influence of capacitance becomes small.

Impedance curves

It becomes the parallel connection of ESL component(1) and capacitance component(2)

Capacitance Component (2), ESL Component (2)
Capacitance Component (1), ESL Component (1)
CAP1, CAP2
|Z| [Ω]
Frequency [Hz]
CAP1 Resonance Point
CAP2 Resonance Point

# 3. Precautions for capacitor use: Anti-resonance

The graph on the right shows the impedance curves with broken lines that were individually measured on each of the two capacitors: one has large capacitance and the other has small capacitance rating, and the graph also shows the other impedance curve with a solid line that was measured on a set of these two capacitors which were together connected in parallel. It can be seen that impedance increases in the vicinity of the intersection between the inductive reactance of the capacitor with large capacitance rating and the capacitive reactance of the capacitor with small capacitance rating due to anti-resonance (parallel resonance).

Based on the above, when connecting capacitors with different characteristics in parallel, attention needs to paid not to rise obstructive anti-resonance point(s) in the frequency range where low impedance value is required.

While an increase in impedance due to anti-resonance is proportional to the ESL of each capacitor, the impedance due to anti-resonance comes to decrease as ESR increases. Therefore, anti-resonance can be mitigated by quite separately placing the capacitors to be connected in parallel. Also, as the capacitor with the smaller capacitance increases in capacitance, the impedance due to anti-resonance comes to decrease. When mounting different capacitors, sufficient attention has to be paid to their combination and layout.

| Large Capacitance Cap. Model	Small Capacitance Cap. Model
Capacitance : 560μF	Capacitance : 1μF
ESR : 9mΩ	ESR : 3mΩ
ESL : 2.8nH	ESL : 0.3nH

Impedance curve 【simulation】
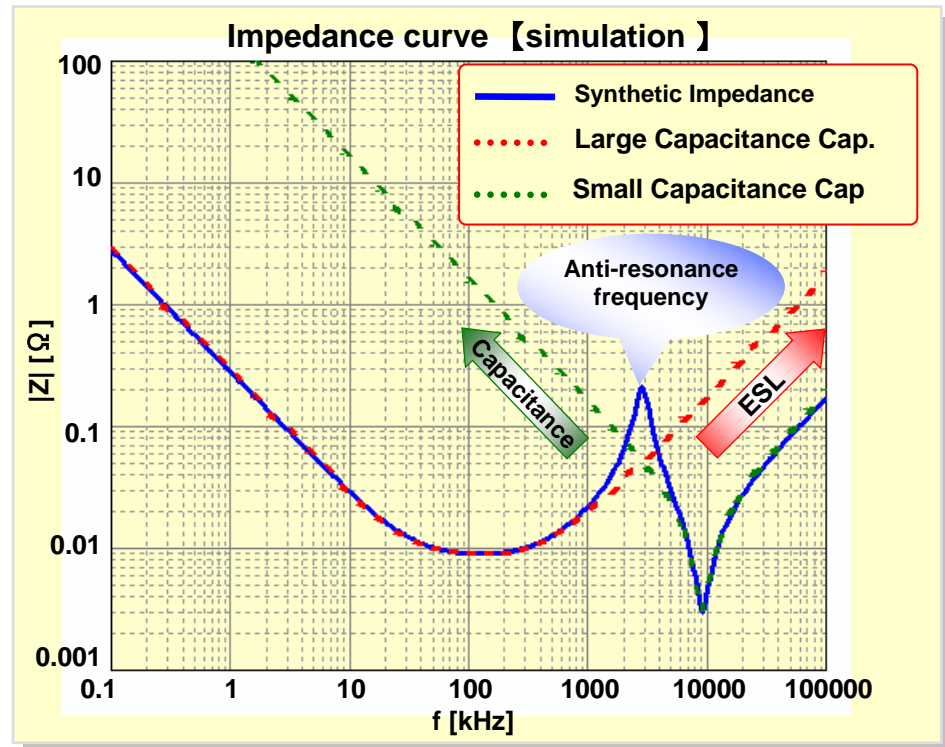
The restraint of anti-resonance

■ Widen the distance between the large capacitance and small capacitance rating capacitor.
■ Increase capacitance rating of small capacitance capacitor.
■ ESR control in the small capacitance capacitor

3. Precautions for capacitor use: Anti-resonance

When connecting capacitors in parallel, here anti-resonance is reviewed in the influence caused by a capacitance difference in the smaller capacitance rating capacitor. As a way to review it, impedance curves are measured on a set of two capacitors: one is large in capacitance rating and the other is small, which were connected in parallel each other. As the large capacitance rating capacitor, a polymer capacitor in the PXF series with low ESR is used. As for the small capacitance rating capacitor, two different capacitance ratings of MLCC's are prepared with 1 µF and 10µF.

The graphs below show the results of measurement when the polymer capacitor has been combined with either of the MLCCs. The combination with 1µF MLCC generates a larger anti-resonance, whereas anti-resonance is suppressed in the combination with 10µF. Based on the results of this measurement, increasing capacitance rating of the small capacitance capacitor is effective as a technique for suppressing anti-resonance.
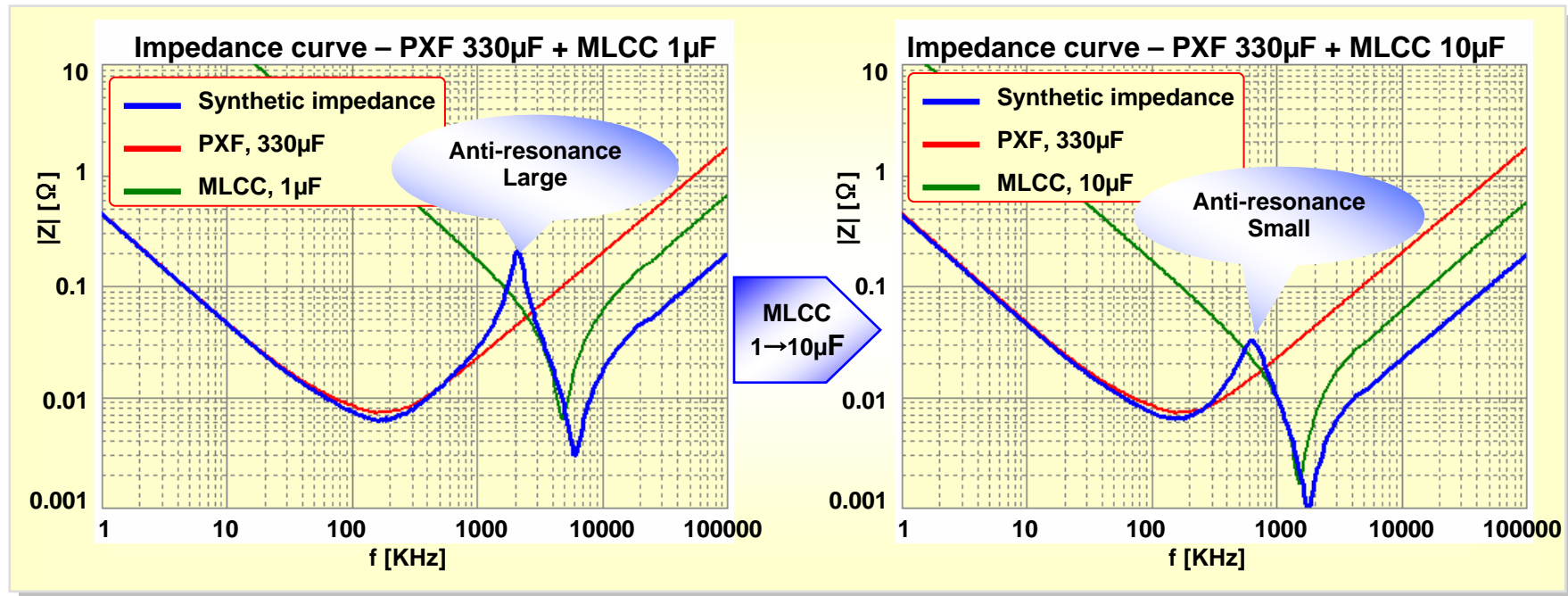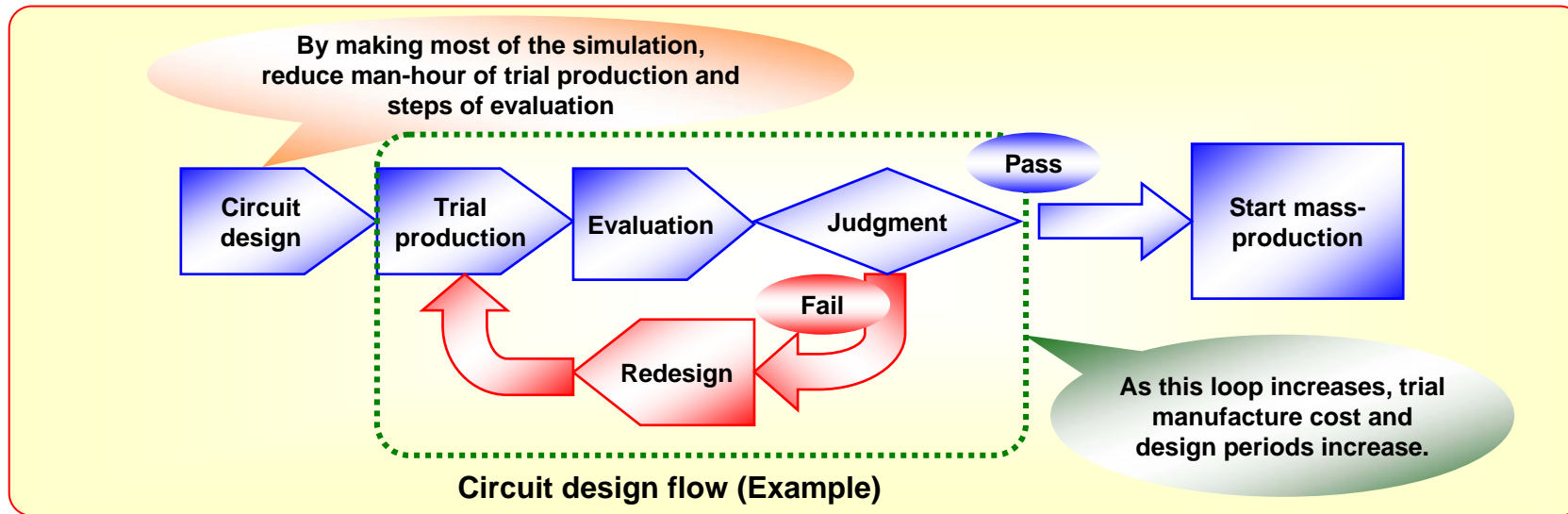
4. Simulation

Background

Circuit simulation is numerical analysis by means of computation of analog operation of an electronic circuit. The operation of the entire circuit can be verified by representing electronic components (wiring), etc. with mathematical logic models and by using computers, etc.

While there is demand for the shortening of the time for developing electronic products, by making use of simulation in circuit design, the circuit operation can be verified prior to confirmation with actual equipment by using circuit board operation. This will contribute to the shortening of the design period and cost reduction as well as to securing quality starting from the design stage.
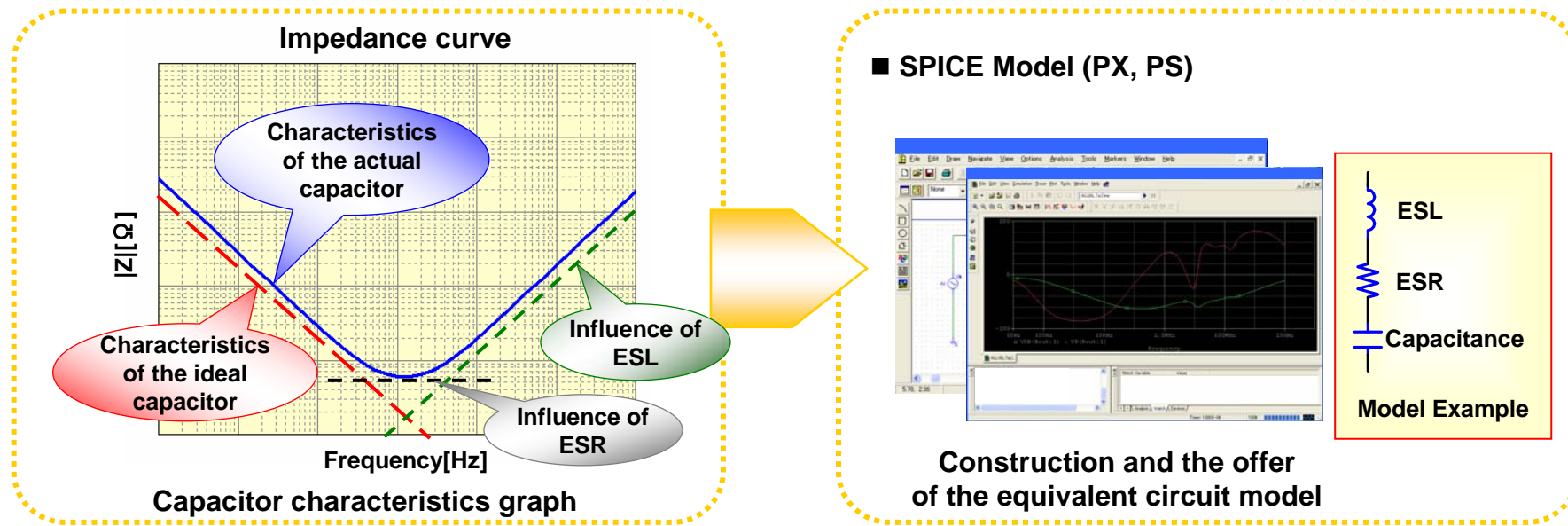
By making most of the simulation, reduce man-hour of trial production and steps of evaluation

Circuit design → Trial production → Evaluation → Judgment — Pass → Start mass-production

Fail → Redesign

As this loop increases, trial manufacture cost and design periods increase.

Circuit design flow (Example)

Use of the simulation ➤ **The reduction of repeating the trial manufacturing reduces cost and a designing period.**

➤ **By verifying circuit designs in the designing stage, early problem presentation become possible.**

4. Simulation

Capacitor models

In order to carry out simulation, modeling of various electronic components is required. The models with higher accuracy lead to higher accuracy in circuit simulation as well. This is also true of capacitors. A capacitor is an element that is mainly made up of the components of capacitive reactance. In the case of being made up of only the pure reactance components, impedance decreases indefinitely with an increase in frequency. However, there actually are parasitic factors such as those of lead wires. These are generally expressed as ESR (Equivalent Series Resistance) and ESL (Equivalent Series Inductance), and the frequency characteristics of the capacitor actually becomes in the form of V as shown in the graph below. In order to define ESR and ESL affecting as parasitic factors to circuit operation, ESR and ESL need to be reflected in capacitor models.
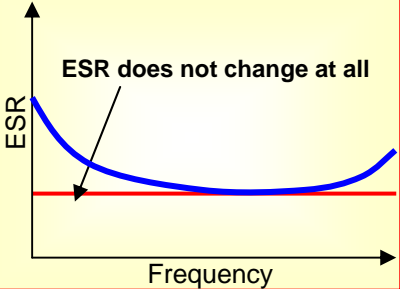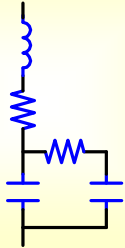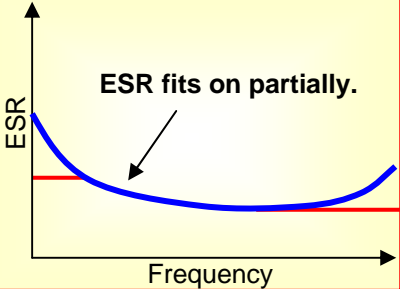
Impedance curve

Characteristics of the actual capacitor

Characteristics of the ideal capacitor

Influence of ESL

Influence of ESR

$|z|[\Omega]$

Frequency[Hz]

Capacitor characteristics graph

■ **SPICE Model (PX, PS)**

ESL

ESR

Capacitance

Model Example

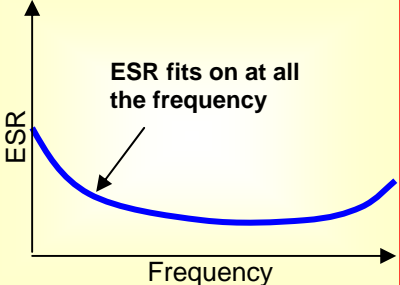**Construction and the offer of the equivalent circuit model**

Modeling of each circuit components is necessary for simulation.

For the capacitors as well as the others, their model is necessary for ESR, ESL and capacitance to correspond with their actual characteristics.

4. Simulation

Presentation of capacitor equivalent models

Equivalent circuit models that are handled by us are presented here.

3-element model	**This is a general capacitor equivalent circuit.** **The capacitor changes in capacitance and ESR over frequencies. However, this model cannot show the changes. This model is only used for convenience to perform simple simulation.**	**ESR does not change at all**
5-element model	**This model adds one step ladder of CR against 3 elements model.** **In specific frequency range, this model can adjust ESR and capacitance component to actual measurement values.**	**ESR fits on partially.**
LDSI model **L: Etching length** **D: Dielectric loss** **S: Skin effect** **I: Interface loss**	**This model includes the structure of the capacitor in details.** **The characteristics can be adjusted to actual values over a wide range of frequencies by using equivalent models of etching depth (L), dielectric loss (D), skin effect (S) and interface loss (I).**	**ESR fits on at all the frequency**

Simulation of frequency characteristics by means of capacitor equivalent models
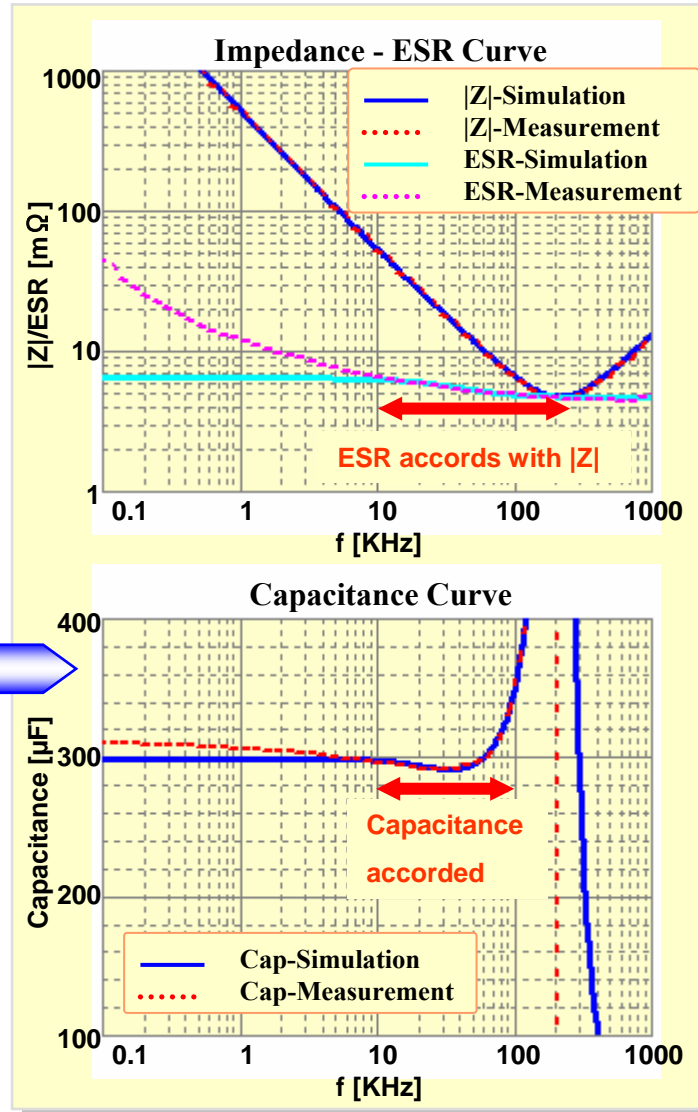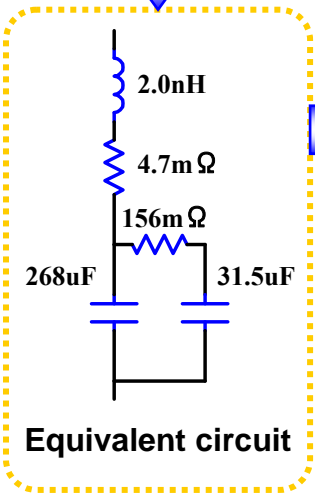
The actual measurement results of frequency characteristics by means of an impedance analyzer are compared with the simulation (AC analysis) results of one of our equivalent models.

In general, the characteristics of a capacitor are defined at a specific frequency. The capacitance is defined at 120 Hz, ESR (or impedance) at 100 kHz or 300 kHz. However, the frequency characteristics of a capacitor are not constant actually, and the 3-element model cannot reflect a change in ESR and a decrease in capacitance at a range of high frequency.

Therefore, by constituting the equivalent circuit of a capacitor with 5 elements, a specific frequency range can be reflected in the circuit. Here the PSE series polymer capacitors are made into a 5-element model and its effect is well verified.

The graphs on the right show the measurement results of frequency characteristics and the simulation (AC analysis) results by means of the 5-element model. It can be well verified that the ESR values coincide at 10 kHz - 300 kHz, and the capacitance values coincide at 10 kHz–100 kHz.

> ➤ **ESR change by frequency**
> ➤ **Capacitance decreases in high frequency range**

5-element model is effective

Sample :

Series : PSE

Voltage : 2.5V

Capacitance :330µF

ESR : 7mΩ

2.0nH

4.7mΩ

156mΩ

268uF   **31.5uF**

Equivalent circuit

Impedance - ESR Curve

— |Z|-Simulation
······ |Z|-Measurement
— ESR-Simulation
······ ESR-Measurement

ESR accords with |Z|

f [KHz]

|Z|/ESR [mΩ]

Capacitance Curve

Capacitance accorded

— Cap-Simulation
······ Cap-Measurement

Capacitance [µF]

f [KHz]

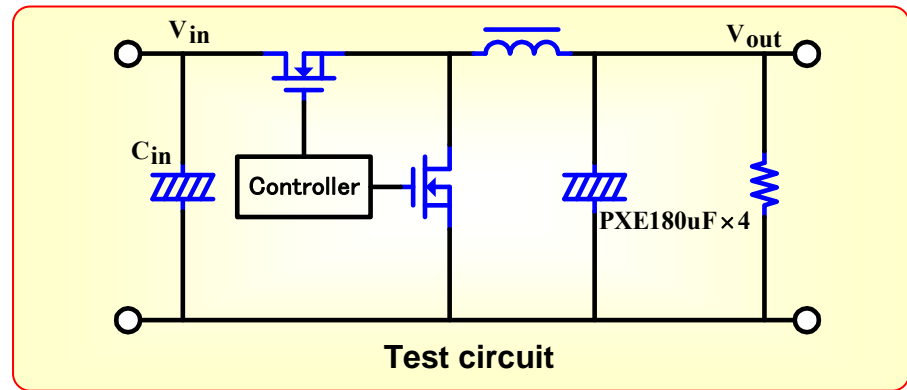# 4. Simulation

Ripple simulation

Here simulation is actually carried out and the validity of the equivalent models is verified. Concerning a method of simulation, simulation of ripple voltage in a buck converter is carried out. When four PXE series polymer capacitors of surface mount type are connected in parallel as output capacitors, the equivalent model simulation is compared with the actual measurement by using an evaluation circuit board in terms of the amplitude of ripple voltage.

The fundamental ripple frequency that includes a major part of ripples is 330 kHz which is the switching frequency, and therefore the 300kHz-measured ESR value, which would be close to the 330kHz, is used to carry out the capacitor simulation. By using an ESR value corresponding to the fundamental ripple frequency, it can be thought that the conventional 3-element model is applicable to modeling the PXE series to be used in simulation. The frequency characteristics (capacitance, ESR and ESL) are measured by means of an impedance analyzer.
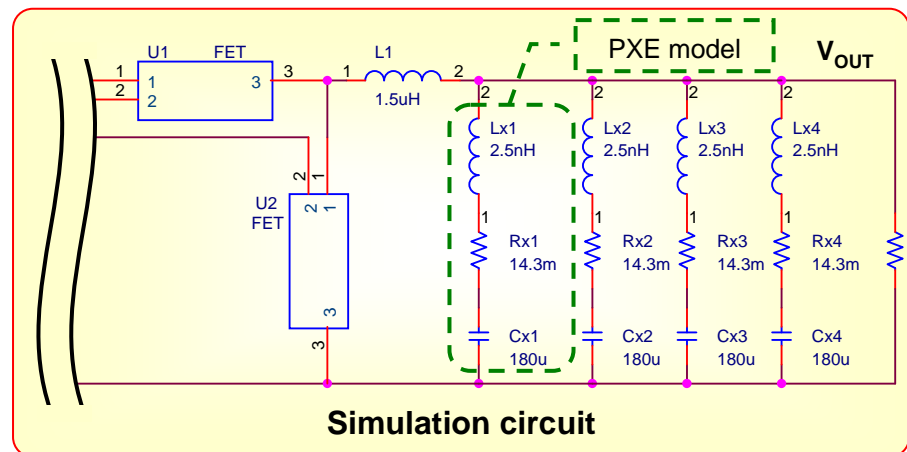
Test Conditions
● SW Regulator :DC-DC Buck Type
● SW Frequency :330kHz
● Inductor :1.5μH
● Input/Output Voltage :12V/1.8V

Capacitor Specifications
● Form: φ5.0×6.1L
● Capacitance:180μF【120Hz】
● ESR:14.3mΩ【300KHz】
● ESL:2.5nH【40MHz】
● Rating:6.3V

Test circuit

**The comparison of
simulation and actual equipment measurement**

Simulation circuit

4. Simulation

The result of actual measurement and the result of the simulation are shown below. According to the waveform shown on the lower left, which is measured by means of the evaluation circuit board, the amplitude of output ripple voltage becomes 15.6 mV. The result of simulation shown on the lower right, output ripple voltage is 15.4 mV, which is almost equivalent to the measured data (15.6mV).

It was verification by simple simulation by using a capacitor model (equivalent circuit). Thus, by utilizing simulation, circuit characteristics can be verified on the desk.

Simulation is a convenient tool that helps increase efficiency in circuit design. In order to carry out simulation, information is required on various components, and the accuracy of the component model (equivalent circuit) becomes the accuracy of simulation. This is true of capacitors as well.

Lastly, actual circuit boards involve the inductance and resistance matters of wiring and also the parasitic factors in each individual component. Therefore it should be noted that the last verification is required by actual equipment to be designed.

Measurement result

Simulation result